Temporal dynamics of decisions on spatial categories and distances do not differ

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ABSTRACT

It has been proposed that spatial relations can be encoded in two different ways: categorically, where the relative position of objects can be described in prepositional terms (to the left/right, above/below, etc.) and coordinately, where a precise distance between the objects is assessed. Processing of categorical and coordinate spatial relations is believed to rely on the parvo- and magnocellular pathways or small and large receptive fields, respectively. We employed the response signal speed-accuracy trade-off procedure to obtain a description of temporal dynamics of information transfer for categorical and coordinate spatial decisions. In the two tasks the same procedure and stimuli were used, while the instructions called for different types of discrimination. We found no differences in information accrual speed between the tasks as would be expected from the parvo/magno cells or small/large receptive fields distinction. Theoretical consequences of these findings are discussed.

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1. Introduction

The brain instantly begins processing visual scenes when we open our eyes and the representations that we derive from incoming visual information can differ depending on our goals. For instance, in some situations it is enough to know that the bed stands to the left of the table. On the other hand, the assessment of distance separating two pieces of furniture might be more useful when one wants to pass between them. Thus, one representation would characterize relative spatial positions, while the other would involve exact distances. In the literature these two types of spatial representation are referred to as categorical and coordinate, respectively (Kosslyn, 1987; Kosslyn et al., 1989).

The main evidence supporting the idea that there is more than one way to encode spatial relations comes from studies on relative hemispheric differences in reaction times and/or accuracy between categorical and coordinate tasks. Categorical spatial decisions are reached faster and/or with fewer errors when the stimuli are presented in the right visual hemifield—the left hemisphere (LH) than in the left visual field—the right hemisphere (RH) (Kosslyn et al., 1989; Van der Ham, van Wezel, Oleksiak, & Postma, 2007). Likewise, decisions about coordinate spatial relations are faster and/or with higher accuracy when stimuli are shown to the RH than stimuli shown to the LH (Hellige & Michimata, 1989; Kosslyn et al., 1989; Michimata, 1997; Rybash & Hoyer, 1992). Still, a number of studies failed to find such interactions (Sergent, 1991; Wilkinson & Donnelly, 1999), especially for the categorical task and the LH advantage

(Hellige & Michimata, 1989; Van der Lubbe, Scholvinck, Kenemans, & Postma, 2006; see for a review Jager & Postma, 2003). Nevertheless, it is agreed that the reported hemispheric asymmetry is linked to the computational distinction between categorical and coordinate processes (Baker, Chabris, & Kosslyn, 1999).

Another line of evidence for two modes of encoding spatial relations comes from neural network simulations (Kosslyn, Chabris, Marsolek, & Koenig, 1992; Jacobs & Kosslyn, 1994; Baker et al., 1999). A neuronal network model that was trained to compute categorical and coordinate mappings performed better when hidden units were split into two subsystems: one with the input units carrying information to the categorical output units and the other set of input units contributing to the coordinate output units (Kosslyn et al., 1992).

Importantly, receptive field (RF) size was examined as a potential physiological factor that might underlie the proposed dissociation. It was suggested that larger, overlapping RFs might be more efficient in encoding precise spatial locations, the so called coarse coding mechanism (O'Reilly et al., 1990), which in turn might be relevant for coordinate judgments (Kosslyn et al., 1992). Accordingly, it was hypothesized that due to smaller, non-overlapping RFs space could be carved into distinct bins corresponding to spatial categories like for instance above/below or left/right (Kosslyn et al., 1992).

The finding that the computer network's performance in coordinate task was improved as RF size increased supported the first premise. Additionally, when the network was trained on the coordinate task, it spontaneously expanded the size of RFs, whereas training on the categorical task resulted in spontaneous development of small RFs (Kosslyn et al., 1992; Jacobs & Kosslyn, 1994; Baker et al., 1999).

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Kosslyn and co-workers (1992) as well as Roth and Hellige (1998) linked the hypothesized properties of the RFs contributing to the two spatial tasks to the well-studied classes of neurons: magno and parvo cells. In short, magno cells that contribute mainly to the magnocellular pathway have generally larger RFs, respond to higher temporal and lower spatial frequencies, display more rapid conduction of impulses and respond transiently and with shorter latencies (for a review see Merigan & Maunsell, 1993). On the other hand, parvo cells that contribute mainly to the parvocellular pathway have relatively smaller RFs, are more sensitive to lower temporal and higher spatial frequencies, their responses are sustained and display later response onsets.

Subsequently, Roth and Hellige (1998) and Hellige and Cumberland (2001) showed that a red background, which is known to disrupt processing relying on the magnocellular pathway (Livingstone & Hubel, 1984; de Monasterio & Schein, 1980; Breitmeyer & Williams, 1990), decreased performance in the coordinate task but not in the categorical task.

The suggestion that coordinate tasks might rely more on processing of the magnocellular pathway or simply larger RFs and categorical tasks more on the parvocellular pathway or smaller RFs seems feasible. However, some logical counterarguments can be raised. Namely, in general coordinate tasks require a somewhat higher spatial resolution of the representation to solve correctly the task and this intuitively would be more adequately accomplished by the means of smaller RFs of parvocellular neurons. In a similar line of reasoning one would rather expect an involvement of the magnocellular large RFs in computing rather crude positions in the categorical tasks. Moreover, in the vast majority of the studies the reported reaction times for coordinate tasks are longer than for categorical (e.g. Kosslyn et al., 1989; Michimata, 1997; Van der Ham et al., 2007; Van der Lubbe et al., 2006), which would counter the well known faster information transfer of the magnocellular system (e.g. Dreher, Fukada, & Rodieck, 1976; Schmolesky et al., 1998). Finally, in all divided-field presentation studies that investigated categorical and coordinate representations stimuli were presented parafoveally (at an eccentricity not larger than 3.5°), where visual input is predominantly received by parvocellular neurons (Azzopardi, Jones, & Cowey, 1999).

Considering just described discrepancies we set out to clarify whether the magno system or large RFs are indeed preferentially involved in processing categorical representations and whether the same is true for the interaction between coordinate tasks and parvo system or small RFs. We speculated, that the two tasks might differ in processing speed, since parvo- and magnocellular neurons differ in both, conduction velocity of their afferents (Dreher et al., 1976; Schiller & Malpeli, 1978; So & Shapley, 1979; Bullier & Henry, 1980; Vidyasagar, Kulikowski, Lipnicki, & Dreher, 2002) and in response latency (e.g. Munk, Nowak, Girard, Chounlamountri, & Bullier, 1995; Schmolesky et al., 1998; Maunsell et al., 1999). Alternatively, if there is no specific involvement of parvo and magno cells, Kosslyn and co-workers' model explicitly predicts that plainly the RF size plays a role in the categorical–coordinate spatial relations distinction. When we consider RFs sizes as a dissociating factor we still can expect to observe different speeds of information transfer in the two tasks due to the known negative correlation between RF size and response latency, i.e. the smaller RF the longer response delay (Weng, Yeh, Stoelzel, & Alonso, 2005).

The knowledge of temporal dynamics of information transfer in categorical and coordinate tasks will shed light on the question whether two distinct neuronal populations, corresponding to small and large RFs or parvo and magno pathways, are involved in these different spatial decisions. Such information can be obtained by the response signal speed-accuracy trade-off (SAT) procedure (Wickelgren, 1977), which allows an approximation of the minimal time necessary for performance

to depart from chance level. Furthermore, the SAT procedure estimates the speed at which performance reaches an asymptotic level, i.e. the information accrual rate.

Apart from the temporal description of the processes at stake, the SAT procedure has an advantage of controlling any possible speed-accuracy trade-offs. In a classical reaction time study most of the recorded data points lie in the vicinity of asymptotic performance. Since at low error rates variation in reaction times is large for extremely small changes in error percentage, speed-accuracy trade-off factor can exert a significant influence on results (Wickelgren, 1977). Moreover, a difference in response times between two conditions can be a consequence of differences in asymptotic accuracy, speed of processing or both (Reed, 1973; McElree & Dosher, 1989; Wickelgren, 1977). To control for such speed-accuracy trade-offs and to objectively compare the processing speed of cognitive tasks irrespective of differences in asymptotic performance we employed the above-mentioned SAT procedure that had been successfully implemented in other studies (e.g. Carrasco & McElree, 2001; Carrasco, McElree, Denisova, & Giordano, 2003; Carrasco, Giordano, & McElree, 2006; Dosher, Han, & Lu, 2004).

To recapitulate, on theoretical grounds we could expect differences in speed of information flow, represented in our study by the parameters estimates of the SAT function, between categorical and coordinate tasks. Owing to the contributions of magnocellular pathway or alternatively larger RFs the coordinate decisions are hypothesized to be processed faster compared to the categorical decisions that are believed to rely more on the parvocellular pathway or smaller RFs. However, it might be that we do not find any temporal dynamics differences implying that the mechanisms or neurons' features underlying the two types of spatial decisions are of some other sort than theorized by Kosslyn and others. It is also likely that we find a pattern of results where the categorical task is processed faster than the coordinate task, pointing to the aforementioned different spatial scale requirements for the two representations.

2. Methods

2.1. Subjects

Five subjects aged from 22 to 27 years old participated in our experiment. Four of the observers were unaware of to the purposes of this study and one was an author (AO). All subjects had normal or corrected-to-normal vision. The naive subjects were paid for their participation.

2.2. Stimuli

The stimuli were presented on a standard color display (Sony CPD-E450, Sony Corporation, United States). The monitor resolution was set to 1280 × 1024 pixels with a refresh rate of 85 Hz. The responses and reaction times were recorded using the USB response pad (model RB 830 Cedrus®). Visual stimuli were generated with Presentation® 9.90 software (Neurobehavioral Systems).

With some adjustments, we used stimuli and instructions similar to those employed in the Van der Ham et al. (2007) study. The stimuli were composed of two black crosses displayed simultaneously on a light gray background, left and right of center, each subtending 2.6 × 2.5° of visual angle (Fig. 1). Each of the crosses had an accompanying dot subtending .14 × .13° of visual angle, which could appear at one of three distances from the center of the cross in any of the four quadrants (Fig. 2). The crosses were aligned horizontally with the level of the fixation dot and their inner edges were placed 2.6° of visual angle away from the center.