Brain and Cognition 77 (2011) 292–297

Contents lists available at SciVerse ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Effects of the global and local attention on the processing of categorical and coordinate spatial relations

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ARTICLE INFO

Article history:
Accepted 26 July 2011

Keywords:
Global and local attention
Categorical and coordinate spatial relations
Hierarchical stimulus
Receptive field size

ABSTRACT

Participants made categorical or coordinate spatial judgments on the global or local elements of shapes. Stimuli were composed of a horizontal line and two dots. In the Categorical task, participants judged whether the line was above or below the dots. In the Coordinate task, they judged whether the line would fit between the dots. Stimuli were made hierarchical so that the global patterns composed of a "global line" made of local dots-and-line units, and "global dot" made of a single dots-and-line unit. The results indicated that the categorical task was better performed when participants attended to the local level of the hierarchical stimuli. On the other hand, the coordinate task was better performed when they attended to the global level. These findings are consistent with computer simulation models of the attentional modulation of neuronal receptive fields' size suggesting that (1) coordinate spatial relations are more efficiently encoded when one attends to a relatively large region of space, whereas (2) categorical spatial relations are more efficiently encoded when one attends to a relatively small region of space.

1. Introduction

According to Kosslyn (1987, 1994), the brain computes two kinds of spatial relationships in different neuronal systems. On one hand, a *Categorical* spatial processing subsystem assigns a category such as left/right or above/below to a spatial relation. On the other hand, a *Coordinate* spatial processing subsystem represents precise location and distance information, such as "object A and object B are 5 cm apart", by use of a metric coordinate system. Kosslyn hypothesized that the two systems reside in the independent neuronal substrata in the left and the right hemispheres (Hellige, 1993; Jager & Postma, 2003; Laeng, Chabris, & Kosslyn, 2003).

In a simulation study, Kosslyn, Chabris, Marsolek, and Koenig (1992) reported that networks that receive input from smaller "receptive fields" computed categorical spatial relations efficiently, whereas networks that receive input from larger "receptive fields" computed coordinate spatial relations efficiently. To account such a finding, Jacobs and Kosslyn (1994) proposed a computational theory of spatial processing. This maintains that categorical relations between objects would be more efficiently obtained by prioritizing information from neural units with small, non-overlapping, receptive fields. For categorical relations, an observer can attend to one object and group the receptive fields for the surrounding space into "bins". This would help to categorize the relation of a second object that falls into one of these bins. On the other hand, distance between objects would be more efficiently obtained by attending to neural units with large, overlapping, receptive fields. This latter argument is counter-intuitive, because neurons with large receptive fields would have lower spatial resolution. However, the spatial resolution achieved by observers in human psychophysical experiments is much higher than the resolution that has been estimated from the size of receptive field of the neurons involved in object localization (e.g., Eurich & Schwegler, 1997; Westheimer & McKee, 1997). The concept of coarse coding mechanism offers a plausible solution to this puzzle (e.g., Ballard, 1986; Fahle & Poggio, 1981). That is, more precise localization than that of each unit can be obtained from decoding the population activity of several units with overlapping receptive fields (Hinton, McClelland, & Rumelhart, 1986).

The Jacobs and Kosslyn (1994) model implies that size of attentional focusing would play an important role in spatial relation processing. Shulman and Wilson (1987) demonstrated that attending to the smaller and larger structures of a stimulus facilitated the processing of high and low spatial frequencies respectively. Since high and low spatial frequencies would be efficiently encoded by smaller and larger receptive fields respectively, these results suggest that neurons with small receptive fields would receive attentional top-down bias when focusing on a small region and vice versa for neurons with larger receptive fields. Moreover, the

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doi:10.1016/j.bandc.2011.07.008

neuronal responsiveness in early visual cortical areas could be dynamically changed by attentional top-down modulation (Connor, Preddie, Gallant, & Van Essen, 1997; Müller, Bartelt, Donner, Villringer, & Brandt, 2003; Womelsdorf, Anton-Erxleben, Pieper, & Treue, 2006). Such studies imply that receptive field size of visual neurons is not static, but dynamically modifiable by attentional modulation. Thus, it seems possible to extend the Jacobs and Kosslyn (1994) model to the domain of attention; size of attention would have systematic effects on categorical and coordinate spatial processing. Specifically, it is inferred that narrow and wide attentional focusing would have beneficial effect in processing categorical and coordinate spatial relations respectively.

Okubo, Laeng, Saneyoshi, and Michimata (2010) specifically examined the effect of exogenous attention (i.e., rapid and involuntary capture of attention by an abrupt stimulation) on the processing of categorical and coordinate spatial relations. They found that the deployment of exogenous attention facilitated categorical spatial processing whereas it disrupted coordinate spatial processing at least when the spatial relation judgment was substantially difficult. In addition, there was no systematic effect of cue size. Carrasco and her colleagues have suggested that exogenous attention may reduce the size of receptive fields at an attended location (e.g., Gobell & Carrasco, 2005; Yeshurun & Carrasco, 1998, 2000), based on their finding that the deployment of attention improved a vernier acuity judgment, which would be efficiently processed by the smaller receptive fields (Yeshurun & Carrasco, 1998). The same researchers have also found that exogenous attention increased perceived spatial frequency and 'decreased' perceived gap size, which is also consistent with the idea that the receptive field size at the cued location was reduced (Gobell & Carrasco, 2005). Moreover, their interpretation is consistent with the neurophysiological evidence showing that receptive fields of neurons in early extrastriate cortex shrunk around the attended region (e.g., (Moran & Desimone, 1985; Reynolds & Chelazzi, 2004; Treue, 2001). This reduction of receptive filed size may have facilitatory effects on the processing of categorical spatial relations, which are more efficiently processed by smaller receptive fields. On the other hand, it may hamper the processing of coordinate spatial relations, which are more efficiently processed by larger receptive fields (Jacobs & Kosslyn, 1994; Kosslyn et al., 1992).

In another subsequent study, Laeng, Okubo, Saneyoshi, and Michimata (2011) conducted two experiments to examine the effect of endogenous attention (i.e., the slow and voluntary allocation of attention according to a cognitive goal), using the same task and stimulus set as Okubo et al. (2010). The critical variable of this experiment was the cue size, since it is known that observers can voluntarily adjust the size of the attention window. Indeed, it was found that smaller and larger cue had beneficial effects in processing the categorical and coordinate spatial relations respectively.

The purpose of the present study is to further examine the hypothesis that the scope of endogenous attention would have differential effect in processing categorical and coordinate spatial relations. In this study, we used a very different experimental paradigm from those of the previous study by Okubo et al. (2010) and Laeng et al. (2011). It is known that visual attention can flexibly expand and narrow between the global and local structural levels of a stimulus and several studies have directly explored this by using hierarchical stimuli (Hübner, 2000; Hübner & Volberg, 2005; Kinchla, Solis-Macias, & Hoffman, 1983; Navon, 1977). Thus, in the following experiment, we asked participants to make categorical or coordinate spatial judgments on the local or global shape of hierarchical stimuli. Specifically, we adopted stimuli originally used by Rybash and Hoyer (1992) in a study of hemispheric asymmetries of the two types of spatial relations, and the stimuli were made hierarchical. We predicted that the categorical task would be better performed when participants attended to the local level than when they attended to the global level. Conversely, the coordinate task would be better performed when they attended to the global level than when they attended to the local level.

At the time of preparation of the present paper, Borst and Kosslyn (2010) reported a similar experiment. Their participants were presented with the "classic" Navon hierarchical letter stimulus to control the size of attention. The Navon stimulus "primed" an immediately subsequent judgment of either categorical or coordinate relation in the traditional dot-and-bar stimulus (Hellige & Michimata, 1989). As predicted, the coordinate task was better-performed after responding to the global level of a Navon stimulus, while the categorical task was better-performed after responding to the local level.

Borst and Kosslyn's (2010) study is an interesting precedent for the present study. However, the priming method used in that study does not guarantee that the same effect can generalize to fast or immediate change in the scope of attention. That is, in Borst and Kosslyn's study, there was a considerable time lag between the first task and the second task. In their experiment, a Navon letter remained on the screen until participants pressed a response key. After the response, a blank screen was presented for 75 ms, followed by a stimulus presentation for Categorical or Coordinate task. In the present study, the adjustment of the scope of attention was designed to occur at the same time that the participants processed the spatial relations. Indeed, our previous results (Laeng et al., 2011; Okubo et al., 2010) strongly suggest that the effects of endogenous attention are accrued very fast (within the first 350–450 ms).

2. Method

2.1. Participants

Twenty-six undergraduate and graduate students (15 males and 11 females) at Teikyo University, Tokyo, Japan, volunteered as participants. Participants' ages were not asked, but they were approximately ranged from 18 to 25. They are all right-handed and had normal or corrected to normal visual acuity in both eyes. Familial sinistrality was not assessed. They signed an informed consent form and were unaware of the hypothesis under investigation.

2.2. Apparatus

Stimuli were presented on a Mitsubishi 21 in. CRT monitor connected to an Apple PowerBook G4 computer running Mathworks Matlab 5 with PsychToolBox (Brainard, 1997; Pelli, 1997). A 10-key pad was connected to the computer and served as two-key response console.

2.3. Stimuli

Stimuli were composed of a horizontal line and two square dots. Two dots were positioned above or below the line. In the Categorical task, participants judged whether the line was above or below the dots. In the Coordinate task, they judged whether the line would fit between the dots (see Rybash & Hoyer, 1992, for the validity of using such stimuli and tasks for examining categorical and coordinate spatial relations). The stimuli were made hierarchical so that the global patterns was composed of a "global line" made of 3–5 local dots-and-line units, and of two "global dots" each made of a single dots-and-line unit (see Fig. 1). In local dots-and-line units, the line was 1.6 mm thick and 5.6, 8.8, or 12 mm long, and the square dots were 2.4 mm on a side. Half of the patterns had the line positioned 4 mm above the dots, and