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A left cerebral hemisphere's superiority in processing spatial-categorical information in a non-verbal semantic format

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ABSTRACT

It has been shown that the left and right cerebral hemispheres (LH and RH) respectively process qualitative or "categorical" spatial relations and metric or "coordinate" spatial relations. However, categorical spatial information could be thought as divided into two types: semantically-coded and visuospatially-coded categorical information. We examined whether a LH's advantage in processing semantic-categorical information is observed in a non-verbal format, and also whether semantic- and visuospatial-categorical processing are differentially lateralized. We manipulated the colors and positions of the standard traffic light sign as semantic- and visuospatial-categorical information respectively, and tested performance with the divided visual field method. In the semantic-categorical matching task, in which the participants judged if the semantic-categorical information of a successive cue and target was the same, a right visual field advantage was observed, suggesting a LH's preference for processing semantic-categorical information in a non-verbal format. In the visuospatial-categorical matching task, in which the participants judged if the visuospatial-categorical information of a successive cue and target was identical, a left visual field advantage was obtained. These results suggest that the processing of semantic-categorical information is lateralized in LH, and we discuss the dissociation between the two types of categorical information.

1. Introduction

Several studies indicate that our visual system computes spatial relations between objects as well as between the parts of objects on the basis of two different perceptual subsystems (e.g., Kosslyn, 1987, 1994, 2006). On the one hand, a subsystem deals with qualitative spatial relation, such as "object A is above/below object B." Such a spatial relation is qualitative (i.e., distance between the objects is not crucial) and it has been referred, due to its abstractness or "digital-like" character, as a "categorical" spatial relation. The other subsystem, on the other hand, would be quantitative in kind and would keep track of the "metric" spatial relations between the same objects, such as "object A is 3 cm/5 cm apart from object B." Such a spatial relation has been termed a "coordinate" spatial relation and can be thought as an "analog" representation of space. The distinction between these two subsystems is supported by several studies indicating the left and right cerebral hemispheres have differential biases for processing these two spatial relations. That is, the left cerebral hemisphere (LH) shows more proficiency in processing categorical spatial relations, whereas the right cerebral hemisphere (RH) shows a better ability in processing coordinate spatial relations (e.g., Hellige & Michimata, 1989; Kosslyn et al., 1989; Laeng & Peters, 1995; Michimata, 1997; for reviews, see: Hellige, Laeng, & Michimata, 2010; Jager & Postma, 2003; Laeng, Chabris, & Kosslyn, 2003, chap. 9). These laterality differences in behavioral performance have also found supporting evidence from neuroimaging studies (e.g., Baciu et al., 1999; Kosslyn, Thompson, Gitelman, & Alpert, 1998; Slotnick & Moo, 2006; Trojano et al., 2002) as well as the emergence of specific spatial deficits after unilateral brain damage in neurological patients (e.g., Laeng, 1994, 2006; Palermo, Bureca, Matano, & Guariglia, 2008).

However, there are good reasons to believe that the human brain's representation of spatial relations is not confined to that of perceptual subsystems. Humans are not simply able to navigate in the space around them and remember the locations of places and objects; they can also cognize about space. We can engage in endless construction of meaning and parse the physical world into classes and concepts. Such an abstraction and recognition of equivalences between events (i.e., categorization) has obvious advantages, as the cultural evolution of man demonstrates. Categories can also be expressed in symbols which can be exchanged. All this applies to spatial representations as well. For example, the category "to the left" identifies as equivalent a whole class of positions and can be expressed either in verbal language or with pictorial symbols (e.g., an arrow: ←). Moreover, humans not only act in

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space and know space; they also talk about space. The role played by spatial cognition in linguistic function cannot be underestimated (e.g., ''thinking for speaking''; Slobin, 1996). A categorical, non-metric, representation of space constitutes an additional spatial ability to the coordinate one that is necessary for acting in space. Such categorical spatial relations could lay the groundwork for spatial reference in language and form a code, referred here as ''semantic'' that can describe, in even more abstract terms than a perceptual parse of the visual field or object, spatial relations like ''above'' vs. ''below'' or ''left'' vs. ''right.'' Such a semantic code could be used efficiently, since in an individual's language there exist already several terms that explicitly identify such relations (e.g., spatial prepositions: Laeng et al., 2003, chap. 9; see also Kemmerer, 2006).

We therefore propose, consistently with Kemmerer and Tranel's (2000) account, that our representation of categorical spatial relations should be thought of consisting of at least two different types: (a) meaning or semantically-coded representations; and (b) visuospatially- or perceptually-coded representations. However, if research has converged in showing a complementary lateralization pattern for the perception of space, it remains unclear whether the evidence that categorical spatial relations are processed more efficiently by the LH relative to the RH reflects this hemisphere's superiority for processing spatial relations in terms of qualitative manner (i.e., categorically), for semantic and/or verbal processing, or for all of the above. A few recent studies are beginning to throw some light about this issue. In an empirical study, Kemmerer and Tranel (2000) compared the performance in spatial tasks of two brain-damaged patients: Each patient had suffered a unilateral lesion; one patient in the LH and the other in the RH. A set of tasks examined the abilities to encode spatial relations semantically or linguistically, whereas another set of tasks examined the abilities to encode spatial relations visuospatially or perceptually. Their results showed that all of the scores for the semantic tasks were remarkably lower for the LH-damaged patient compared to the RH-damaged patient or control patients. In contrast, scores for the visuospatial tasks were notably lower for the RH-damaged patient than for the LH-damaged patient or control patients. Such a pattern of results indicates a ''double dissociation'' supporting the idea that semantic and visuospatial representations for categorical spatial relations are to some extent distinct. These results may also suggest that semantic-categorical and visuospatial-categorical spatial information may tend to be more efficiently processed in the LH and RH respectively. However, previous group studies have converged in showing that a majority of patients will actually show LH lateralization for visuospatial-categorical processing. Hence, the fact that two patients showed a double dissociation constitutes better evidence for the separability of the two types of categorical spatial function than for a typical lateralization profile for them. Kemmerer (2006) has also suggested, based on a review of the neuropsychological data, that the left inferior parietal lobe and especially the left supramarginal gyrus, may play a critical role in processing semantic-categorical spatial relations. Tranel and Kemmerer (2004) had previously pointed out that the conceptual knowledge (or ''meaning'') of locative prepositions could be represented in the brain independently of perceptually coded categorical spatial relations. As commented by van der Ham and Borst (2011), it would seem that a ''trichotomy'', instead of a traditional dichotomy in processing subsystems, may be a better account of the manner the human brain processes spatial relations.

Van der Ham and Postma (2010) have also investigated the existence of a split between semantic- and visuospatial-categorical information. In the study, they used a sequential match-to-sample task coupled to the divided visual field method. In one experiment, three different stimulus formats were employed to depict categorical spatial relations. One was the visuospatial format, in which a dot could appear in one of the four quadrants. Another was the abstract visuospatial format, in which one of the four quadrants could instead be filled in gray. Both formats were employed as a means of presenting categorical spatial information in a visual and spatial format. The other format was the verbal format, in which semantic-categorical information was presented by means of presenting words on the computer screen (e.g., ''top left''). A LH's advantage over RH was found for semantic-categorical information processing, whereas no hemispheric difference was found for visuospatial-categorical information processing. In a second experiment, van der Ham and Postma also manipulated expectancy for a specific format so as to ''set'' the participants' encoding of the spatial relations. The results showed a LH's advantage for the verbal format, which was observed, not only when the verbal format was expected, but also when the visuospatial format was expected, thus suggesting that the format of the stimuli alone could determine the lateralization pattern.

However, according to Tranel and Kemmerer (2004), semantic-categorical information consists in the meaning or conceptual knowledge of the categorical spatial relation and not just in a verbal description of the categorical spatial relation (e.g., word presentation of spatial category). Interestingly, van der Ham and Postma's (2010) suggest that the LH's advantage for semantic-categorical information processing reported in the previous studies (e.g., Kemmerer & Tranel, 2000) might have originated from 'verbal' aspects of the stimuli. Within van der Ham and Postma's (2010) account, a LH's advantage for semantic-categorical information processing may no longer be obtained if such semantic-categorical information were to be presented in a non-verbal format.

The present study primarily aims to examine whether a LH's advantage for semantic-categorical information processing in previous studies (e.g., Kemmerer & Tranel, 2000) can still be observed when such information is represented in a non-verbal format. An additional aim of the present study is to shed light on whether the processing of semantic-categorical information can be teased apart from the visuospatial-categorical information. Thus, we employed a sample-to-match task but we avoided introducing a verbal format into the experimental paradigm. Our reasoning is that semantic-categorical information presented in a non-verbal format ought to provide the same type of spatial information as words like ''above'' or ''below.'' Therefore, we decided to use as stimuli for the present study, the picture of a standard European traffic light, which is a familiar and probably over learned combination of colors and spatial locations (e.g., the red light on top or above, and the green light in the bottom or below). In other words, we employed the colors of a traffic light as an uncontroversial type of semantic-categorical information that is known in a non-verbal format. In Norway, the typical traffic light has three lights in tandem arrangement, and specific colors are assigned to each position: Red is allocated to top, yellow is in the middle, and green is bottom. Importantly, in the case of a traffic light, the colors do not intend to convey any spatial information per se and both the colors and the positions are arbitrary signs that indicate whether an action is allowed or not (i.e., move, stop); nevertheless, the three lights in a traffic light are conceptually strongly linked to their relative positions within the spatial structure of a traffic light. Therefore, the colors of a traffic light may enable us to efficiently present semantic-categorical spatial information in a non-verbal format that is already available and possibly quite natural to the individual participant. Presenting such stimuli by use of a divided visual field paradigm, moreover, allows throwing light on the pattern of laterality for the different types of spatial relation information. We hypothesized that the LH proficiently process semantic-categorical spatial information not only in a perceptual code (cf. Tranel & Kemmerer, 2004) but also in a semantic, albeit non-verbal (cf. van der Ham & Postma, 2010).

2. Method

2.1. Participants

Forty right-handed participants (29 females) were recruited as volunteers for an experiment on visual perception. Mean age of the participants was 25.40 years old (*SD* = 5.23), and they received a gift card that was worth 100 Norwegian Crowns (i.e. about 17 U.S. dollars) in consideration of their participation. All the participants had normal or corrected-to-normal visual acuity. Mean score on the Edinburgh Handedness Inventory (Oldfield, 1971) was 84.61 (*SD* = 16.06). Before the experiment, each participant was asked to recognize the standard traffic light from among possible six combinations between the color of the light (red, yellow, or green) and its position (top, middle, or bottom). In addition, before taking part in the main experiment, each of the participants participated in an initial, brief, eye-fixation training session that has been specifically designed for divided visual field experiments (Guzman-Martinez, Leung, Franconeri, Grabowecky, & Suzuki, 2009) and has been shown to improve the ability to maintain fixation and therefore the reliability of the lateralization procedure.

2.2. Apparatus

All stimuli were presented on a 21-in. CRT monitor with 75 Hz refreshing rate (EIZO Flex Scan T960), that was connected to an Apple MacBook Pro (2.8 GHz Intel Core 2 Duo) running Mathworks MATLAB R2008b with the Psychophysics Toolbox 3 (Brainard, 1997). A 10-key pad was connected to the computer and served as a response console. The CRT monitor was located in front of the participant, with 89 cm of viewing distance.

2.3. Stimuli

2.3.1. Eye-fixation training

The stimuli developed by Guzman-Martinez et al. (2009) were closely duplicated, except the fixation cue. Two circles of 17.27° (visual angle) diameter, filled by 50% of black (the RGB values were 0, 0, 0) and 50% of white (255, 255, 255) random dot pattern (0.04°/dot) or its contrast–reversed pattern, were created for flickering presentation of random dot patterns. In both random dot patterns, a circle with 1.14° diameter and vertically-long rectangle of 1.44° by 4.00° were drawn by means of 0.04° wide of black hairlines. The size and position of the embedded hairline circle were identical to those of the middle light in the stimulus for the main experiment. Likewise, the size and position of the hairline rectangle were identical to the outline of the stimulus for the main experiment (see Fig. 1).

2.3.2. Main experiment

The stimuli were designed so as to be seen as a traffic light sign (Fig. 1). The outline of the stimulus was a vertically long black rectangle; 1.44° in width and 4.00° in height. Three gray (40, 40, 40) squares, 1.20° on a side, were embedded in tandem: One of the squares was located on 0.10° below the upper base of the outline, another on the center, and the other on 0.10° above the lower base. Three black circles of 1.14° diameters were placed on the center of each square as lights. Turning each light on was depicted by adding small circle of 1.12° diameter in the center of each light. Each light could have one of the four colors; white, red (255, 0, 0), yellow (125, 125, 0), or green (0, 0, 255). The stimulus, with a red light on the top, a yellow in the middle, and a green on the bottom, was defined as the standard traffic light stimulus.

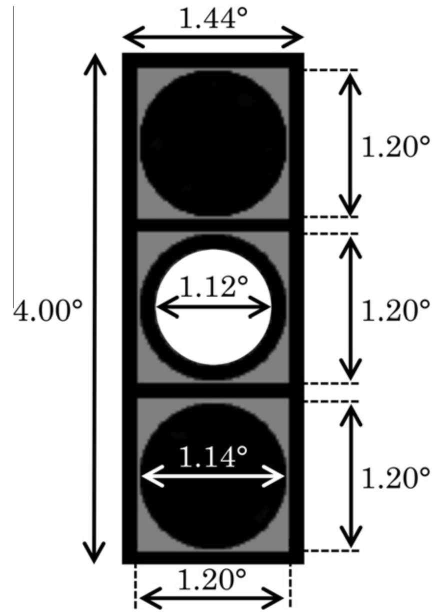

Fig. 1. Pictorial description of the stimuli.

2.4. Procedure

2.4.1. Eye-fixation training

The procedure was based on that of Guzman-Martinez et al. (2009). The participant was seated in front of the CRT monitor in a dark room, and asked to fix her or his eyes into the center of the fixation cue. The participant was able to start each trial by hitting the appropriate key at her or his own pace. Hitting the key led to 133 ms of alternating presentations of the two circles that included random dot patterns for 5 s. Each participant was instructed that the flickered circles would become almost uniform gray if she or he fixed her or his eyes into the center of the fixation cue. After 5 s of flickered presentation, the participant was able to have a short break. This training had 30 trials and took about 5 min.

2.4.2. Main experiment

After the eye-fixation training session, the participant took part in the main experiment. The apparatus was the same used in the training session. The main experiment had two tasks: A semantic-categorical matching task and a visuospatial-categorical matching task. Half of all the participants performed the semantic-categorical matching first and then the visuospatial-categorical matching; the other half performed each task in the reversed order.

The same stimuli and trial sequence were employed in both tasks (Fig. 2). At the beginning of each trial, the standard traffic light stimulus appeared in the center of the screen for 1000 ms. After 500 ms with all lights turned off or "blank", one of the three lights turned into white for 146 ms as a cue. After a 500 ms of blank screen, a target was presented in one of four possible positions. The target had the same outline as the cue but only one of the three lights (top, middle, or bottom) showed one of the three colors (red, yellow, or green). The target was presented 2.00° left (i.e., left visual field or LVF) or right (i.e., right visual field or RVF) from the center of the screen. For both of LVF and RVF presentation, the target was presented in 1.00° above or below the center of the screen, thus ensuring that the visuospatial-categorical information of the target was not defined by merely its horizontal position of the screen but by its relative position among the three lights (cf. Saneyoshi & Michimata, 2009).

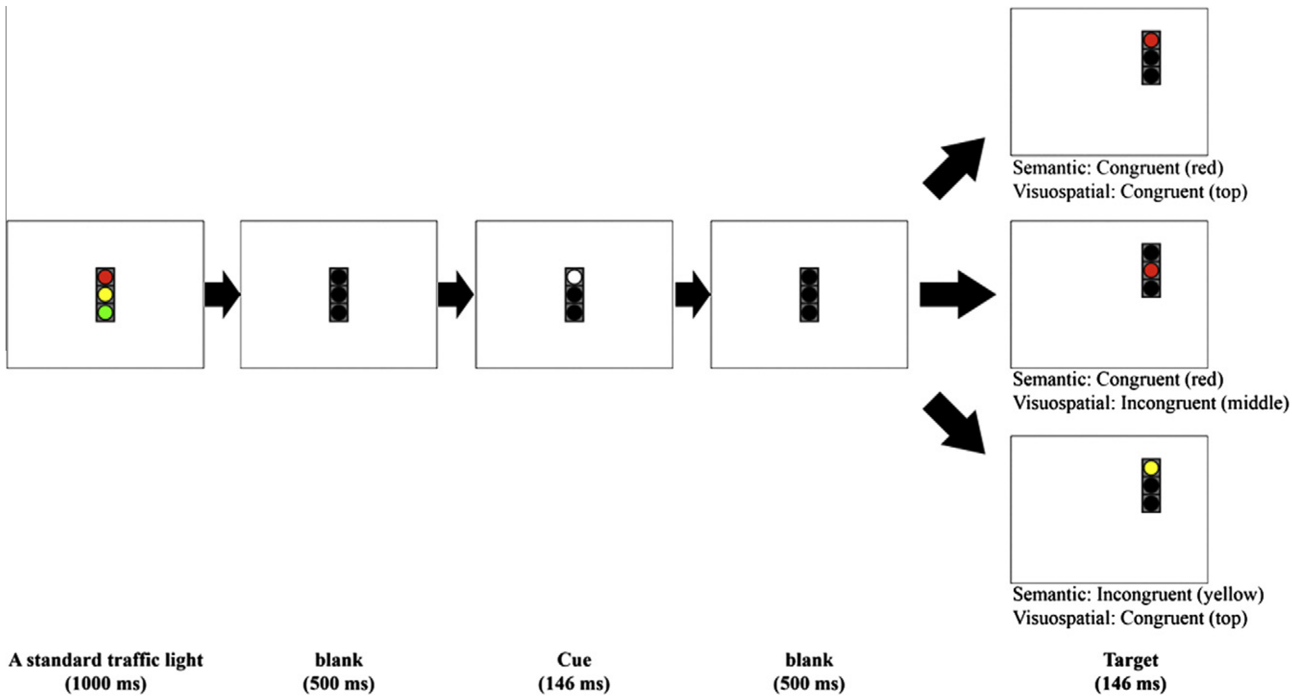

Fig. 2. Illustration of a trial sequence. Each cue could be followed by one of the three types of target.

In the semantic-categorical matching task, the participant judged whether the color indicated by the cue and the color of the target matched, regardless of the target's position. For instance, if the cue had appeared on the top, such a cue had indicated "red" and the participants should judge whether the color of the successive target was red. In the visuospatial-categorical matching task, on the other hand, the participant judged whether the positions of the cue and the target matched, regardless of the target's color. For example, if the cue had appeared on the top, the participants should judge whether the successive target appeared on the top.

For both of the tasks, each response was made by pressing two inner keys, among four keys, on the response console by both index fingers, or by pressing two outer keys by both middle fingers. Half of the participants used the inner keys as "match" response, and used the outer keys as "non match" response. The type of response associated with the keys was reversed for the other half of the participants. Response times (RTs) were recorded from the onset of the lateralized stimuli until 2000 ms had elapsed. If no response occurred before this deadline, the trial was categorized as an error. After a response had been made or 2000 ms had elapsed, there was a 1000 ms of inter trial interval followed by the next trial. In both tasks, the participant was asked to respond as accurately and quickly as possible and also asked to fix gaze onto the center of the screen during the whole trial sequence.

For both tasks, there were three types of a target; one in which both relevant and irrelevant categorical information were congruent, another in which the relevant information was congruent but the irrelevant was incongruent, and the other in which the relevant information was incongruent but the irrelevant was congruent. For the semantic-categorical matching task, for example, the cue in the top could be followed by a target with red light on the top (i.e. same relevant with congruent irrelevant categorical information), with red light in the middle or on the bottom (i.e. same relevant with incongruent irrelevant), or with yellow or green light on the top (i.e. different relevant with congruent irrelevant). For the visuospatial-categorical matching task, in another example, such a cue in the top could be followed by a target with red light on the top (i.e. same relevant with congruent irrelevant), with yellow or green light on the top (i.e. same relevant with incongruent irrelevant), or with red light in the middle or on the bottom (i.e. different relevant with congruent irrelevant). In both tasks, a target was presented in one of four possible positions and each type of target was presented 48 times. The resulting 144 trials were sorted in a pseudo-random order and divided into four blocks of 36 trials. The participant was able to have a short break at the end of each block. A block of 15 practice trials was held before starting each task, in order to familiarize the participant with the task. In the practice trials, the target was presented in the center of the screen, instead of LVF or RVF. For each practice trial, the response was followed by 500 ms of feedback for her or his response ("Good!" or "Miss…"). If the error rate of the practice trials was over 25%, another block of 15 practice trials was repeated.

3. Results and discussion

Eight participants were excluded from the analyses. Four of them failed to recognize the standard traffic light. Other three showed a significant speed-accuracy trade-off ($rs < -.75$, $ps < .05$). Another was ruled out for excluding a potential left-handed or mix-handed; the participant did not get a score above +50 on the Edinburgh Handedness Inventory (Dragovic, 2004) and declared using either hand for throwing (Laeng & Peters, 1995). Thus, the data from 32 participants were employed for following analyses. In regard to the semantic- and visuospatial-categorical matching task, mean error rates (panel A and B in Fig. 3, respectively) and median RTs for correct responses (panel C and D in Fig. 3, respectively) were computed. The error rates and RTs were positively correlated, $r = +.47$ (listed on Table 1), thus excluding a speed-accuracy tradeoff.

3.1. Error rates

The error rates were analyzed by a four-way analysis of variance (ANOVA), with sex (female or male) as a between-participants factor, and task (semantic-categorical matching or visuospatial-cate-

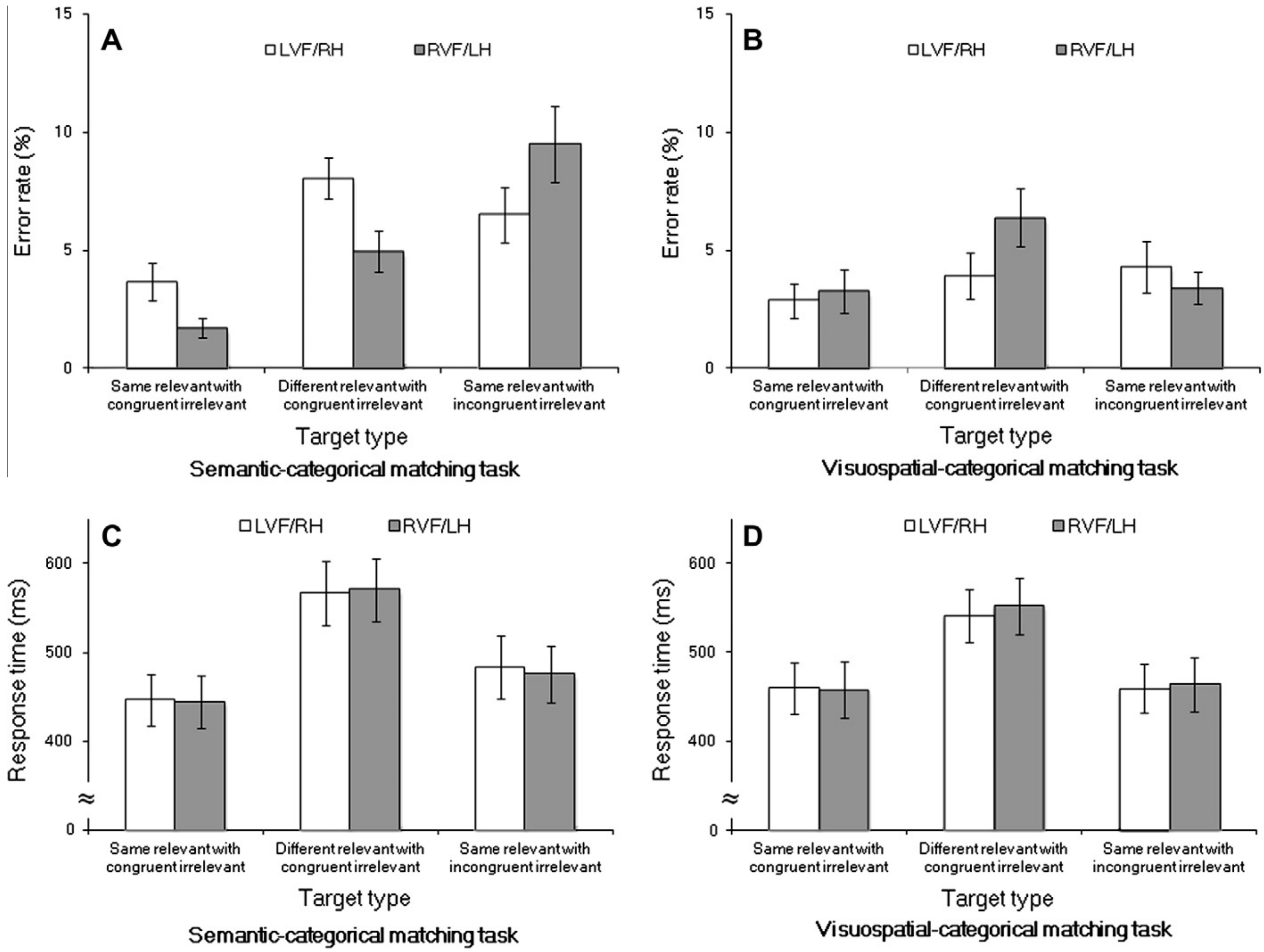

Fig. 3. The upper panels show the error rates for each target type and each visual field in the semantic-categorical matching task (panel A) and in the visuospatial-categorical matching task (panel B). The lower panels show the RTs for each target type and each visual field in the semantic-categorical matching task (panel C) and in the visuospatial-categorical matching task (panel D). In all figures, the error bars show ± 1 standard errors.

gorical matching), target type (same relevant with congruent irrelevant categorical information, different relevant with congruent irrelevant categorical information, or same relevant with incongruent irrelevant categorical information), and visual field (LVF or RVF) as within-participants factors. Neither a main effect of sex, $p = .242$, $\eta_p^2 = .05$, nor any interaction among sex and any other factors, $ps > .218$, $\eta_p^2\,s < .05$, were significant. Thus, we collapsed the sex factor, and then a three-way ANOVA with task, target type, and visual field was conducted. Most importantly, an interaction among the three factors was significant[1], $F(1, 31) = 10.21$, $MSE = 36.46$, $p = .003$, $\eta_p^2 = .25$. This interaction led further two-way ANOVAs for each task as described below. A main effect of task was also significant, $F(1, 31) = 5.78$, $MSE = 48.71$, $p = .022$, $\eta_p^2 = .16$, reflecting that overall error rate for the semantic-categorical matching task (5.7%) was higher than that for the visuospatial-categorical matching task (4.0%). There were also a significant main effect of target type, $F(2, 62) = 14.33$, $MSE = 26.99$, $p < .001$, $\eta_p^2 = .32$, and an interaction between task and target Type, $F(1, 31) = 6.41$, $MSE = 52.55$, $p = .017$, $\eta_p^2 = .17$ (see Footnote 1). Both main effect and interaction were further examined by following analyses for each task. No other effects or interactions reached significance ($ps > .107$, $\eta_p^2\,s < 0.82$).

[1] The degrees of freedom were adjusted by employing .50 of the epsilon for lower-bound.

In addition, the correlation between overall error rate for the semantic- and visuospatial-categorical matching task in each participant was not significant, $r = +.08$, $p = .689$. Asymmetry scores (error rate for LVF minus that for RVF; see Andresen & Marsolek, 2005) for each target type were calculated for each task, but none of the target types showed significant correlation between the tasks, $ps > .495$, $-.13 < rs < +.13$. These results suggest that the semantic- and visuospatial-categorical processing could be to some extent independent.

3.1.1. Error rates for the semantic-categorical matching task

A two-way ANOVA with target type and visual field as factors, showed a significant interaction, $F(1, 31) = 7.92$, $MSE = 42.48$, $p = .008$, $\eta_p^2 = .20$ (see Footnote 1), and also a significant main effect of target type, $F(1, 31) = 15.07$, $MSE = 32.15$, $p = .001$, $\eta_p^2 = .33$ (see Footnote 1). Thus, the following analyses were further conducted.

The differences between LVF and RVF were analyzed by post hoc t-tests for each target type. For the same relevant with congruent irrelevant condition, the error rate for RVF was significantly lower than that for LVF, $t(31) = 2.13$, $p = .041$, $d = 0.55$. For the different relevant with congruent irrelevant condition, the error rate for RVF was also significantly lower than that for LVF, $t(31) = 2.46$, $p = .020$, $d = 0.38$. These advantages in RVF can be interpreted as indicating the presence of a LH's advantage (see

Table 1
Error rates (%) and median response times (in milliseconds) for each target type and each visual field.

Measured valuable	Task	Target type					
		Same relevant with congruent irrelevant		Different relevant with congruent irrelevant		Same relevant with incongruent irrelevant	
		LVF	RVF	LVF	RVF	LVF	RVF
Error rate (%)	Semantic-categorical matching	3.6 (0.8)	1.7 (0.4)	8.1 (0.9)	4.9 (0.9)	6.5 (1.2)	9.5 (1.6)
	Visuospatial-categorical matching	2.9 (0.7)	3.3 (0.9)	3.9 (1.0)	6.4 (1.2)	4.3 (1.1)	3.4 (0.7)
Response time (ms)	Semantic-categorical matching	436 (29)	439 (32)	550 (38)	564 (33)	475 (39)	464 (40)
	Visuospatial-categorical matching	469 (33)	465 (35)	556 (33)	562 (35)	468 (30)	476 (34)

Note: Standard errors are within parentheses.

Hellige & Sergent, 1986; Sergent & Hellige, 1986, for reviews). Hence, as predicted, a LH's advantage in semantic-categorical processing was observed for both "same" and "different" response, with the irrelevant visuospatial-categorical information congruent. For the same relevant with incongruent irrelevant condition, on the contrary, the error rate for LVF was significantly lower than that for RVF instead, $t(31) = 2.82$, $p = .008$, $d = 0.63$, suggesting that the presence of an unexpected RH's advantage in semantic-categorical processing for "same" response with irrelevant visuospatial-categorical information incongruent.

One-way ANOVAs with target type as a factor, were further conducted for each visual field. In the LVF, there was a main effect of target type, $F(1, 31) = 6.92$, $MSE = 46.35$, $p = .013$, $\eta_p^2 = .18$ (see Footnote 1). Bonferroni's multiple comparisons revealed the error rate for the same relevant with congruent irrelevant condition was significantly lower than that for the different relevant with congruent irrelevant condition, $p < .001$, $d = 0.95$. The error rate for the same relevant with congruent irrelevant condition was lower than that for the same relevant with incongruent irrelevant condition, showing a medium effect size ($d = 0.51$), although the difference did not reach significance, $p = .101$. The difference between the error rate for the different relevant with congruent irrelevant condition and that for the same relevant with incongruent irrelevant condition was negligible, $p > .792$, $d = 0.27$. For these results, it could be argued that semantic-categorical processing in RH was disrupted when the semantic-categorical information was different and, in addition, it could be disrupted when the irrelevant visuospatial-categorical information was incongruent.

In the RVF, a main effect of target type was also significant, $F(1, 31) = 16.29$, $MSE = 30.21$, $p < .001$, $\eta_p^2 = .35$ (see Footnote 1). Bonferroni's multiple comparisons revealed that the error rate for the same relevant with congruent irrelevant condition was significantly lower than that for the different relevant with congruent irrelevant condition, $p = .005$, $d = 0.83$, as well as than that for the same relevant with incongruent irrelevant condition, $p < .001$, $d = 1.19$. Moreover, the error rate for the different relevant with congruent irrelevant condition was significantly lower than that for the same relevant with incongruent irrelevant condition, $p = .009$, $d = 0.63$. These results indicate that semantic-categorical processing in LH is substantially disrupted when the semantic-categorical information is different, even though such processing can also be disrupted when the irrelevant visuospatial-categorical information is incongruent.

The above results in the semantic-categorical matching task show that a LH's advantage in semantic-categorical processing can be obtained when the semantic-categorical information of the target is the same as the cue. When the semantic-categorical information of the target is different from the cue, such a LH's advantage still exists. When incongruent visuospatial-categorical information is presented, a RH's advantage may prevail over the LH's advantage, possibly because such incongruent visuospatial-categorical information can substantially disrupt semantic-categorical processing in LH.

3.1.2. Error rates for the visuospatial-categorical matching task

Two-way ANOVA with target type and visual field as factors, showed a significant interaction[2], $F(2.00, 62.00) = 3.81$, $MSE = 12.21$, $p = .027$, $\eta_p^2 = .11$. A main effect of target type was marginally significant, $F(1.60, 49.53) = 3.36$, $MSE = 26.43$, $p = .053$, $\eta_p^2 = .10$ (see Footnote 2). Thus, the following analyses were further conducted.

The differences between LVF and RVF were analyzed by post hoc *t*-tests as to each target type. Only for the different relevant with congruent irrelevant condition, the error rate for LVF was significantly lower than that for RVF, $t(31) = 2.77$, $p = .009$, $d = 0.40$. However, for both the same relevant with congruent irrelevant condition and for the same relevant with incongruent irrelevant condition, differences between LVF and RVF were negligible, *p*s > .383, *d*s < 0.19. These results indicate that a RH's advantage in visuospatial-categorical processing is obtained in only "different" responses with irrelevant semantic-categorical information congruent, and that there is no laterality effect in visuospatial-categorical processing in "same" response, irrespective of irrelevant semantic-categorical information.

One-way ANOVAs with target type as a factor were further conducted for each visual field. A main effect of target type was significant in RVF, $F(1, 31) = 5.84$, $MSE = 34.19$, $p = .022$, $\eta_p^2 = .16$ (see Footnote 1), but it was not the case in LVF, $p = .345$, $\eta_p^2 = .03$. Bonferroni's multiple comparisons in RVF revealed that the error rate for the same relevant with congruent irrelevant condition was significantly lower than that for the different relevant with congruent irrelevant condition, $p = .005$, $d = 0.53$. The error rate for the same relevant with incongruent irrelevant condition was lower than that for the different relevant with congruent irrelevant condition, marginally failing to reach significance ($p = .067$) and with a medium effect size ($d = 0.51$). The difference between the error rate for the same relevant with congruent irrelevant condition and that for the same relevant with incongruent irrelevant condition was negligible, $p > .999$, $d = 0.03$. These results indicate that visuospatial-categorical processing in LH can be disrupted when the visuospatial-categorical information is different, but it is not affected by irrelevant semantic-categorical information.

For these results in the visuospatial-categorical matching task, it could be argued that a RH's advantage was observed only when the visuospatial-categorical information of the target was different from the cue. Such a RH's advantage could result from selective effects of the incongruent visuospatial-categorical information on visuospatial-categorical processing in LH.

3.2. RTs

In the same manner as the error rates, a four-way ANOVA with sex as a between-participants factor, and task, target type, and visual field as within-participants factors, was conducted. Neither a

[2] The degrees of freedom were adjusted by employing the Huynh-Feldt's epsilon.

main effect of sex, $p = .416$, $\eta_p^2 = .02$, nor any interaction among sex and any other factors, $ps > .306$, $\eta_p^2\ s < .04$, were significant. Thus, we collapsed the sex factor, and then a three-way ANOVA with task, target type, and visual field was conducted. In contrast with the error rates, an interaction among the three factors was no longer significant, $p = .779$, $\eta_p^2 = .01$. A main effect of target type, $F(1, 31) = 68.91$, $MSE = 11830.81$, $p < .001$, $\eta_p^2 = .69$, and the interaction between task and target type, $F(2, 62) = 4.45$, MSE = 2608.89, $p = .016$, $\eta_p^2 = .13$, were significant, as also obtained for error rates. No other effects or interactions were significant ($ps > .471$, $\eta_p^2\ s < .03$). Due to the significant interaction between task and target type, the effects of target type for each task were further analyzed with collapsing visual field factor.

3.2.1. RTs for the semantic-categorical matching task

A one-way ANOVA with target type as a factor, showed a significant main effect, $F(1, 31) = 50.83$, $MSE = 10188.12$, $p < .001$, $\eta_p^2 = .62$ (see Footnote 1). Bonferroni's multiple comparisons revealed the RTs for the same relevant with congruent irrelevant condition was significantly shorter than that for the different relevant with congruent irrelevant condition, $p < .001$, $d = 0.67$. The RTs for the same relevant with congruent irrelevant condition were also significantly shorter than that for the same relevant with incongruent irrelevant condition, $p = .001$, but the effect size was too small, $d = 0.19$. The RTs for the same relevant with incongruent irrelevant condition, moreover, were shorter than that for the different relevant with congruent irrelevant condition, $p < .001$, $d = 0.46$. These results indicate that semantic-categorical processing is disrupted when the semantic-categorical information of the target is different from the cue, and also that it can be affected to some degree by irrelevant visuospatial-categorical information.

3.2.2. RTs for the visuospatial-categorical matching task

One-way ANOVA with target type as a factor, showed a significant main effect of target type, $F(1, 31) = 46.74$, $MSE = 6860.46$, $p < .001$, $\eta_p^2 = .60$ (see Footnote 1). Bonferroni's multiple comparisons revealed the RTs for the same relevant with congruent irrelevant condition was significantly shorter than that for the different relevant with congruent irrelevant condition, $p < .001$, $d = 0.51$, but was not significantly different from that for the same relevant with incongruent irrelevant, $p > .999$, $d = 0.02$. The RTs for the same relevant with incongruent irrelevant condition, moreover, were significantly shorter than that for the different relevant with congruent irrelevant condition, $p < .001$, $d = 0.51$. These results indicate that visuospatial-categorical processing is disrupted when the visuospatial-categorical information of the target is different from the cue, but it is not affected by irrelevant visuospatial-categorical information.

4. General discussion

The primal goal of the present study was to assess whether a LH's advantage for semantic-categorical information processing, as documented in previous studies (e.g., Kemmerer & Tranel, 2000), could be obtained even when such a semantic-categorical information had been presented in a non-verbal format. Two different tasks were conducted using identical stimuli and trial sequences within a paradigm based on the divided visual field technique: a semantic-categorical matching task and a visuospatial-categorical matching task. We reasoned that, if a RVF advantage were to be obtained in the semantic-categorical matching task, then such a result would suggest that there is a LH's superiority in processing semantic-categorical information. Thus, the LH's superiority shown in previous studies (e.g., Kemmerer & Tranel, 2000) may not derive from nonessential verbal aspects of the stimuli (i.e., word presentation of the stimuli), given that the current semantic-categorical matching task did not employ any verbal format or word presentation of the stimuli. If such a RVF advantage were not to be observed, on the other hand, the LH's advantages in the previous studies could then be attributed to merely nonessential verbal aspects and not to semantic-categorical information processing per se.

For the error rate, we observed a RVF advantage when the semantic-categorical information of the target was identical to that of the cue. When the semantic-categorical information of the target was different from the cue, such a RVF advantage still existed. These results indicate a LH's advantage for semantic-categorical processing. Because the semantic-categorical information in our study was presented in non-verbal format, these LH's advantages cannot be attributed to nonessential verbal aspects of the stimuli, as discussed in van der Ham and Postma (2010). Therefore, these results can be taken as further evidence for a LH lateralization of semantic-categorical information processing. Interestingly, however, incongruent visuospatial-categorical information produced a LVF advantage. This LVF advantage is discussed below with regards to the lateralization of visuospatial-categorical processing.

The present study also attempted to shed light on whether the processing of semantic-categorical information could be teased apart from the visuospatial-categorical information. For this purpose, the current study employed a visuospatial-categorical matching task as well as a semantic-categorical matching task. If a RVF advantage were to be obtained in the visuospatial-categorical matching task, as well as the semantic-categorical matching task, such an advantage would suggest that not only semantic-categorical information but also visuospatial-categorical information are processed in LH effectively, in accordance with the traditional dichotomy of spatial relation processing (e.g., Hellige & Michimata, 1989; Kosslyn et al., 1989; Laeng & Peters, 1995; Michimata, 1997). If a LVF advantage were to be observed, on the other hand, such an advantage would indicate that semantic- and visuospatial-categorical information processing are lateralized into LH and RH respectively, consistently with a "trichotomy" of the spatial relation processing (e.g., Kemmerer, 2006; Kemmerer & Tranel, 2000; Tranel & Kemmerer, 2004).

In the visuospatial-categorical matching task, a LVF advantage was observed but only when the visuospatial-categorical information of the target was different from that of the cue. These results could provide a moderate support for a RH's advantage in processing visuospatial-categorical information. A RH's advantage in visuospatial-categorical processing, moreover, could also account for the "reversed" lateralization pattern in the semantic-categorical matching task. Indeed, for the condition in which the RH's advantage was observed, incongruent irrelevant visuospatial-categorical information was presented with semantic-categorical information. Such incongruent visuospatial-categorical information would cause the RH to be more engaged in the task and would therefore yield a RH's advantage instead of LH's advantage. These interpretations are consistent with the trichotomic view of the laterality for the processing of spatial relation (e.g., Kemmerer, 2006; Kemmerer & Tranel, 2000; Tranel & Kemmerer, 2004). In addition, some indirect supports for existing different subsystems for semantic- and visuospatial-categorical processing were also obtained. First, the overall error rate for the semantic-categorical matching task in individual participant showed neither positive nor negative correlation with that for the visuospatial-categorical matching task. According to the asymmetry scores, the lateralization effect for each target type did not show any correlation between both tasks. The effect size of the target type by visual field interaction for the semantic-categorical matching task, moreover, was larger than that for the visuospatial-categorical matching task. These results could be additional evidence for the dissociation between semantic- and visuospatial-categorical processing.

Given that a RH's advantage in visuospatial-categorical processing would fit our data, it needs to be explained why incongruent irrelevant categorical information yielded a "reversed lateralization" in the semantic-categorical matching task but not in the visuospatial-categorical matching task. A possible account for such unidirectional interference may lie in the coding processes for each categorical matching task. In the current study, the semantic-categorical information derived from the visuospatial-categorical information, since the cue indicates specific color by specific position. That is, in the semantic-categorical matching task, the visuospatial-categorical information ought to be transformed into the semantic-categorical information. In the visuospatial-categorical matching, on the other hand, a transformation of codes would seem unnecessary. Thus, adding incongruent visuospatial-categorical information would interfere with the semantic-categorical matching task, whereas adding incongruent semantic-categorical information would not disrupt the visuospatial-categorical matching task.

To sum up, the present results provide moderate support for RH's advantage in visuospatial-categorical processing and hence for a trichotomy of spatial processing. It should be noted, however, that a RH's advantage could also reflect coordinate processing. In the current tasks, each visuospatial-categorical information was defined by one of the three possible positions (i.e., top, middle, or bottom), but it could also be defined by some metric features or coordinate information (e.g., the distance from the center of the stimuli). Hence, residual coordinate information could override a LH's advantage in processing categorical spatial relations (e.g., van der Ham & Postma, 2010). Therefore, further research with controlling residual coordinate information would be necessary.

The above discussion is mainly based on the results for error rates and the results for RTs did not show laterality effects. Nevertheless, the RTs showed the same pattern to the error rates except for a laterality effect ($r = +.47$) and, importantly, no evidence for the speed-accuracy trade-off was found. Thus, we conclude that the results for RTs are not inconsistent with those for error rates.

The unequal distribution of participants' sex in our study could be also a problem. Several studies showed that both sex (e.g., Laeng & Peters, 1995) and female menstrual cycle (e.g., Postma, Winkel, Tuiten, & van Honk, 1999) could affect the lateralized pattern of spatial cognition. In the present study, however, participants' sex did affect neither error rates nor RTs. A recent study with same kind of sample-to-match task also showed no effects of sex on laterality of categorical and coordinate spatial relation processing (van der Ham & Borst, 2011). Despite we did not control participants' cycle, it could be argued the effects of sex and menstrual cycle would have been small for the present tasks.

One could also argue that employing the colors of the traffic light signs was an inappropriate manner for presenting semantic-categorical information. That is, the colors of the traffic light may be less associated with specific spatial categories than words like "top left" (cf. van der Ham & Postma, 2010). Despite this caveat, the present study succeeded in showing that, even when the semantic or conceptual representation is weakly associated with a spatial category, it is possible to observe a clear LH's advantage. We would also argue that the association between each spatial category and its specific color may be weak but it is definitely conceptual. In contrast, presenting the semantic-categorical information by means of words could result in a LH's advantage merely on the basis of engaging word reading per se. Thus, the present stimuli may have enabled us to prevent such a LH's advantage in processing visual lexical information.

Another possible criticism may concern which of the cue or the target needs to be transformed in each semantic-categorical match. We presume that the position of the cue was associated to a specific color (i.e., semantic-categorical information) and then it was compared with the color of following target. However, one could argue that the color of the target was first associated with its specific position and then compared to the position of prior cue. Such a possibility, however, seems to be unlikely since the participants were explicitly requested to match the color indicated by the cue and by the color of the target. Thus, associating the position of the cue to its specific color would be more natural than associating the color of the target to its position.

The present results suggested that semantic or abstract representation of spatial categorical information is lateralized in LH. Several studies also argued that abstract representations would be lateralized in LH. For example, Marsolek (1999) showed abstract information of object categories (e.g., "piano") and specific exemplars of each category (e.g., "grand piano" or "upright piano") would be represented in LH and RH respectively (see also Laeng, Zarrinpar, & Kosslyn, 2003). Some other studies showed categorical perception of color (better discrimination for between-category colors relative to within-category colors) would be verbally mediated (e.g., Roberson & Davidoff, 2000; Suegami & Michimata, 2010; Wiggett & Davies, 2008) and be lateralized in LH (e.g., Drivonikou et al., 2007; Gilbert, Regier, Kay, & Ivry, 2006; Roberson, Pak, & Hanley, 2008). Andresen and Marsolek (2005) found two lateralized subsystems for abstract categories and specific exemplars would not originate from lower level asymmetry (i.e., laterality for the categorical and coordinate spatial relation processing). Yet linking those studies to the present result is premature, comparing these studies could shed more light on comprehensive understanding for the role of abstract representation on our perception for spatial relation, color, and other domains or modalities.

5. Conclusion

The most important finding of the present study was that semantic-categorical information processing was better processed in LH, even in the non-verbal format. Our results do not support claims that a LH advantage for semantic-categorical information processing may be simply attributed to its verbal format. Rather, the present findings indicate that abstract representations that perceptually parse the visual field or object exist and are processed in the LH.

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