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# The development of categorical and coordinate spatial relations

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## Abstract

Two classes of spatial relations can be distinguished in between and within object representations. Kosslyn [Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148–175] suggested that the right hemisphere (RH) is specialized for processing coordinate (metric) spatial information and the left hemisphere (LH) processes categorical (abstract) information more effectively. The present study examined the developmental pattern of spatial relation processing in 6–8-year old, 10–12-year old and adults. Using signal detection analyses we calculated sensitivity and bias scores for all age groups. The results indicated that older children and adults showed a greater response bias than younger children. Also, discrimination sensitivity for spatial relation changes clearly improved with age. For the oldest children (10–12-year old) and adults this improvement was accompanied by a RH specialization. In contrast with Kosslyn's claim, this RH advantage also applied to the processing of categorical spatial information. The results are discussed in terms of a right hemispheric specialization for spatial relation processing which matures with age.

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**Keywords:** Categorical and coordinate spatial relations; Hemispheric specialization; Children; Development

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## 1. Introduction

The visual processing of spatial relations between objects and the relations between features within objects enables us to identify objects, to guide actions and navigate through our complex environment. Two general classes of spatial relations between objects or within single objects are assumed to exist (Kosslyn, 1987; Kosslyn et al., 1989). The so-called *coordinate* relations

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offer fine-grained and subtle metric descriptions of the visual world, necessary to guide precise movements. In contrast, *categorical* spatial relations afford invariant abstract spatial relations useful for viewpoint independent object recognition and prototypical spatial location coding (Kosslyn et al., 1987; Jager & Postma, 2003). Kosslyn (1987) hypothesized that both forms of spatial relations are processed through distinct hemispheric networks. He suggested that the right cerebral hemisphere (RH) processes coordinate spatial relations more effectively and the left cerebral hemisphere (LH) is specialized in processing categorical spatial relations. Subsequently, a number of studies concentrating on different functional domains (perception, action, imagery, verbal communication, working and long-term memory) and using different methodological set-ups (visual half field studies, computer simulations, patient lesions and brain imaging studies), task qualities (task difficulty, response mode, practice and feedback), stimuli features (display features and exposure duration) and subject characteristics (gender and handedness) has investigated this dichotomy (Haun, Allen, & Wedell, 2005; Huttenlocher, Hedges, & Duncan, 1991; Jager & Postma, 2003; Wang, 2004). Thus far, most studies indeed reported an advantage for the RH in encoding coordinate relations. However, the hypothesized LH specialization for processing categorical information appears weaker (Banich & Federmeier, 1999; Dépy, Fagot, & Vauclair, 1998; Koenig, Reiss, & Kosslyn, 1990; Hellige et al., 1994; Hellige & Michimata, 1989; Kosslyn et al., 1989; Kosslyn, Chabris, Koenig, & Marsolek, 1992; Kosslyn, Behrmann, & Jeannerods, 1995; Laeng, 1994; Laeng & Peters, 1995; Laeng, Shah, & Kosslyn, 1999; Michimata, 1997; Parrot, Doyon, Démonet, & Cardebat, 1999; Rybash & Hoyer, 1992).

An interesting question arises as to how the processing of categorical and coordinate spatial information and corresponding hemispheric preferences change with age. Huttenlocher et al. (1991) asked children and adults to search for hidden toys in a rectangular sandbox. They proposed a hierarchical dual coding system, in which coordinate spatial information is weighted with general categorical information. While coordinate information alone will normally suffice to retrieve any hidden target, categorical information alone is ineffective. Thus, in order to reduce cognitive load and in such way effectively remember an object's location, fine-grained and categorical information need to be combined, 'hierarchical coding'. In the study of Huttenlocher, Newcombe, and Sandberg (1994), it was shown that children as young as 16 months of age are capable of selecting the correct locations. Even more interesting, however, was the finding that the children showed a pattern of bias towards a category prototype, indicating the combined usage of categorical and coordinate information is already present at this early age. Though, since this pattern of bias did not (yet) correspond to a mature representation, it was suggested that the ability to process both exact, coordinate information and categorical spatial relations between objects in order to establish subjective categories seems to systematically improve with age (Huttenlocher et al., 1994; Newcombe & Huttenlocher, 2000).

Related to the question whether and how processing of different types of spatial relations develop with age, there is the intriguing issue of concomitant changes in hemispheric specialization. To our knowledge, up to this point only two developmental neurocognitive studies actually did examine age differences in processing the distinct forms of spatial relations (Koenig et al., 1990; Reese & Stiles, 2005). However, these studies have yielded inconsistent findings. Koenig et al. (1990) concluded that children as young as 5 years of age show hemispheric processing differences. On the contrary, Reese and Stiles indicated that, testing children of 8 years and older, hemispheric specialization only appears at the age of 10. A possible explanation for this difference in findings is that the cognitive domains under study were not the same; Koenig et al. (1990) focused on the perceptual encoding of spatial relations whereas Reese and Stiles (2005) were more interested in the developmental pattern of spatial relations in visual mental imagery.

In light of the foregoing, the aim of the present study was to gain more insight in the developmental changes in processing of categorical and coordinate spatial relations and the corresponding changes in hemispheric specialization. Hence we tested three age groups (6–8 years, 10–12 years, and 18–25 years) on a spatial relation change detection task. In this computerized divided-visual-field task, children and adults had to decide whether animal line drawings did or did not change. In case the drawings did change, they either changed in a categorical or a coordinate manner. This paradigm is similar to the ‘identity test’ developed by Laeng (1994), and is specifically suitable for research with children. Postma and Laeng (2006) pointed out that the exact hemispheric engagement in spatial relation processing might differ across perceptual, memory, imagery or constructive cognitive domains. We studied spatial relation processing in a perceptual working memory situation. Although a general progress with age in spatial relation processing can be expected, it was of particular interest to determine whether the two classes of spatial relations differed and whether concomitant changes in hemispheric involvement were present. Moreover, since the current change-detection task afforded a signal detection approach, we could establish to what extent cognitive development comprises sensitivity and bias changes. This is specifically interesting since previous research has shown that sensitivity and bias scores on recognition memory tasks are, to a certain extent, correlated with age and hemisphere (Berch & Evans, 1973; Glosser, Deutsch, Cole, Corwin, & Saykin, 1998; Windmann, Daum, & Güntürkün, 2002; Windmann, Urbach, & Kutas, 2002). For example, older children were shown to exhibit greater response biases (Berch & Evans, 1973) and a more liberal response bias was reported for visuo-spatial information encoded by the RH (Glosser et al., 1998).

## 2. Method

### 2.1. Participants

One hundred and twenty right-handed participants (80 children and 40 adult students) were included in the study. The children were divided into two groups defined by age: 6–8-year old (mean age = 7 years 3 months S.D. = 1.15) and 10–12-year old (mean age = 11-4, S.D. = .84). The youngest age group included an equal number of boys and girls. The older age group consisted of 18 girls and 22 boys. All children were recruited from a local elementary school and their primary caregiver gave consent for participation. The students (mean age = 22-2, S.D. = 3.29) were recruited through advertisements at Utrecht University. They either received credit points or a small amount of money for participating. All adult participants gave written consent for participating in the study. Again equal numbers of males and females participated. All children and adults reported to be healthy had normal or corrected to normal vision and were unaware of the purpose of the experiment.

### 2.2. Design

To assess possible age differences in hemispheric specialization for processing spatial relations, a task of the matching-to-sample kind was used. This ‘memory’ task prohibited the participants to use other perceptual cues (e.g., contour differences), or to develop strategies (e.g., comparing patterns of eye movements when visually inspecting the stimuli) that may lead to the recognition of differences in the stimuli (Laeng, 1994). The task was similar to a paradigm first developed by Laeng and colleagues (Laeng, 1994; Laeng & Peters, 1995; Laeng et al., 1999). Participants needed to decide whether animal line drawings did or did not change. In successive order, a

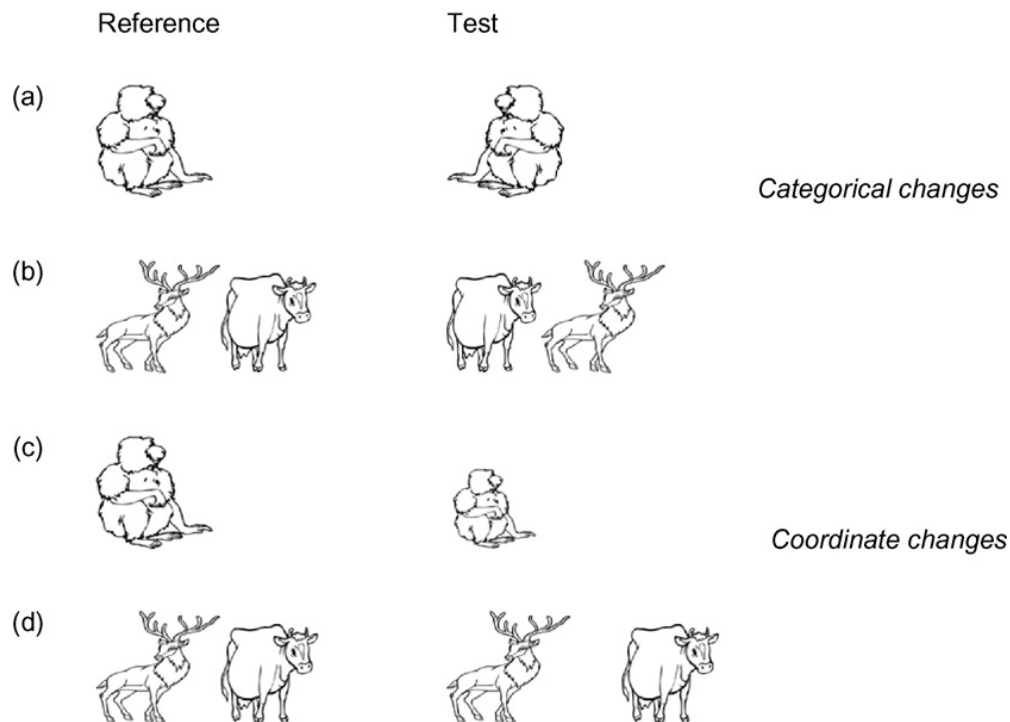


Fig. 1. Reference and test stimuli for categorical (a and b) and coordinate (c and d) changes.

reference drawing and a test drawing were presented on the computer screen and the subject was asked to assess whether the test drawing was the same or different compared to the reference drawing. On half of the trials participants should have responded ‘same’ and on the other half ‘different’. In half of the ‘different’ trials a categorical transformation (i.e., laterality change) was involved, and the other half consisted of a coordinate transformation (i.e., size or distance). The categorical and coordinate changes used in the task are illustrated in Fig. 1. These test stimuli manipulations were previously successfully used by Laeng and Peters (1995).

### 2.3. Procedure

The task was presented on a high-resolution 15-in. computer. Participants were seated approximately 52 cm from the computer screen and were asked to rest their head on a chin pole, which was aligned with the centre of the computer screen. Every participant first received a practice block and thereafter two blocks of 80 testing trials. In each test block a total of 20 categorical changes and 20 coordinate changes were included. The regular size of each drawing was 4 cm × 3.5 cm and if a coordinate change took place for the single animal pictures the size of the drawing was 2.7 cm × 2.3 cm. When two animals were presented, the distance between the figures was 2 mm and in case of a coordinate change 3.2 cm.

An experimental trial consisted of five consecutive displays: first, a central red fixation point appeared for 500 ms on the screen to indicate the beginning of the trial. Second, a cue (or reference drawing), consisting of a black-and-white drawing of one or two animal(s), was presented in the centre of the screen for 750 ms. Both one and two animal(s) pictures were used in order to guarantee the generalizability of spatial relation processing to spatial relations between objects and between features within objects. If two animals were shown, these were placed adjacent to (horizontally) or above (vertically) each other. Third, again for 500 ms a central fixation point appeared, but this time in black to signify the transition from reference to test stimulus. Next,

the test drawing, which was the same or categorically or coordinately different, was shown for 100 ms in either the left visual field (LVF) or in the right visual field (RVF). The test drawing appeared at 1.1–13.5° from the fixation point (range is caused by differences in presentation of reference and test drawings). An equal number of test stimuli appearances in either visual field were randomized across trials. Finally, a blank screen appeared until the participant decided whether the test drawing was the same or different compared to the reference drawing previously presented. After the participant made a decision by pressing either a green ('same') button or a red ('different') button, the trial ended. The assignment of 'same' and 'different' buttons to both hands was counterbalanced across participants and was kept fixed across the experiment.

Before the test trials were administered, together with the experimenter, participants read the task instructions from the computer screen. After the participants indicated they had understood the instructions, they were familiarized with the reference and test drawings and the possible categorical or coordinate changes. The participants completed eight practice trials in which they were specifically asked to focus on the little star in the middle of the computer screen. During these practice trials participants received feedback about their performance, while during the actual test trials this was not the case. After practice, participants were told that they would receive the test stimuli, and that these would proceed faster than the ones in the practice trials. Again it was pointed out that they needed to attend to the fixation point in the middle of the computer screen. After participants received the two test blocks, they were told that they did well and were thanked for participation. Total testing time took about 10 min.

### 3. Results

Percentage of errors and reaction times (time between presentation of test stimulus and the response in milliseconds) were recorded. For all three groups, reaction times (RTs) and error percentages were positively correlated, indicating no speed-accuracy trade off. However, because error percentages were relatively high for both the categorical and coordinate trials (especially for the youngest age group), insufficient data were available for the reaction time analysis since only correct RTs should be included. Therefore, we chose to limit our analyses to error rates. As a measure of recognition memory, sensitivity ( $Pr$ ) and response bias ( $Br$ ) were calculated based on a two-high-threshold model underlying signal detection theory. Sensitivity (also called memory discrimination) refers to the accuracy of memory and represents the degree to which participant is certain in deciding whether or not an item was previously presented. Response bias refers to the strategy that is adopted (that is, saying 'seen before') when participants are uncertain about whether or not they have seen the item before (Glosser et al., 1998; Windmann, Daum, et al., 2002; Windmann, Urbach, et al., 2002). At a behavioral level, these measurements are largely independent of one another (Snodgrass & Corwin, 1988). Participants' performance was summarized by the following two measures: the hit rate ( $H$ ), which is the probability that the participant correctly responded that test and reference drawing were the same and the false alarm ( $FA$ ) rate, the probability that the participant incorrectly classified the drawings as same while they were actually different.<sup>1</sup> To compute sensitivity and bias scores the following formulae were used:  $Pr = H - FA$  and  $Br = FA / (1 - Pr)$  (Snodgrass

<sup>1</sup> We thank one of our reviewers for the comment that in the classic perceptual signal detection situations, a false alarm means incorrectly detecting a change. On the contrary, we adopted the approach that is often used in the memory domain, in which the hit rate corresponds to the probability that the subject classifies an old item as old, and the false alarm rate



Table 1  
Performance on the spatial-relation change-detection task by age

Group	H	LH/RH	FA (cat/coo)	LH/RH	Pr	LH/RH	Br	LH/RH
6–8 years	.78 [.14]	.79/.77	.42 [.13] (.53/.30)	.42/.41	.37 [.22]	.37/.36	.68 [.13]	.70/.66
10–12 years	.90 [.08]	.90/.90	.27 [.07] (.43/.09)	.29/.24	.64 [.13]	.62/.65	.75 [.13]	.77/.73
18–25 years	.92 [.06]	.93/.92	.22 [.04] (.39/.03)	.25/.19	.71 [.07]	.68/.73	.76 [.13]	.79/.72

Note: H = hit rate [S.D.]; FA = false alarm rate [S.D.] (cat/coo); Pr = sensitivity score (H-FA) [S.D.]; Br = bias score [FA/(1 - Pr)] [S.D.]; LH/RH = left hemisphere/right hemisphere.

& Corwin, 1988). To eliminate hit rates of 1.0 and FA rates of 0, the overall hit and FA rates were corrected by adding .5 and divided by  $N + 1$ , in which  $N$  corresponds to the number of same and different items. Both sensitivity and bias scores ranged from nearly 0 to almost 1.0. In Table 1 mean proportion of hit, FA, sensitivity and bias scores are shown age group. Next, sensitivity scores, bias scores, hit rates and FAs are subjected to different analyses.

### 3.1. Sensitivity

First, overall sensitivity scores were subjected to a repeated measure ANOVA with Group (3) as between-subjects factor and Hemisphere (2) as the within-subject factor. The analysis revealed a significant difference between age groups,  $F(2, 117) = 56.61, p < .001$ , indicating that participants become more sensitive to spatial changes with age. Post hoc comparisons showed that 10–12-year old ( $Pr = .64$ ) and adults ( $Pr = .71$ ) did not differ from each other in sensitivity ( $p = .094$ ), but that they were significantly more sensitive to the spatial transformations than 6–8-year old ( $Pr = .37$ ). Additionally, the Hemisphere main effect also reached significance,  $F(1, 117) = 5.92, p < .05$ . This effect indicated that participants were more sensitive to spatial transformations presented to the LVF/RH than presented to the RVF/LH. This latter effect interacted significantly with the group factor,  $F(2, 117) = 4.57, p < .05$ . A paired-samples  $t$ -test showed that for the youngest age group (6–8 years) there was no hemispheric difference in sensitivity,  $t(39) = -.80, p > .05$ , whereas there was for the older children (10–12 years) and adults, respectively  $t(39) = 2.52, p < .05$  and  $t(39) = 4.0, p < .001$ .

### 3.2. Bias

Groups also differed from one another in bias measure (Br),  $F(2, 117) = 4.63, p > .05$ . A post hoc test (Bonferroni corrected) revealed that, when uncertain about the similarity of the stimuli, children as well as adults showed a moderate response bias in responding 'same' more than 'different'. This tendency was stronger for the older children (.75) and adults (.76) than for the youngest age group (.68). Also, a main effect was found for the hemisphere factor,  $F(1, 117) = 33.21, p < .001$ . That is, overall participants showed a smaller response bias for the test stimuli presented to the LVF/RH (.71) compared to the RVF/LH (.75).

corresponds to the probability that the subject classifies a new item as old (Snodgrass & Corwin, 1988). It is for this reason that we labelled a (categorical or coordinate) change, which can be considered comparable to the new items in the original recognition memory tests, a false alarm.

### 3.3. Hit rates

The third ANOVA performed on the hit rates did not showed no significant effects, for hemisphere or age.

### 3.4. Categorical and coordinate changes (FAs)

Since hit rates cannot be broken down in categorical and coordinate spatial changes as these only include the probability that the participant correctly responded that test and reference drawing were the same, type of spatial change (categorical and coordinate) could not be added as a factor to the sensitivity and bias analyses. However, in order to gain further insight in how the above-mentioned developmental changes to the class of categorical and coordinate spatial relations, the trials on which a change had taken place were analysed further. Errors on these trials corresponded to what above has been labelled as false alarms (FAs). The reported false alarm rates differed significantly between both spatial transformations ( $F(1, 117) = 581.11, p < .001$ ) showing that, overall, participants recognized the coordinate spatial changes better than the categorical changes. Type of spatial change interacted with group,  $F(2, 117) = 8.37, p < .001$ , indicating that while the younger children produced more FAs than the older age groups, they especially did so for the coordinate spatial changes ( $F_{\text{coo}}(2, 117) = 44.45, p < .001$ ;  $F_{\text{cat}}(2, 117) = 24.41, p < .001$ ). Furthermore, a two-way interaction effect of type of spatial change by hemisphere,  $F(1, 117) = 29.82, p < .001$  was obtained as well as a higher-order interaction of type of spatial change, hemisphere and age,  $F(2, 117) = 4.61, p < .05$ . These effects showed no hemisphere effect for the coordinate task condition ( $p > .05$ ), but for the categorical task the overall false alarm rate was significantly higher for the items presented to the LH than to the RH. The latter, and in our opinion most interesting, result that emerged from this analysis (plotted in Fig. 2) concerned the older children (10–12 years,  $t(39) = 6.38, p < .001$ ) and adults ( $t(39) = 7.04, p < .001$ ), but not the younger children (6–8 years),  $t(39) = .55, p = .584$ .

## 4. Discussion

The present study examined developmental changes in processing categorical and coordinate spatial relations and corresponding (changes in) hemispheric specialization. We compared 6–8-year old, 10–12-year old and adults in their overall performance on a computerized spatial-relation change-detection task, in which categorical and coordinate object relations were assessed. Using signal detection analyses we calculated sensitivity and bias scores for all age groups.

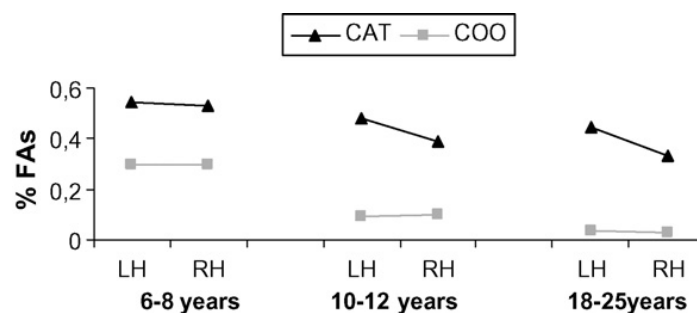


Fig. 2. Percentages FAs for the categorical and coordinate changes presented to the LVF/RH and to the RVF/LH for each age group separately.



Discrimination sensitivity for spatial-relation changes clearly improved with age: 10–12-year old and adults detected spatial transformations better than 6–8-year old. This finding is consistent with earlier research addressing categorical and coordinate spatial relation processing in different age groups (Huttenlocher et al., 1994; Newcombe & Huttenlocher, 2000). More specifically, we observed that this sensitivity group effect interacted with the visual field (i.e., hemisphere) in which the test stimulus was presented. The older children (10–12 years) and adults, in contrast to the youngest age group (6–8 years), showed an advantage for the RH in processing spatial relations. The adult RH advantage for perceiving spatial transformations in general (thus averaged over both categorical and coordinate changes) and the lack of such an overall laterality effect in young children (5 and 7 years old) corroborates and extends previous studies (Koenig et al., 1990; Laeng et al., 1999; Rybash & Hoyer, 1992; Sergent, 1991). Reese and Stiles (2005) found older children (8 and 10 years old), comparable to adults, to perform more accurately on the trials presented to the LVF/RH. These results together with our findings might suggest that an overall RH advantage for processing spatial relations emerges between 8 and 10 years and seems almost complete after age 10, since the older children in our study did not differ from the adults in general sensitivity nor in recruitment of specific hemispheric resources (i.e., the RH).

In addition to discrimination sensitivity, an age difference was found for the response bias. All participants had the tendency to say ‘same’ more often than ‘different’. However, this effect was stronger for the older children and adults. Different potential explanations exist for this finding. Affective, contextual or executive factors all contribute to making decisions in uncertain situations and might have a differential impact at different stages of development (Glosser et al., 1998). A plausible explanation, related to the executive factors mentioned, might be sought in the maturity of the frontal regions of the brain during development. Windmann, Urbach, et al. (2002) proposed that response bias is top-down controlled process, mediated by prefrontal areas. Consequently, the maturation of these areas might cause younger children to respond differently in the face of uncertainty. In addition, the RH showed a smaller response bias than the LH. Laterality effects for response bias have been reported before and retraced to the early organization of the visual system (Glosser et al., 1998). It should be acknowledged that Glosser et al. (1998) for a different task obtained slightly different hemispheric bias trends. Future research should more thoroughly examine the function of age (and related to this the development of the prefrontal cortex) and hemispheric processing differences in the use of strategies in uncertain circumstances.

More specific insights in to the development of processing categorical and coordinate spatial information were gained by analyzing the type of errors when producing a FA (i.e., the probability that the participant incorrectly missed a categorical or coordinate change). The results indicated that all participants performed very poorly on the categorical trials. In order to perform correctly, participants needed to assign an invariant abstract spatial label to describe the relation between the depicted animals (Laeng, 1994; Laeng & Peters, 1995; Laeng et al., 1999). It has been reasoned before that the LH specialization for language processing is related to its preference for categorical spatial relation processing (Kosslyn, 1987; but also Parrot et al., 1999). Noticeably, in many circumstances, participants might use a verbalization strategy for representing categorical spatial relations. However, the categorical changes used in our task appeared to be quite difficult (possibly due to the limited presentation time of the stimulus), thus preventing effective employment of such a verbalization strategy. Consequently, participants might have chosen instead to focus on the (metric) details in or the global contour of the pictures presented (instead of identifying the animals and their laterality), and in such a way apply a coordinate strategy. Converging evidence for this suggestion is offered by the corresponding hemisphere effects. That is, the older children (10–12 years) and adults made fewer ‘categorical’ FAs in the RH. The younger children (6–8 years), in

contrast, did not show a successful right hemispheric strategy for processing these spatial relations. The fact that Laeng and Peters (1995) did find a LH effect using similar categorical stimuli might indeed be sought in time of presentation. In their task, the stimuli appeared one and a half times longer (150 ms) on the computer screen, giving the participants the opportunity to more easily identify the relation between the depicted animals.

In conclusion, the present study showed that young children process spatial relation information in a qualitatively different way than older children. First, children become more sensitive to spatial changes with age. Second, improvement is accompanied by a hemispheric specialization, namely an increased RH efficiency. Third, older children and adults showed a differential response bias, possibly indicating a greater involvement of the prefrontal cortex. Fourth, with respect to functional lateralization, Kosslyn's (1987) claim that categorical and coordinate spatial relations are processed by the LH and RH respectively was not replicated in this study. On the contrary, the older children and adults showed a RH advantage for processing categorical spatial information. We speculate that this advantage might be caused by the difficulty of the categorical transformations used in this study. Because of limited presentation time, participants might have made a coordinate decision on these trials instead of using a categorical strategy. Future research will have to extend these results to other cognitive domains in which spatial-relation processing is relevant, such as (delayed) memory and spatial language usage (Bowerman, 1996; Kemmerer, 2006; Postma, Huntjens, Meuwissen, & Laeng, 2006; Postma & Laeng, 2006).

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## References

- Banich, M. T., & Federmeier, K. D. (1999). Categorical and metric spatial processes distinguished by task demands and practice. *Journal of Cognitive Neuroscience*, 11, 153–166.
- Berch, D. B., & Evans, R. C. (1973). Decision processes in children's recognition memory. *Journal of Experimental Child Psychology*, 16, 148–164.
- Bowerman, M. (1996). Learning how to structure space for language: A crosslinguistic perspective. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 385–436). Cambridge, MA: MIT Press.
- Dépy, D., Fagot, J., & Vauclair, J. (1998). Comparative assessment of distance processing and hemispheric specialization in humans and baboons (papio papio). *Brain and Cognition*, 38, 165–182.
- Glosser, G., Deutsch, G. K., Cole, L. C., Corwin, J., & Saykin, A. J. (1998). Differential lateralization of memory discrimination and response bias in temporal lobe epilepsy patients. *Journal of International Neuropsychological Society*, 4, 502–511.
- Haun, D. B. M., Allen, G. L., & Wedell, D. H. (2005). Bias in spatial memory: A categorical endorsement. *Acta Psychologica*, 118, 149–170.
- Hellige, J. B., Bloch, M. I., Cowin, E. L., Lee Eng, T., 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.
- Huttenlocher, J., Hedges, L. V., & Duncan, S. (1991). Categories and particulars: prototype effects in estimating spatial location. *Psychological Review*, 98, 352–376.
- Huttenlocher, J., Newcombe, N., & Sandberg, E. H. (1994). The coding of spatial location in young children. *Cognitive Psychology*, 27, 115–147.

- 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.
- Koenig, O., Reiss, L. P., & Kosslyn, S. M. (1990). The development of spatial relation representations: Evidence from studies of cerebral lateralization. *Journal of Experimental Child Psychology*, 50, 119–130.
- Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148–175.
- Kosslyn, S. M., Chabris, C. F., Koenig, O., & Marsolek, C. J. (1992). Categorical versus coordinate spatial relations: computational analyses and computer simulations. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 562–577.
- Kosslyn, S. M., Koenig, O., Barrett, A., Backer Cave, C., 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., Behrmann, M., & Jeannerods, M. (1995). The cognitive neuroscience of mental imagery. *Neuropsychologia*, 33, 1335–1344.
- Laeng, B. (1994). Lateralization of categorical and coordinate spatial functions: A study of unilateral stroke patients. *Journal of Cognitive Neuroscience*, 6, 189–203.
- Laeng, B., & Peters, M. (1995). Cerebral lateralization for the processing of spatial coordinates and categories in left- and right-handers. *Neuropsychologia*, 33, 421–439.
- Laeng, B., Shah, J., & Kosslyn, S. M. (1999). Identifying objects in conventional and contorted poses: Contributions of hemisphere-specific mechanisms. *Cognition*, 70, 53–85.
- Michimata, C. (1997). Hemispheric processing of categorical and coordinate spatial relations in vision and visual imagery. *Brain and Cognition*, 33, 370–387.
- Newcombe, N. S., & Huttenlocher, J. (2000). *Making space: The development of spatial representation and reasoning*. Cambridge, MA: MIT Press.
- Parrot, M., Doyon, B., Démonet, J.-F., & Cardebat, D. (1999). Hemispheric preponderance in categorical and coordinate visual processes. *Neuropsychologia*, 37, 1215–1225.
- Postma, A., & Laeng, B. (2006). New insights in categorical and coordinate processing of spatial relations. *Neuropsychologia*, 44, 1515–1518.
- Postma, A., Huntjens, R. J. C., Meuwissen, M., & Laeng, B. (2006). The time course of spatial memory processing in the two hemispheres. *Neuropsychologia*, 44, 1914–1918.
- 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.
- Rybash, J. M., & Hoyer, W. J. (1992). Hemispheric specialization for categorical and coordinate spatial representations: A reappraisal. *Memory & Cognition*, 20, 271–276.
- Sergent, J. (1991). Judgements of relative position and distance on representations of spatial relations. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 762–780.
- Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General*, 117, 34–50.
- Wang, R. F. (2004). Action, verbal response and spatial reasoning. *Cognition*, 94, 185–192.
- Windmann, S., Daum, I., & Güntürkün, O. (2002). Dissociating prelexical and postlexical processing of affective information in the two hemispheres: Effects of the stimulus presentation format. *Brain and Language*, 80, 269–286.
- Windmann, S., Urbach, T. P., & Kutas, M. (2002). Cognitive and neural mechanisms of decision biases in recognition memory. *Cerebral Cortex*, 12, 808–817.