Brain and Cognition xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Brain and Cognition

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

Individual differences in spatial relation processing: Effects of strategy, ability, and gender

Ineke J.M. van der Ham [a,*], Gregoire Borst [b]

[a] Helmholtz Institute, Experimental Psychology, Utrecht University, The Netherlands
[b] Department of Psychology, Harvard University, Cambridge, MA, USA

ARTICLE INFO

Article history:
Accepted 23 January 2011
Available online xxxx

Keywords:
Categorical and coordinate spatial relation processing
Individual differences
Gender
Strategy use
Cognitive ability

ABSTRACT

Numerous studies have focused on the distinction between categorical and coordinate spatial relations. Categorical relations are propositional and abstract, and often related to a left hemisphere advantage. Coordinate relations specify the metric information of the relative locations of objects, and can be linked to right hemisphere processing. Yet, not all studies have reported such a clear double dissociation; in particular the categorical left hemisphere advantage is not always reported. In the current study we investigated whether verbal and spatial strategies, verbal and spatial cognitive abilities, and gender could account for the discrepancies observed in hemispheric lateralization of spatial relations. Seventy-five participants performed two visual half field, match-to-sample tasks (Van der Ham, van Wezel, Oleksiak, & Postma, 2007; Van der Ham, Raemaekers, van Wezel, Oleksiak, and Postma, 2009) to study the lateralization of categorical and coordinate relation processing. For each participant we determined the strategy they used in each of the two tasks. Consistent with previous findings, we found an overall categorical left hemisphere advantage and coordinate right hemisphere advantage. The lateralization pattern was affected selectively by the degree to which participants used a spatial strategy and by none of the other variables (i.e., verbal strategy, cognitive abilities, and gender). Critically, the categorical left hemisphere advantage was observed only for participants that relied strongly on a spatial strategy. This result is another piece of evidence that categorical spatial relation processing relies on spatial and not verbal processes.

1. Introduction

Processing visual information relies on the ability of the visual system to process spatial relations between objects or parts of an object. Kosslyn (1987) proposed a dissociation between two types of spatial relations representations in the visual system. Categorical representations specify spatial relations within and between objects using a relative abstract terms, such as ‘‘Object A is above Object B’’. Coordinate representations specify the precise and concrete, metric distances between objects, such as ‘‘Object A is 1 inch away from Object B’’. The two types of spatial relations representations differ in their format and thus the two representations make different information explicit and accessible (Marr, 1982). Coordinate spatial relations encoding relies on depictive representations in which the distance between the object in the representation corresponds to the distance between the objects in the physical world. Conversely, depictive representations are not necessary to encode categorical spatial relations, one can rely on more abstract representations such as propositional representations that specify the conceptual relations (e.g., above) and the entities (e.g., Object A and Object B) using notation such as ‘‘Above (Object A and Object B)’’ (see Kosslyn, Thompson, & Ganis (2006) for a discussion). Crucially, propositional representation would not allow one to determine the distance between objects.

Behavioral, neuropsychological, and neuroimaging findings support differential hemispheric lateralization of these two types of representations with a left hemisphere advantage for categorical spatial relation representations and a right hemisphere advantage for coordinate spatial relation representations (for a review see Jager & Postma, 2003). Kosslyn (1987) and Kosslyn et al. (1989) theorize that the categorical left hemisphere advantage has emerged because of the pre-existing dominance of the left hemisphere for language and of the importance of category formation in language. On the other hand, the coordinate right hemisphere advantage is explained by the right hemisphere’s pivotal role in navigation and attentional search. However, the strength of this pattern of hemispheric lateralization is still a matter of debate. While the coordinate right hemisphere advantage is widely documented, the categorical left hemisphere advantage seems less robust (e.g. Jager & Postma, 2003; Rybash & Hoyer, 1992).

* Corresponding author. Address: Heidelberglaan 2, 3584 CS Utrecht, The Netherlands. Fax: +31 30 253 4511.
E-mail address: c.j.m.vanderham@uu.nl (I.J.M. van der Ham).

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doi:10.1016/j.bandc.2011.01.008

A number of factors (e.g., task properties, but also participant characteristics) have been considered independently, but with little success, to explain discrepancies in the hemispheric lateralization of spatial processing and categorical processing in particular. For example, mixed results have been reported on the effect of gender on the hemispheric lateralization of the representations of spatial relations (e.g. Hellige et al., 1994; Laeng & Peters, 1995; Reese & Stiles, 2005; Rybash & Hoyer, 1992). It has been theorized that gender should affect spatial relation processing because males tend to outperform females when fine metric properties of objects are needed (i.e. coordinate spatial relations) whereas the reverse is true when relative positional information of the objects (i.e. categorical spatial relations) is processed (e.g. Postma, Izendoorn, & De Haan, 1998). Yet, such advantages of coordinate processing for males, and categorical processing for females has not been consistently found. In addition, males and females have shown to differ in general lateralization patterns with less pronounced differences between both hemispheres for females compared to males (e.g. Landsdell, 1962) and a stronger right hemisphere dominance for males (e.g. Wisniewski, 1998). However, more recent studies indicate that such lateralization differences between males and females are small or even negligible (e.g. Boles, 2005; Hellige et al., 1994; Hiscock, Israelian, Inch, Jacek, & Hiscock-Kadil, 1995).

Surprisingly, little is known about the contribution of the type of strategy spontaneously used to perform spatial relation tasks to the hemispheric lateralization of spatial relation processing. In the experiment reported here, we investigated whether the type of strategy (verbal, spatial) selected by the participants can modulate the left hemisphere advantage for categorical spatial relations and the right hemisphere advantage for coordinate spatial relations.

The type of strategy used by the participants might explain the absence of hemispheric lateralization in categorical relation processing reported in some studies. In fact, some argue that the nature of the spatial processing (verbal versus spatial) is at the root of the hemispheric lateralization of spatial processing. This hypothesis is supported by two brain-damaged studies. Kemmerer and Tranel (2000) found a selective impairment to process English spatial prepositions but not visuo-spatial categorical relations for a patient with a left hemisphere lesion and the reverse dissociation for a patient with a right hemisphere lesion. In other words spatial relation processing was impaired when the task was verbal in nature, not when it was spatial. Tranel and Kemmerer (2004) reported converging evidence of left-hemisphere specialization for English spatial prepositions. These findings led some to argue for a trichotomy of spatial relations processing into verbal categorical processing, spatial categorical processing, and spatial coordinate processing (e.g. Jager & Postma, 2003). Critically, verbal categorical processing would be linked to a left hemisphere bias whereas any type of visuo-spatial processing, categorical or coordinate, would show a right hemisphere advantage (Kemmerer, 2006).

However, it should be noted that the tasks that Kemmerer and Tranel used to reveal the difference between verbal and spatial processing, were not designed to specifically test categorical and coordinate spatial relation processing. One could argue that some of their spatial categorical tasks require a certain amount of coordinate processing, which could account for the right hemisphere involvement. Furthermore, as illustrated in this paper, there is a certain amount of individual variation in lateralization, therefore a single case study should be interpreted with caution. Van der Ham and Postma (2010) only partially replicated Tranel and Kemmer's findings. They found that the left hemisphere advantage for categorical processing was enhanced by increasing the verbal nature of the task (i.e., by using verbal stimuli) but found no evidence for a right hemisphere advantage for spatial categories. Finally, using a similar design, Van der Ham et al. (2007) showed that a verbal strategy was more often reported for categorical processing whereas a spatial strategy was more often reported for coordinate processing, but with clear individual differences.

The experiment reported in this study follows directly on the heels of those reported above. We reasoned that if the left hemisphere bias for categorical spatial relations reflects the degree to which participants rely on a verbal strategy, then participants who report above average verbal strategy use in the categorical task should display a stronger left hemisphere lateralization than participants who report above average spatial strategy use in this task. On the other hand, if the hemispheric lateralization of visuo-spatial processing is due to the type of spatial relation processed (categorical versus coordinate), then we expect stronger hemispheric lateralization for participants who report above average spatial strategy use than below average spatial strategy use, for both categorical (left hemisphere) and coordinate processing (right hemisphere).

In order to demonstrate that the type of strategy used by participants was the crucial factor that influences hemispheric lateralization, we considered other factors such as cognitive abilities and gender. These factors might affect the lateralization of spatial relation processing. First, cognitive abilities could have an indirect effect on the hemispheric lateralization of spatial processing by affecting the choice of the strategies used in categorical or coordinate spatial relation. For example, Reichle, Carpenter, and Just (2000) demonstrated that participants select the strategy that leads to the largest reduction of cognitive load in the task they perform.

Second, based on previous reports that females tend to be better than males on verbal tasks, while males show an advantage in spatial tasks (e.g. Crucian & Berenbaum, 1998; Vecci & Girelli, 1998; Weiss, Kemmler, Deisenhammer, & Fleishhacker, 2003), we hypothesized that females are more likely to process the categorical spatial relation task verbally than males which in turn could affect the pattern of hemispheric lateralization. However, given that recent findings report no gender differences in hemispheric lateralization in general, we expected no gender effects on hemispheric lateralization in the categorical and coordinate spatial relation tasks.

In the current experiment, we relied on a match-to-sample task (see Van der Ham et al., 2007) to test our hypotheses concerning strategy use, cognitive ability, and gender. In this paradigm, in each trial two similar stimuli (a combination of a cross and a dot) are presented sequentially; the first stimulus in the center of the screen, and the second in the left or right visual hemifield. The visual half field presentation of the second stimulus allows for inferences about hemispheric lateralization as a visual stimulus presented briefly in one visual hemifield is initially perceived and processed by the contralateral hemisphere (Beaumont, 1983). In the categorical task, participants decided whether the dots in the two stimuli were in same quadrant (relative to the cross). Crucially, due to the retention interval the match-to-sample procedure we used allowed participants to encode the first stimulus verbally as opposed to other traditional categorical spatial relation paradigms such as the dot-bar paradigm (Hellige & Michimata, 1989). In the coordinate task, participants decided whether the dots were positioned at the same distance from the center of the cross. We determined the strategy used by the participants in each task with two 7-point scales; one for spatial strategy use and one for verbal strategy use. As we were specifically interested in the naturally occurring preferences for these strategies, we chose to assess them by means of self-reports on two scales (see e.g. Glück & Fitting, 2003), which also allows us to identify subjects with mixed or alternative strategies. In addition, general spatial and verbal cognitive abilities of the participants were measured with four classical paper-and-pencil tests (two spatial tests and two verbal tests). In order to determine whether the hemispheric lateralization of spatial relation processing was affected by spatial and verbal abilities, we selected two spatial and two verbal ability tests that cover a wide spectrum of those abilities. We then computed two composite scores by adding the *z*-scores in the two spatial tests and the z-scores in the two verbal tests. This approach will reduce task specificity and provide a more general measure of spatial and verbal abilities (see e.g. MacLeod, Hunt, & Mathews, 1978; Roberts, Wood, & Gilmore, 1994).

2. Method

2.1. Participants

Eighty-five Harvard students and Cambridge community members volunteered to take part in the study for pay or course credit. Ten participants were removed from the sample because of accuracy levels at or below 50% in one or more conditions. The final sample consisted of 37 females (mean age 22.7 years) and 38 males (mean age 23.3 years). All participants were right-handed according to the Edinburgh Handedness Inventory, with a mean score of 83.8 (SD = 18.6, range 40–100) (Oldfield, 1971). All participants were physically and psychologically healthy. All participants provided written 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 and procedure

2.2.1. Match-to-sample task

We derived the main task assessing spatial relation processing from a visual half field, match-to-sample task reported by Van der Ham et al. (2007) and Van der Ham et al. (2009). Each stimulus consisted of a black "+" shaped cross (14 ∗ 14 pixels, visual angle 0.35°) with a black dot (six pixels in diameter, visual angle 0.15°) at one of forty possible positions, presented on a white background (see Fig. 1). On each trial, after the presentation of an "x" shaped fixation cross (500 ms), the first cross-dot stimulus was displayed centrally (150 ms), followed by the presentation of a 1500 ms blank screen and another "x" shaped fixation cross (500 ms), then the second cross-dot stimulus was presented laterally (left or right) for 150 ms (2.5° from the inner edge of the image to the center of the screen), which was immediately followed by a blank screen. Only responses given within 2000 ms were registered. A single trial sequence is depicted in Fig. 2. On each trial participants were asked to compare two cross-dot stimuli. In the categorical task, participants decided whether the dot in the second cross-dot stimulus appeared in the same quadrant of the simultaneously presented cross as the dot in the first cross-dot stimulus presented earlier ("match") or in one of the other three quadrants ("non match"), regardless of its exact position. In the coordinate task, we asked

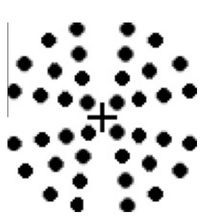

Fig. 1. All possible dot positions in the stimuli used. The arms of the cross indicate the four quadrants (categorical task) while dots could appear at four different radial distances from the center of the cross (coordinate task). Note that only one dot was visible in a single stimulus.

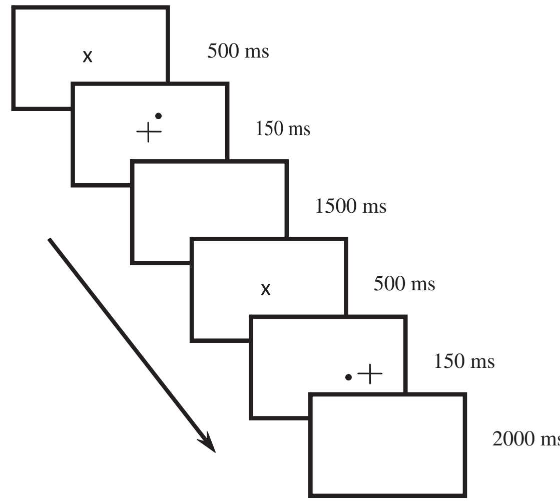

Fig. 2. The sequence of a single trial. Each trial element is depicted with its duration in ms.

participants to determine whether the radial distance between the dot and the center of the cross was the same ("match") or different ("non match") in the two cross-dot stimuli, regardless of the quadrant the dots appeared in. There were four quadrants and four possible radial distances for the figures used, but participants were told that the dots could appear at any position with regard to the cross. The instructions stressed that participants should always take into account the dot position relative to the cross presented simultaneously, and to ignore the position of the cross itself with regard to the computer screen.

We randomized left and right visual field presentation of the second cross-dot stimulus and match-no match responses over trials; laterality of presentation and type of response were presented equally. We grouped categorical and coordinate trials in two separate tasks, each with their own set of instructions and practice trials. The order of the two tasks was counterbalanced over participants. In each task, participants performed two blocks of 40 trials. Stimuli were presented on a 1024 ∗ 768 pixels computer screen with a 75 Hz refresh rate. Participants sat 60 cm from the screen. They provided their answers by pressing two keys on a regular keyboard with the index and the middle finger of their right hand. We recorded both the error rates (ERs) and the response times (RTs), which were measured from the offset of the second cross-dot stimulus until a response was registered. Two other computerized tasks were administered as well, but those will not be discussed here.

2.2.2. Strategy ratings

After performing both tasks, participants filled out a questionnaire about the strategy they used to perform the categorical and coordinate tasks. We asked each participant to rate the degree with which they used a visuospatial strategy and a verbal strategy in each task on a seven point Likert scale (1 = did not use this strategy, 7 = used this strategy). In the strategy debriefing form we defined what the two strategies would imply and provided examples verbally to illustrate these definitions. For the verbal strategy, the following sentence was used "I have used a verbal strategy to solve this task (e.g., use of inner speech)", and for the spatial strategy the sentence was "I have used a spatial strategy to solve this task (e.g., imagining the picture)". Participants were asked to respond for both the task in which they "compared quadrants" and in which they "compared distance". It was stressed that there were no right or wrong answers to these questions. If asked, the experimenter elaborated on the meaning of both strategy types. Participants

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were also asked to specify the use of any other strategies than the two we mentioned.

2.2.3. Spatial ability tests

We administered two classical paper-and-pencil spatial tests to assess spatial ability. In each trial of the Vandenberg mental rotation test (i.e., MRT, Vandenberg & Kuse, 1978) participants determined which two out of four three-dimensional block figures were identical to the target figure regardless of their orientation. In each trial of the paper folding test (i.e., PF, Ekstrom, French, Harman, & Dermen, 1976) a figure was presented that represented a square piece of paper that has been folded, with one or two circles drawn on it to show where holes were punched in the paper. Participants indicated the correct appearance of the paper when completely unfolded by selecting one of five possible answers. In each test, participants completed two sets of ten trials with a maximum completion time of three minutes per set. For each test, the score was the number of correct responses.

2.2.4. Verbal ability tests

We assessed verbal abilities of the participants with the word beginnings test (i.e., WB, Ekstrom et al., 1976) and the digit span test (DS, derived from WAIS III, Wechsler adult intelligence scale, Wechsler, 1997). In the WB test, two combinations of three letters ("PRO" and "SUB") were presented and participants were asked to write down as many words that started with those letters. Participants were given three minutes for each combination. The score represents the total number of words produced for both letter combinations. The DS test required participants to listen to and directly repeat increasingly longer series of numbers (from 2 to 8 numbers, each length is repeated three times). The test was stopped if the participant was unable to recall two out of three series of the same length. The score indicates the number of series correctly recalled.

For each participant, we calculated a composite score by adding (a) the standard z scores of the two spatial tests to obtain a general measure of spatial ability and (b) the standard z scores of the two verbal tests in order to obtain a general measure of their verbal ability (see Shah & Miyake, 1996).

3. Results

First, we analyzed general effects of task and visual field to determine whether we could replicate the classical left hemisphere advantage for categorical spatial relations and right hemisphere advantage for coordinate spatial relations. To do so, we first performed a data transformation of the ERs. As accuracy was above 50% for every participant in every condition, we computed a lateralization coefficient using the following formula (LVFcorrect − RVFcorrect)/(LVFerror + RVFerror). 'Correct' represents the proportion of correct responses and 'error' the proportion of incorrect responses. This measure controls for potential ceiling and floor effects (see e.g. Birkett, 1977; Marshall, Caplan, & Holmes, 1975). No such correction was needed for RTs, therefore the RT lateralization coefficient was calculated as follows: (LVF − RVF)/(LVF + RVF) (e.g. Sommer, Ramsey, Mandl, Van Oel, & Kahn, 2004; Thiran & Clarke, 2003). We first performed a one sample t-test for both the categorical and coordinate task, comparing the lateralization effect to zero (corresponds to no lateralization), to examine potential lateralization effects on ERs and RTs.

Secondly, we analyzed the effects of strategy, ability, and gender on the hemispheric lateralization of spatial processes for both ERs and RTs. Based on their relative verbal and spatial strategy scores, participants were divided into two groups for each measure; low spatial and high spatial, and low and high verbal. The cut-off for high and low scores was the median of all participants for the verbal and spatial score separately. Correspondingly, such groups were also composed with regard to ability. Consequently, verbal strategy (2) and spatial strategy (2), verbal ability (2) and spatial ability (2), and gender (2) were treated as between-subject factors in three separate analyses, each including task and visual field. These analyses were ANOVAs implemented by way of general linear models (GLM). If appropriate, Bonferroni corrected post hoc pairwise comparisons were used to follow-up on significant effects. Again, the laterality coefficients were used for both ERs and RTs. In Table 1 all scores on the strategy ratings and ability tasks are reported. In Table 2 both accuracy and response times are given for all separate groups for all conditions.

Lastly, we carried out correlational analyses in order to further determine whether categorical and coordinate tasks rely on distinct lateralized cognitive processes. In addition, we included strategy, cognitive abilities and gender in the correlational analyses in order to determine whether these variables modulate the hemispheric lateralization of both categorical and coordinate processes.

3.1. Overall analysis

The one sample t -tests performed for the lateralization coefficients of ERs showed a significant effect of lateralization for both the categorical, $t(74) = 4.40$, $p < .001$, $d = .17$, and the coordinate task, $t(74) = 8.11$, $p < .001$, $d = 1.34$. As depicted in Fig. 3A, participants were more accurate in processing coordinate spatial relations when the stimuli were presented in the left visual field/right hemisphere (positive value) whereas the opposite effect was found for categorical spatial relations (negative value).

The one sample t-tests for RTs showed no lateralization effect for the categorical task, $t(74) = 1.75$, $p = .17$, or for the coordinate task, $t(74) = 2.15$, $p = .07$. Although there is a slight trend for a RVF/LH advantage in the coordinate task (see Fig. 3B).

3.2. Individual differences analysis

A three way ANOVA on the lateralization coefficients of ERs including task, spatial strategy, and verbal strategy showed a significant interaction of task and spatial strategy, $F(1, 74) = 13.51$, $p < .001$, $\eta^2 = .16$. In addition, a significant main effect of spatial strategy was found, $F(1, 74) = 8.12$, $p < .01$, $\eta^2 = .10$. Follow-up tests showed that there was a significant main effect of spatial strategy for the categorical task, $F(1, 74) = 13{,}21$, $p < .001$, but not for the coordinate task, $F < 1$. The high spatial strategy group showed a significant effect of lateralization for both the categorical, $t(37) = 5.56$, $p < .001$, $d = 1.25$, and coordinate task, $t(37) = 6.38$, $p < .001$, $d = 1.58$. For the low spatial strategy group the lateralization effect was significant for the coordinate task, $t(36) = 4.77$, $p < .001$, $d = 1.06$, but not for the categorical task, $t < 1$. In Fig. 4, the interaction pattern of task and visual field is depicted for both the low spatial strategy and high spatial strategy group. A more leftward lateralization effect was found in the categorical task for the high spatial strategy group, compared to the low spatial strategy group. Analysis of the effect of spatial and verbal strategy on RTs revealed no significant effect of strategy.

The separate three way ANOVA on the lateralization coefficients of ERs including task, spatial ability, and verbal ability, did not lead to any significant effects of spatial or verbal ability ($p > .10$). Separate analyses on the effect of these two variables on the lateralization coefficients of RTs did not reveal significant interaction ($p > .10$).

The comparable approach to the effects of gender did not show any significant effects of gender for either lateralization coefficients of ERs or RTs ($p > .10$ in all cases).

Table 1
Summary of the mean scores on the degree of verbal strategy use, the degree of spatial strategy use and on the four paper-and-pencil tests (i.e. MRT = mental rotation, PF = paper folding, DS = digit span, WB = word beginnings) for all participants and for males and females separately. Note: standard deviation in parentheses.

	N	Verbal strategy	Spatial strategy	MRT	PF	Spatial ability	DS	WB	Verbal ability
Total	75	4.12 (1.6)	5.08 (1.4)	15.01 (9.1)	12.87 (4.4)	0.00 (1.7)	17.60 (2.8)	37.12 (13.4)	0.00 (1.6)
Male	38	4.09 (1.7)	5.12 (1.4)	16.95 (9.8)	13.13 (4.3)	0.27 (1.8)	17.74 (2.7)	38.05 (14.0)	0.12 (1.7)
Female	37	4.15 (1.5)	5.04 (1.4)	13.03 (8.0)	12.59 (4.5)	−0.28 (1.6)	17.46 (3.0)	36.16 (12.8)	−0.12 (1.5)

Table 2
Summary of the mean RTs and ERs in the two tasks (i.e. categorical and coordinate tasks) and the two visual field (i.e. left and right) for the high low groups in function of spatial strategy, verbal strategy, spatial ability, verbal ability groups, and for males and females, separately. Note: standard deviation in parentheses, cat = categorical task, coo = coordinate task, LVF/RH = left visual field/right hemisphere, RVF/LH = right visual field/left hemisphere, V = verbal, S = spatial, ER = error rate, RT = response time.

		N	ER				RT			
			Cat LVF/RH	Cat RVF/LH	Coo LVF/RH	Coo RVF/LH	Cat LVF/RH	Cat RVF/LH	Coo LVF/RH	Coo RVF/LH
Total		75	12 (10)	10 (11)	23 (9)	32 (8)	723 (190)	732 (196)	704 (155)	692 (159)
Gender	Males	38	11 (11)	9 (12)	22 (9)	32 (9)	693 (182)	702 (190)	674 (133)	653 (139)
	Females	37	12 (9)	11 (10)	25 (9)	32 (8)	753 (195)	762 (199)	734 (171)	731 (169)
Strategy	High spatial	38	12 (8)	7 (7)	22 (8)	32 (9)	725 (168	729 (170)	714 (153)	697 (163)
	Low spatial	37	12 (12)	12 (14)	24 (10)	32 (8)	720 (213)	734 (221)	693 (157)	685 (155)
	High verbal	37	14 (12)	13 (14)	24 (10)	34 (9)	721 (195)	736 (207)	693 (153)	690 (172)
	Low verbal	38	9 (7)	7 (6)	22 (8)	30 (7)	724 (188)	727 (186)	714 (158)	693 (146)
Ability	High spatial	37	9 (7)	6 (7)	23 (9)	30 (8)	684 (189)	693 (206)	683 (150)	667 (143)
	Low spatial	38	15 (11)	13 (13)	24 (9)	34 (8)	760 (186)	769 (179)	724 (158)	716 (171)
	High verbal	37	11 (9)	8 (10)	24 (9)	33 (8)	727 (199)	743 (220)	716 (162)	700 (173)
	Low verbal	38	13 (11)	11 (13)	23 (10)	31 (8)	719 (183)	721 (170)	692 (148)	683 (144)

3.3. Correlational analysis

In order to consider (a) whether coordinate and categorical spatial relations relied on the same cognitive processes and (b) whether hemispheric lateralization of spatial relations processes were affected by strategies and cognitive abilities, we examined the correlation between all dependent variables, by computing Pearson correlation coefficients between these variables (see Table 3). As lateralization was only found in ERs, the correlational analysis was performed for this measure, not for RTs.

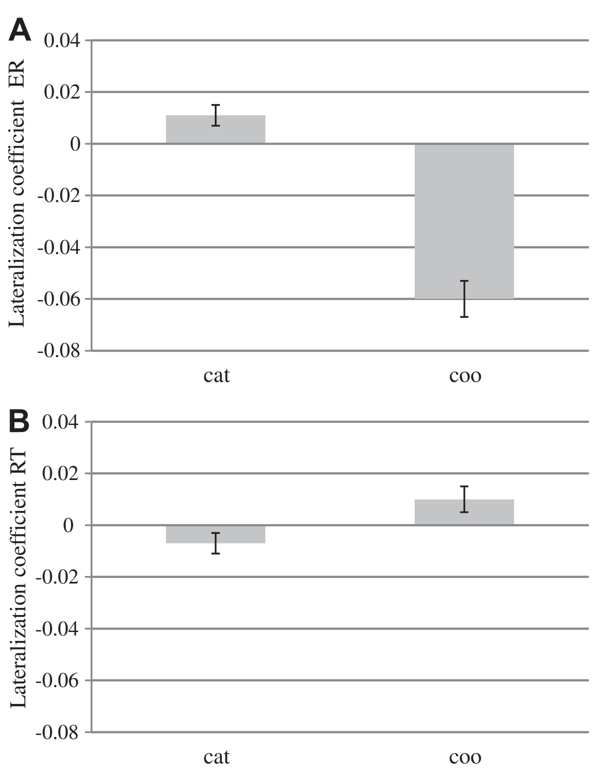

Fig. 3. The mean lateralization coefficients of (A) ER and (B) RT. Note: Cat = categorical, coo = coordinate, negative = right hemisphere advantage, positive = left hemisphere advantage. Error bars represent standard error of the mean (SEM).

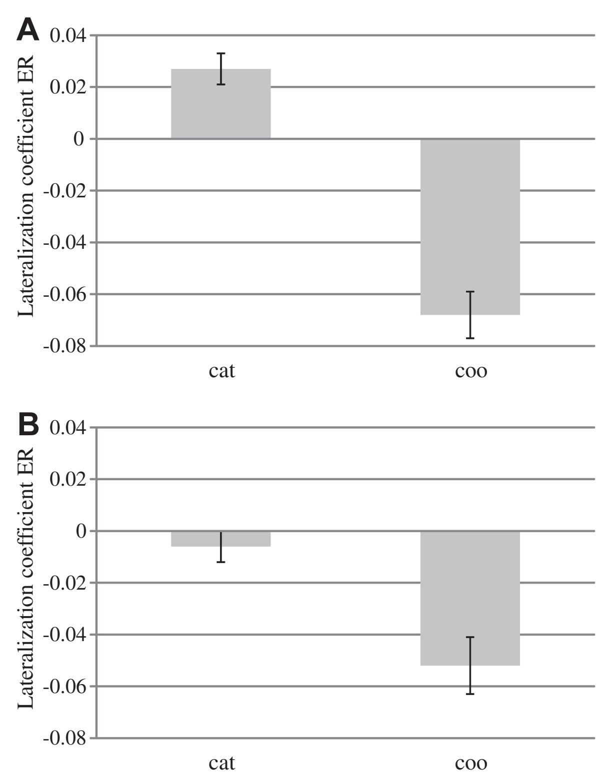

Fig. 4. The mean lateralization coefficients of ER values for the (A) high and (B) low spatial strategy groups for both visual fields. Note: Cat = categorical, coo = coordinate, negative = right hemisphere advantage, positive = left hemisphere advantage. Error bars represent standard error of the mean (SEM).

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Table 3
Correlation matrix for all behavioral and individual differences measures. LC = lateralization coefficient, ER = error rate, cat = categorical, coo = coordinate.

	LC ER cat	LC ER coo	Verbal strategy	Spatial strategy	Verbal ability	Spatial ability
LC ER coo	−.03					
Verbal strategy	−.03	.16				
Spatial strategy	−.41***	.02	−.18			
Verbal ability	−.22	.09	.09	.02		
Spatial ability	−.02	−.03	−.02	.14	.13	
Gender	.12	−.19	.08	−.03	−.08	−.16

*** $p < .001$.

There was clearly no significant correlation between lateralization coefficients on the categorical and coordinate task ERs, $r(73) = -.03$, $p = .82$. We found only one significant correlation between lateralization coefficients and other variables: categorical lateralization was significantly correlated with the degree to which participants used a spatial strategy, $r\ (73) = -.41$, $p < .001$. Thus, participants relying more strongly on a spatial strategy showed a stronger RVF/LH advantage in the categorical task. Finally, we note that the spatial ratings and the verbal ratings did not significantly correlate, $r(73) = -.16$, $p = .17$.

4. Discussion

In the current study we attempted to re-evaluate the double dissociation of categorical and coordinate spatial relations with a left and right hemisphere advantage, respectively. By investigating the effects of strategy use, ability, and gender, we aimed to shed more light on some of the inconsistencies in literature, in particular the theorized left hemisphere advantage for categorical processing.

First of all, we have replicated the outcome of the cross dot paradigm (Van der Ham et al., 2007, 2009); we found a significant left hemisphere advantage for categorical processing and a significant right hemisphere advantage for coordinate processing on the accuracy but not the time needed to perform the categorical or the coordinate judgments.

Our analyses including strategy, ability, and gender clearly showed that strategy was the only factor that affected lateralization. The categorical left hemisphere advantage was modulated by the degree to which participants reported using a spatial strategy. Participants relying strongly on a spatial strategy showed a clear left hemisphere advantage in the categorical task. In contrast, participants that reported a low use of spatial strategy showed no hemispheric lateralization in the categorical task. In addition, verbal strategy did not lead to a stronger overall left hemisphere advantage for categorical spatial relation processing in our study. Taken together, our results suggest that the left hemisphere advantage in categorical processing is unlikely to be accounted for by the fact that one relies more on verbal processing to process such spatial relations. Thus, our findings contradict the proposal that the left hemisphere advantage for categorical relations only exists due to the verbal nature of processing or the task itself and that more perceptual, spatial categories are related to a right hemisphere advantage (Kemmerer & Tranel, 2000).

The overall coordinate right hemisphere advantage was not affected by spatial strategy use In addition, none of the other factors affected this relatively strong effect. This suggests that the right hemisphere advantage related to coordinate relation processing is robust, in line with many previous findings in this field. Taking together the present results, spatial strategy use appears to be a more likely explanation for variation in lateralization of categorical processing than the distinction between verbal and perceptual categories suggested by Kemmerer and Tranel (2000).

One could argue that self-report strategy ratings is a questionable tool to infer the strategy used by the participants. For example, we described the spatial strategy as a strategy in which one is "imagining a picture". However, one could rely on a spatial strategy but without focusing on figural properties of the objects in the stimuli. We are well aware of the limitation of the self-reports approach, however this approach allowed us to study naturally occurring preferences in a sample of participants, without manipulating the task in any way.

One could also argue that the introspective reports of the type of strategy use to perform the categorical spatial relations task fail to capture the use of implicit linguistic strategies (e.g., propositional coding). Although we did not specifically take into account this type of implicit strategies, it is likely that a participant relying on such strategy would report having used neither a verbal nor a spatial strategy, leading to a low score on both scales. Our data shows that lateralization is not present for the low spatial strategy group, whereas level of verbal strategy is not related to lateralization. This suggests that these implicit strategies are not a crucial factor accounting for the hemispheric lateralization patterns reported.

In contrast, neither gender nor verbal or spatial ability modulated the hemispheric lateralization of spatial relation processing. Therefore our results suggest that gender and ability are not crucial factors that could account for inconsistencies in lateralization patterns reported in previous experiments.

In conclusion, we found that an explanation for the different effects of lateralization related to categorical spatial relation processing can be found in spatial strategy use, and not in gender or cognitive ability. Only when the categorical task is solved in a spatial manner, the left hemisphere advantage was clear, emphasizing the spatial nature of categorical relation processing. The outcome of this study should be taken into account when interpreting previous research and when designing new experiments concerning spatial relation processing. Additionally, this study adds to the debate on the role of gender in spatial relation processing, which seems trivial, given the lacking influence on lateralization found here.

Acknowledgments

This research was supported by the Netherlands Organization for Scientific Research (NWO), under Grant Evolution and Behaviour: 051-14-027 and the National Institutes of Health (NIH), under Grant R01 MH060734; any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NIH. The authors would like to thank Stephen M. Kosslyn for helpful discussion and his advice regarding the design of the experiment.

References

Beaumont, J. G. (1983). Methods for studying cerebral hemispheric function. In A. W. Young (Ed.), *Functions of the right cerebral hemisphere* (pp. 114–146). London: Academic Press.

Birkett, P. (1977). Measures of laterality and theories of hemispheric processes. *Neuropsychologia, 15*, 693–696.

Boles, D. B. (2005). A large-sample study of sex differences in functional cerebral lateralization. *Journal of Clinical and Experimental Neuropsychology, 27*, 759–768.

Crucian, G. P., & Berenbaum, S. A. (1998). Sex differences in right hemisphere tasks. *Brain and Cognition, 36*, 377–389.

Ekstrom, R., French, J., Harman, H., & Dermen, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton, NJ: Educational Testing Services.

Glück, J., & Fitting, S. (2003). Spatial strategy selection: Interesting incremental information. *International Journal of Testing, 3*, 293–308.

Hellige, J. B., Bloch, M. A., Cowin, E. L., Eng, T. L., Eviatar, Z., & Sergent, V. (1994). Individual variation in hemispheric asymmetry: Multitask study of effects related to handedness and sex. *Journal of Experimental Psychology: General, 123*, 235–256.

Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory & Cognition, 17*, 770–776.

Hiscock, M., Israelian, M., Inch, R., Jacek, C., & Hiscock-Kadil, C. (1995). Is there a sex difference in human laterality? An exhaustive survey of visual laterality studies from six neuropsychology journals. *Journal of Clinical and Experimental Neuropsychology, 17*, 590–610.

Jager, G., & Postma, A. (2003). On the hemispheric specialization for categorical and coordinate spatial relations: A review of the current evidence. *Neuropsychologia, 41*, 504–515.

Kemmerer, D. (2006). The semantics of space: Integrating linguistic typology and cognitive neuroscience. *Neuropsychologia, 44*, 1607–1621.

Kemmerer, D., & Tranel, D. (2000). A double dissociation between linguistic and perceptual representations of spatial relationships. *Cognitive Neuropsychology, 17*, 393–414.

Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review, 94*, 148–175.

Kosslyn, S. M., Koenig, O., Barrett, A., Cave, C. B., Tang, J., & Gabrieli, J. D. E. (1989). Evidence for two types of spatial representations: Hemispheric specialization for categorical and coordinate relations. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 723–735.

Kosslyn, S. M., Thompson, W. L., & Ganis, G. (2006). *The Case for Mental Imagery*. Oxford: Oxford University Press.

Laeng, B., & Peters, M. (1995). Cerebral lateralization for the processing of spatial coordinates and categories in left- and right-handers. *Neuropsychologia, 33*, 421–439.

Landsdell, H. (1962). A sex difference effect of temporal lobe neurosurgery on design preference. *Nature, 194*, 852–854.

MacLeod, C. M., Hunt, E. B., & Mathews, N. N. (1978). Individual differences in the verification of sentence-picture relationships. *Journal of verbal learning and verbal behavior, 17*, 493–507.

Marr, D. (1982). *Vision*. San Francisco: Freeman.

Marshall, J. C., Caplan, D., & Holmes, J. M. (1975). The measure of laterality. *Neuropsychologia, 13*, 315–321.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97–113.

Postma, A., Izendoorn, R., & De Haan, E. H. F. (1998). Sex differences and object location memory. *Brain and Cognition, 36*, 334–345.

Reese, C. J., & Stiles, J. (2005). Hemispheric specialization for categorical and coordinate spatial relations during an image generation task: Evidence from children and adults. *Neuropsychologia, 43*, 517–529.

Reichle, E. D., Carpenter, P. A., & Just, M. A. (2000). The neural basis of strategy and skill in sentence-picture verification. *Cognitive Psychology, 40*, 261–295.

Roberts, M. J., Wood, D. J., & Gilmore, D. J. (1994). The sentence-picture verification task: Methodological and theoretical difficulties. *British Journal of Psychology, 85*, 413–432.

Rybash, J. M., & Hoyer, W. J. (1992). Hemispheric specialization for categorical and coordinate spatial representations: A reappraisal. *Memory & Cognition, 20*, 271–276.

Shah, P., & Miyake, A. (1996). The separability of working memory resources for spatial thinking and language processing: An individual differences approach. *Journal of Experimental Psychology: General, 125*, 4–27.

Sommer, I. E. C., Ramsey, N. F., Mandl, R. C. W., Van Oel, C. J., & Kahn, R. S. (2004). Language activation in monozygotic twins discordant for schizophrenia. *British Journal of Psychiatry, 184*, 128–135.

Thiran, A. B., & Clarke, S. (2003). Preserved use of spatial cues for sound segregation in a case of spatial deafness. *Neuropsychologia, 41*, 1254–1261.

Tranel, D., & Kemmerer, D. (2004). Neuroanatomical correlates of locative prepositions. *Cognitive Neuropsychology, 21*, 719–749.

Van der Ham, I. J. M., & Postma, A. (2010). Lateralization of spatial categories: A comparison of verbal and visuospatial categorical relations. *Memory & Cognition, 38*, 582–590.

Van der Ham, I. J. M., Raemaekers, M., van Wezel, R. J. A., Oleksiak, A., & Postma, A. (2009). Categorical and coordinate spatial relations in working memory: An fMRI study. *Brain Research, 1297*, 70–79.

Van der Ham, I. J. M., van Wezel, R. J. A., Oleksiak, A., & Postma, A. (2007). The time course of hemispheric differences in categorical and coordinate spatial processing. *Neuropsychologia, 45*, 2492–2498.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*, 599–601.

Vecci, T., & Girelli, L. (1998). Gender differences in visuo-spatial processing: The importance of distinguishing between passive storage and active manipulation. *Acta Psychologica, 99*, 1–16.

Wechsler, D. (1997). *Wechsler adult intelligence scale* (3rd ed.). San Antonio, TX: The Psychological Corporation.

Weiss, E. M., Kemmler, G., Deisenhammer, E. A., & Fleishhacker, W. W. (2003). Sex differences in cognitive functions. *Personality and Individual Differences, 35*, 863–875.

Wisniewski, A. B. (1998). Sexually-dimorphic patterns of cortical asymmetry, and the role for sex steroid hormones in determining cortical patterns of lateralization. *Psychoneuroendocrinology, 23*, 519–547.

Please cite this article in press as: van der Ham, I. J. M., & Borst, G. Individual differences in spatial relation processing: Effects of strategy, ability, and gender. *Brain and Cognition* (2011), doi:10.1016/j.bandc.2011.01.008