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Brief communication

Varying the scope of attention alters the encoding of categorical and coordinate spatial relations

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ABSTRACT

Two types of representations can be used to specify spatial relations: Coordinate spatial relations representations specify the precise distance between two objects, whereas categorical spatial relations representations assign a category (such as above or below) to specify a spatial relation between two objects. Computer simulation models suggest that coordinate spatial relations representations should be easier to encode if one attends to a relatively large region of space, whereas categorical spatial relations should be easier to encode if one attends to a relatively small region of space. We tested these predictions. To vary the scope of attention, we asked participants to focus on the local or global level of Navon letters, and immediately afterwards had them decide whether a dot was within 2.54 cm of a bar (coordinate judgment) or was above or below the bar (categorical judgment). Participants were faster in the coordinate task after they had just focused on the global level of a Navon letter whereas they were faster in the categorical task after they had just focused on the local level. Although we did not test the hemispheric lateralization of these effects, these findings have direct implications for theories of why the cerebral hemispheres differ in their relative ease of encoding the two kinds of spatial relations.

1. Introduction

Researchers in cognitive psychology and cognitive neuroscience have often shown that what intuitively may seem to be a single ability, such as memory or perception, actually comprises multiple specialized functions. Such research has further shown that even what appear to be individual specialized functions often can be further subdivided. One example of such research has shown that spatial relations can be encoded in more than one way, by processes that encode coordinate versus categorical spatial relations representations (Kosslyn, 1987, 2006). Coordinate representations preserve the precise metric distance between objects and specify their locations within a coordinate system. In contrast, categorical representations assign a category, such as "left of," "above," or "behind," to characterize the spatial relation between objects or parts of an object. The two types of spatial relations serve different functions. Coordinate spatial relations representations are used to guide one's actions, such as reaching and manipulating an object or navigating efficiently in an environment. In contrast, categorical spatial relations representations are used to recognize shapes that are contorted in an unfamiliar way, by preserving the category of relations among parts (e.g., an upper arm and forearm remain "connected by a hinge" no matter how they are positioned; Laeng, Carlesimo, Caltagirone, Capasso, & Miceli, 2002).

A growing number of findings from behavioral (e.g., Hellige & Michimata, 1989; Kosslyn et al., 1989), neuroimaging (e.g., Baciu et al., 1999; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Slotnick & Moo, 2006), transcranial magnetic stimulation (TMS, e.g., Trojano, Conson, Maffei, & Grossi, 2006), and lesions studies (e.g., Laeng, 1994; Palermo, Bureca, Matano, & Guariglia, 2008) document that the brain computes categorical spatial relations more efficiently in the left cerebral hemisphere whereas it computes coordinate spatial relations more efficiently in the right cerebral hemisphere (for reviews, see Jager & Postma, 2003; Kosslyn, 1987, 2006). Although researchers now generally agree that the two types of spatial relations are processed more efficiently in different hemispheres, the cause of this hemispheric specialization remains to be determined. In the present study, we generated predictions on the basis of what is known about the hemispheric specialization of spatial relations representation and processing.

One explanation for the observed lateralization of spatial relations processing hinges on differences in the sizes of regions of space attended to by the two hemispheres. Kosslyn, Chabris, Marsolek, and Koenig (1992) report a series of neural-network computer simulations in which they showed that (a) networks receiving input from units with small non-overlapping receptive fields computed categorical spatial relations representations more effectively than coordinate spatial relations representations, and

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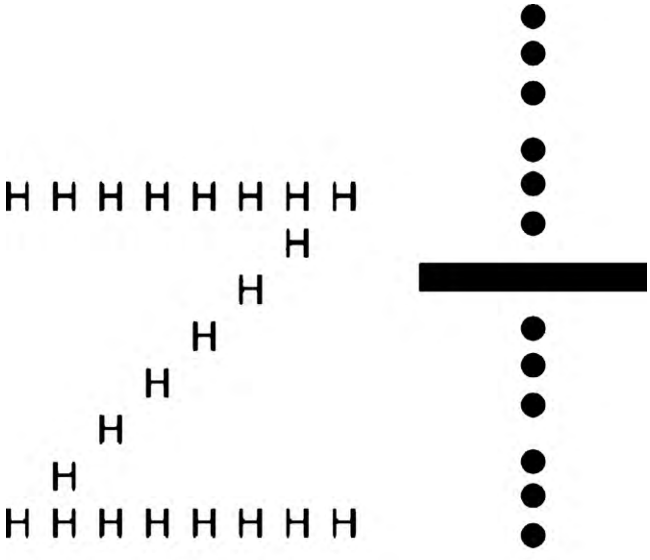

Fig. 1. Examples of (a) a stimulus used in the local condition of the Navon task, and (b) the 12 locations of the dots in the spatial relations tasks, only one dot was shown at a time.

that (b) networks receiving input from units with large overlapping receptive fields computed coordinate spatial relations representations more effectively than categorical spatial relations representations. Small non-overlapping receptive fields served to carve space into small bins, and the relations among these bins were easily specified; in contrast, large overlapping receptive fields can use coarse coding to register metric information about the input (e.g., O'Reilly, Kosslyn, Marsolek, & Chabris, 1990). Jacobs and Kosslyn (1994), using more sophisticated models, replicated these findings.

And in fact, researchers have presented evidence that the hemispheres do differ in the scope of space that typically is efficiently encoded. For example, lesions of the right temporo-parietal junction impair selectively the processing of an overall pattern whereas lesions of the left temporo-parietal junction impair selectively the processing of component parts of a pattern (e.g., Lamb, Robertson, & Knight, 1989). In addition, using a divided-visual-field method, Kosslyn, Anderson, Hillger, and Hamilton (1994) found that normal participants could compare two diagonal lines that were far apart more easily when the stimuli were presented briefly in the left visual field (and hence initially encoded by the right hemisphere) than when they were presented briefly in the right visual field (and hence encoded initially by the left hemisphere). This finding makes sense if the right hemisphere registers input from larger regions of space than does the left. Similarly, people generally can compare relatively low spatial frequency displays better when they are presented briefly to the left visual field, and relatively high spatial frequency displays better when they are presented briefly to the right visual field (e.g., Christman, 1997).

In the experiment reported here, we investigate whether attending to relatively large regions of space facilitates encoding coordinate spatial relations representations more than encoding categorical spatial representations, whereas attending to relatively small regions of space has the reverse effect. In order to prime participants' attention to relatively large or small regions of space, we used Navon (1977) stimuli; these stimuli consist of large letters that are composed of many small letters (see Fig. 1a). We asked participants to make a decision based either on the large (global) letter or on the small (local) letter. After each presentation of a Navon stimulus, we presented a horizontal bar and dot (see Fig. 1b). In the categorical task, participants were asked to determine whether the dot was above or below the bar. In the coordinate task, participants decided whether the dot was located within 2.54 cm (one inch) from the bar (this task was introduced by Hellige & Michimata, 1989). If encoding categorical spatial relations representations is achieved by delineating small discrete regions in space, then participants should be more efficient in the categorical task when their attention had just been set in the Navon task to focus on small, local areas rather than large, global areas. And if encoding coordinate spatial relations representations is achieved by coarse coding, then participants should be more efficient in the coordinate task when their attention had just been set to focus on large, global areas than on small, local areas.

2. Methods

2.1. Participants

Thirty-six right-handed adults with normal or corrected-to-normal vision (20 females and 16 males with a mean age of 21 years and 2 months) from Harvard University and the local community volunteered to participate for pay or course credit. Data from one additional participant were not analyzed because he performed at chance levels, and hence we had no reason to believe that he actually performed the tasks. Participants were randomly assigned to the global or local conditions of the Navon task (for a total of 18 participants per condition). There were no significant gender and age differences between the two groups, $ts < 1$. All participants provided written informed consent and were tested in accordance with national and international norms governing the use of human research participants. The research was approved by the Harvard University Institutional Review Board.

2.2. Materials

Stimuli were presented on a 17-in IBM monitor (1280×1024 pixels resolution and refresh rate of 75 Hz). For the Navon task, we created two sets of 16 Navon letters – one set for each condition (local or global). Each global letter was created in a 8×8 matrix as illustrated in Fig. 1a. Global letters subtended 8° of visual angle and local letters subtended 1° of visual angle. Stimuli in the global condition were H or R letters, composed by sets of small letters, A, D, F, K, P, T, V or Z. Stimuli in the local condition were A, D, F, K, P, T, V or Z global letters which had H or R local letters. For the categorical and coordinate tasks, we created 12 dot-bar stimuli (adapted from Hellige & Michimata, 1989). The horizontal bar ($4° \times 0.4°$) was always displayed in the center of the screen and a dot (0.2° of visual angle) was positioned at one of 12 locations above or below the bar (see Fig. 1b). Starting with the dot location nearest to the bar, dots were placed at 0.5°, 1°, 1.5°, 2.5°, 3°, and 3.5° of visual angle from the bar.

2.3. Procedure

Participants were tested individually, sitting 73 cm from a computer screen, with their heads positioned on a chin rest. On each trial, a black fixation point (subtending 0.4° of visual angle) was first presented for 1000 ms on a white background. Participants were asked to focus their gaze on the fixation point. Then, a Navon letter was displayed and remained on the screen until participants provided an answer by pressing with their non-dominant hand one of two response keys ("q" or "w"). In both conditions (local or global), participants were asked to decide as quickly and accurately as possible whether the letter presented was an "H" or an "R". A blank screen was then shown for 75 ms, followed by one of the 12 dot-bar stimuli, which was presented for 150 ms followed by a blank screen (2000 ms). In the categorical task, participants decided whether the dot appeared above or below the bar. In the coordinate task, participants decided whether the dot was located within an inch (2.54 cm) from the edge of the bar. For both spatial relations judgments, participants used their dominant hand to press one of two response keys ("k" or "l"). We recorded separately response times (RTs) and the nature of the responses for the Navon letter judgments and the dot-bar judgments.

Each participant performed the categorical and the coordinate tasks in the same session. The order of the two tasks was counterbalanced across participants. At the beginning of the experiment, participants performed 16 practice trials (with feedback on their answers) on the Navon task, focusing either on the global letters or the local letters depending on the condition to which they were assigned. In each of the spatial relations tasks, participants first performed 12 practice trials with only the dot-bar stimuli, then 12 practice trials combining the Navon task and one of the spatial relations tasks, and finally performed 64 experimental trials. In the coordinate task, before the first practice trial, participants were shown a dot located 2.54 cm from the bar four times, in order to ensure that they were familiar with this distance.

During the experimental phase, each Navon letter was presented four times and associated two times with dots located above (categorical task) or within 2.54 cm from the bar (coordinate task) and two times with dots located below or more than 2.54 cm from the bar. The order of the trials was random except than no more than

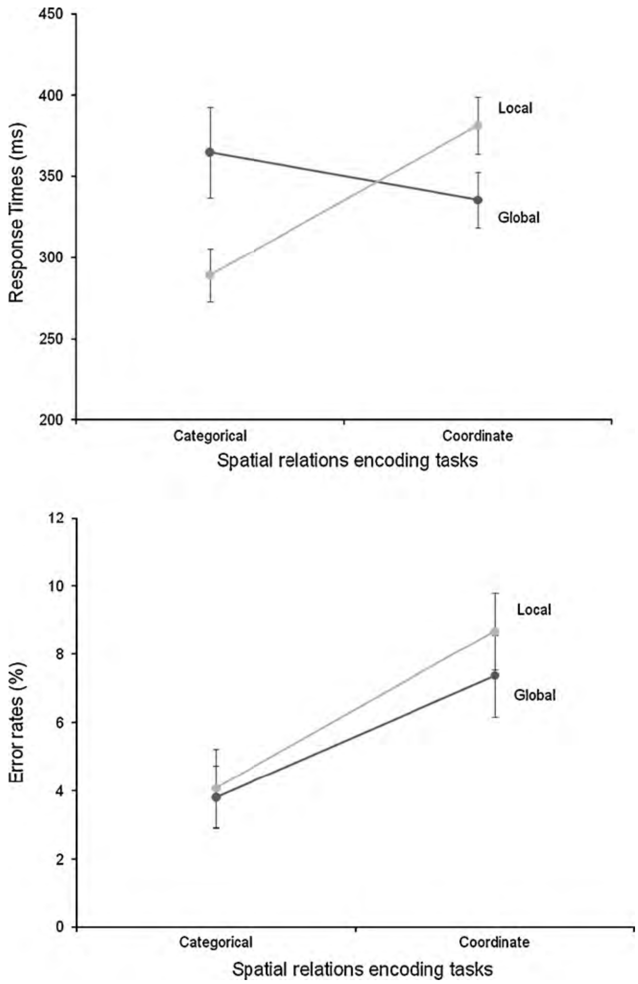

Fig. 2. Response times (RTs) and error rates (ERs) in the categorical and coordinate spatial relations tasks after participants focused on the local or global level of the Navon letters. Error bars denote standard error of the mean (SEM).

three trials with the same answer occurred consecutively, for both the Navon task and the spatial relations tasks.

3. Results

We analyzed separately the data from the Navon task and from the spatial relations tasks. All analyses of RTs included only data from trials on which participants responded correctly. Outliers were defined as RTs greater than 2 SDs from the mean for that participant. Outliers occurred on 1.2–1.8% of the trials in the different tasks. After removing outliers, for each participant, the average RTs for the Navon task, the categorical task and the coordinate task were computed.

As a first step, we conducted a 2 (level of focus for Navon letters, i.e., global or local) $\times$ 2 (type of spatial relations encoding task, i.e., categorical or coordinate) analysis of variance (ANOVA) on the RTs and on the error rates (ERs). In addition, we analyzed participants' performance on the Navon task to determine whether carry-over effects between the Navon task and the spatial relations tasks could account for the pattern of interactions observed on the spatial tasks. For each of the analyses, we report the effect size, either in the ANOVA (partial eta squared) or in terms of the difference of the means (Cohen's d). Preliminary analyses revealed no effect of the gender of the participants or of the order of the tasks on the dependent variables; thus we pooled the data over these variables.

As is evident in Fig. 2, a two-way mixed-design ANOVA on the spatial relations tasks RTs revealed that the level of focus on the Navon figures did affect the two spatial tasks in different ways, as witnessed by a significant interaction between the focus in the Navon task and the type of spatial relations task, $F(1, 34) = 17.63$, $p < 0.0005$, $\eta^2 = 0.34$. In addition, the participants required less time to make their judgments in the categorical task ($M = 326$ ms) than in the coordinate task ($M = 358$ ms), $F(1, 34) = 4.74$, $p < 0.05$, $\eta^2 = 0.12$, but required comparable amounts of time for both levels of focus in the Navon task (local versus global), $F < 1$. Crucially, planned comparisons demonstrated that participants judged whether a dot was above or below the bar (categorical task) faster after having just focused on local rather than global letters, respectively $M = 289$ ms vs. $M = 365$ ms, $t(34) = 2.33$, $p < 0.025$, $d = 0.78$., and judged whether the dot was located within 2.54 cm from the bar (coordinate task) faster after having just focused on global rather than local letters, $M = 335$ ms vs. $M = 381$ ms, $t(34) = 1.88$, $p < 0.05$, $d = 0.64$.

The two-way mixed design ANOVA of the ERs (see Fig. 2) revealed that participants made more errors for coordinate judgments ($M = 8\%$ of errors) than for categorical judgments ($M = 4\%$), $F(1, 34) = 19.47$, $p < 0.0005$, $\eta^2 = 0.36$, but we did not find a significant two-way interaction or main effect of the level of focus for Navon letters, $F\text{s} < 1$. Thus, it is unlikely that the interaction observed with the RTs reflects a speed-accuracy trade-off. In fact, participants were more accurate and required less time to process categorical than coordinate spatial relations, which is consistent with previous results.

Given that the categorical task was easier than the coordinate task, one could argue that difficulty could be at the root of our findings. In order to test this hypothesis, we removed trials on which the dot in the coordinate task was closest to the 2.54 cm criterion (i.e., very difficult trials). Nevertheless, we again found that participants performed the coordinate task faster after having just focused on global rather than local letters, $M = 328$ ms vs. $M = 373$ ms, $t(34) = 1.93$, $p < 0.05$, $d = 0.65$. Thus, it is unlikely that a general effect of difficulty accounts for the results.

Finally, we analyzed RTs and ERs on the Navon task. No significant two-way interactions were observed on RTs, $F(1, 34) = 1.13$, $p = 0.3$, or on ERs, $F < 1$ (see Fig. 3). In addition, the participants required comparable amounts of time and made comparable number of errors for the two levels of focus, $F(1, 34) = 1.07$, $p = 0.31$ for RTs, and $F(1, 34) = 1.72$, $p = 0.20$ for ERs; and for the two types of spatial encoding tasks, $F < 1$ for RTs and $F(1, 34) = 1.47$, $p = 0.26$ for ERs. Thus, any effect of the Navon letters on participants' performance in the spatial relation tasks cannot be attributed to difference in their performance in the Navon task itself.

4. Discussion

As predicted, participants encoded categorical spatial relations faster if they had just focused on local letters in the Navon task, whereas they encoded coordinate spatial relations faster if they had just focused on global letters in the Navon task. The results are consistent with neural-network simulations (Jacobs & Kosslyn, 1994; Kosslyn et al., 1992) indicating that coordinate and categorical judgments operate most efficiently on outputs from units with, respectively, large or small receptive fields.

One could argue that the priming effects we reported do not reflect the effect of the scope of attention but instead are a result of more general hemispheric asymmetries. According to this view, participants are faster in the categorical (or coordinate) task because the recognition of local (or global) letters activates the same hemisphere, not because participants focus their attention on small or large regions of space. However, this account implies that priming should be bidirectional—the spatial relation tasks should have primed the Navon task (as well as vice versa). But

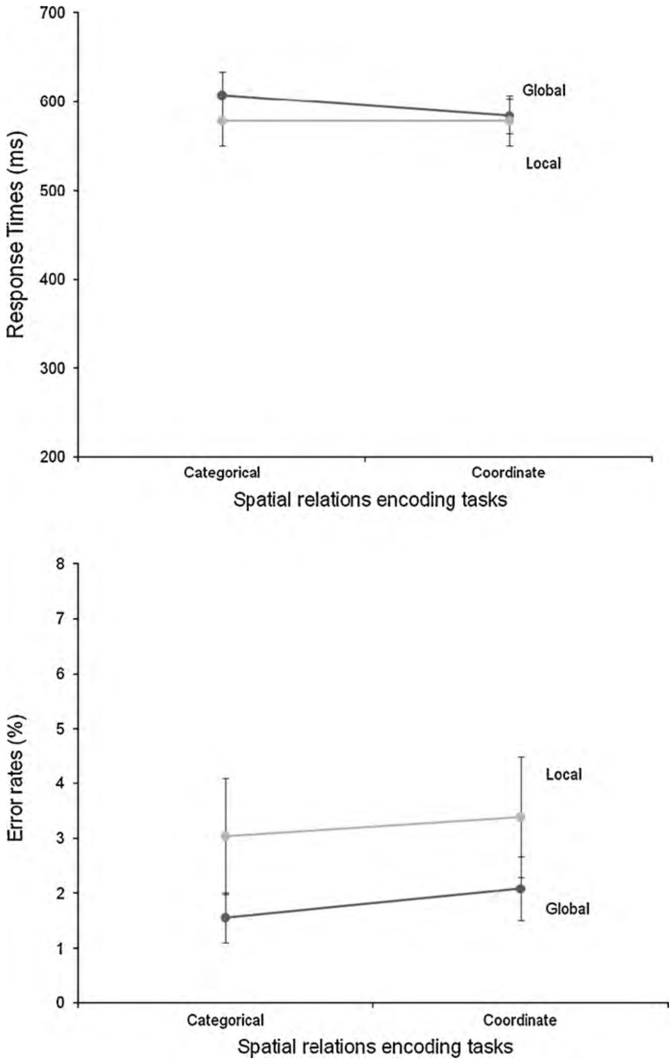

Fig. 3. Response times (RTs) and error rates (ERs) in the two conditions of the Navon task (local and global) for the two types of spatial relations tasks. Error bars denote SEM.

we found no hint of an effect of the spatial relations tasks on the Navon tasks.

Although we did not directly test hemispheric lateralization of the spatial relation processing or of the scope of attention in this study, the present findings make sense given that attention to large objects in a visual scene increases activation in brain regions with relatively large receptive fields whereas attention to small objects increases activation in brain regions with relatively small receptive fields (Rijpkemaa, van Aalderen, Schwarzbachb, & Verstratena, 2008). Such findings dovetail with those noted in the introduction, showing that the left hemisphere more efficiently registers information from smaller regions of space than does the right, but vice versa for larger regions of space.

It is possible that this cerebral lateralization may ultimately arise from anatomical distinctions between the two hemispheres, with the left hemisphere's receiving more inputs from the magnocellular pathway (the neurons of which have relatively large receptive fields) and the right hemisphere's receiving more inputs from the parvocellular pathway (the neurons of which have relatively small receptive fields).

However, even if such anatomical differences exist, they may have simply biased the hemispheres to be more efficient at one or the other type of processing (Laeng et al., 2003). If so, then the observed effects may reflect biases in the sizes of regions that are attended to, not hard-wired anatomical differences. In fact, Kosslyn et al. (1994) present evidence that attentional manipulations can override these biases. And if attentional processes are not only at the root of the present findings, but also of many other aspects of cerebral lateralization, then this may be a step in understanding why cerebral lateralization effects sometimes are difficult to replicate.

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