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Research report

Categorical and coordinate spatial representations within object-location memory

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ABSTRACT

An important aspect of spatial memory is the ability to remember the positions of objects around us. There is evidence that spatial information can be represented in different ways, involving a coordinate representation (fine-grained, metric information) and a categorical representation (above/below, right/left relations). The current study is aimed at investigating possible lateralization effects for categorical and coordinate information when encoding position information alone and when integrating position information and object information in memory. Twenty-five patients who had suffered from a stroke and 36 healthy controls were tested with different tests assessing categorical and coordinate position memory, and categorical and coordinate object-to-position memory. The identity task that was used by (Laeng, 1994) was included as well as a control task for measuring lateralization effect for categorical and coordinate information. Moreover, object-recognition and visuo-spatial perception were assessed. The results showed that processing categorical and coordinate spatial information were impaired by a lesion in the left and right hemisphere, respectively. No lateralization effects were found when spatial information had to be integrated with object information. These results bear on the functional components of object-location memory and their underlying hemispheric basis.

1. Introduction

Object-location memory is an important aspect of spatial memory, enabling us to remember the positions of objects in our environment. Smith and Milner (1981, 1989) showed that object-location memory is impaired by damage to the right medial temporal lobe (MTL) (Kopelman et al., 1997). In particular, the right parahippocampal gyrus (Milner et al., 1997) and the right hippocampus (Crane and Milner, 2004; Stepankova et al., 2004) seem to be involved in processing object-location information in memory. Importantly, however, object-location memory is not a unitary construct, but can be subdivided into a number of components. Processing object information and position information clearly deal with distinct aspects (Moscovitch et al., 1995), whereas a third process is responsible for the integration of these two features. These components can be selectively impaired, as was shown by examining patients with focal lesions with

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different tasks assessing the ability to encode object or position information or both features (Kessels et al., 2002). Interestingly, lesions in the right hemisphere resulted in impaired position memory, whereas lesions in the left hemisphere disrupted object-location binding, indicating that object-location memory does not simply rely upon a right sided circuitry (Kessels et al., 2002).

This lateralization effect might be the result of the coordinate and categorical nature of these two memory tasks. Categorical representations refer to relative spatial relations, such as remembering that your cup is on the right of the computer. This type of information ignores the exact spatial position of an object, and categorizes objects according to a certain relation (above/below, left/right, inside/outside). In contrast, coordinate representations contain fine-grained, metric information, which can be used to guide actions, particularly when visual information is not at hand or insufficient, such as when walking around in the dark (Kosslyn et al., 1989). Arguably, encoding of coordinate spatial information and of categorical spatial information rely on distinct subsystems. Categorical relations would be primarily subserved by brain areas in the left hemisphere, whereas the more "purely" spatial nature of coordinate representations suggests that they are more effectively encoded by the right hemisphere. This lateralization effect might be related to the fact that language processes depend on the left hemisphere, whereas spatial processes (e.g., navigation) depend on the right hemisphere (Kosslyn et al., 1989). However, whereas this might be the case when processing the relative or exact positions of objects (i.e., binding processes), this does not seem likely when merely remembering categorical or coordinate position information. Kosslyn et al. (1989) showed that healthy participants could evaluate categorical representations better when they were initially presented to the left hemisphere, whereas coordinate representations were evaluated better when information was initially presented to the right hemisphere (Kosslyn et al., 1989). Similar effects were found when examining the processing of categorical and coordinate position information in patients with focal lesions in either the left or right hemisphere (Laeng, 1994). The "identity task" was used in which a drawing of one or more objects was shown during a short period of time. Subsequently, two drawings were presented, one of which being the same as the initially presented drawing, whereas the other was altered by changing either the categorical or coordinate spatial relation. Participants were instructed to judge which of these two drawings was the same as the initially presented drawing. Results showed that patients who had suffered from a stroke with a lesion in the right hemisphere made more errors when the coordinate spatial relation was changed, whereas patients with a lesion in the left hemisphere made more errors when the categorical spatial relation was changed. It should be noticed that in the original Laeng study the two stimuli followed each other very closely in time, so the task could rather be seen as a perceptual than a real memory test.

A recent review including cognitive, neuroimaging and patient studies showed moderate support for a functional and neuroanatomical dissociation between categorical and coordinate spatial relations (Jager and Postma, 2003). Importantly, it was emphasized that finding lateralization effects seem to be highly dependent of methodological aspects of the individual experiments (Jager and Postma, 2003; Wilkinson and Donnely, 1999). Interestingly, object-location memory studies also show a wide diversity in methodology employed. In several studies of object-location memory, patients are asked to remember and relocate the exact positions of objects that were presented on a square board (Crane and Milner, 2004; Smith and Milner, 1981, 1989), or a more real life 'arena' (Stepankova et al., 2004). In contrast, Kessels et al. (2002) used a computerized task to assess object-location memory, including various task conditions to test coordinate and categorical spatial memory, single feature and binding processes. The latter study found specific lateralisization effects, depending on what aspect of object-location memory was studied. Thus, contradictory lateralization effects regarding object-location memory seem to be the result of methodological differences and specific subtypes of object-location memory that are tested.

In a recent paper, Postma et al. (2003) sketched a tentative working model of object-location memory, including the categorical/coordinate distinction. They speculated that object-location memory entails five different processing components: (1) encoding object information, (2a) encoding categorical position information; (2b) encoding coordinate position information, (3a) binding object and categorical position information; (3b) binding object and coordinate position information. In line with the foregoing logic, Kessels et al. (2004) demonstrated that right amygdalohippocampectomy patients were impaired on a task assessing coordinate position information, whereas left amygdalohippocampectomy patients were impaired on a task assessing binding of object and coordinate location information. However, processing categorical position information in isolation was not impaired. This might have been due to the fact that patients that were included in this study had specific damage to the hippocampus, which is thought to be particularly involved in integrating different types of information in memory, including object and spatial information (Eichenbaum and Bunsey, 1995). Also, patients with chronic epilepsy who received neurosurgical treatment, might have different lateralization of function due to plasticity of the brain (Vingerhoets et al., 2004). In contrast, encoding position information in isolation may rely predominantly on the posterior parietal cortex, in particular in the right hemisphere (e.g., Smith and Jonides, 1999; Wilson et al., 1993). Additionally, it remains unclear whether a similar hemispheric specialization for categorical and coordinate information processing is found when spatial information is integrated with object information. That is, Kessels et al. (2004) reported that patients with a lesion in the left MTL were impaired on a task assessing the ability to integrate object and coordinate location information, but not object and categorical location information, suggesting they rely on different processes.

Clearly to test the above mentioned working model of object-location memory in a neuropsychological manner both a broader range of task conditions are necessary and a larger variety in brain damaged patients. Therefore the goal of the current study was to attempt a systematic, inclusive mapping of the functional components involved in object-location memory in patients with various cortical and hippocampal lesions. Former patients are particularly important considering the expected involvement of cortical areas, such as the parietal and frontal cortex in spatial memory processes. Importantly, a distinction was made between processing spatial information in isolation and integrating or 'binding together' spatial and object information. Patients with focal cerebral lesions due to unilateral stroke were tested with an object-location memory task, in which separate conditions were included to assess object-location memory. Two task conditions were used to assess categorical position information; one task condition requiring participants to remember the categorical locations per se, and one task condition assessing the ability to integrate categorical spatial information with object information. The two other tasks conditions tested the ability to process coordinate spatial information per se, and the ability to integrate this information with object identity information. Additionally, two control task conditions were used, i.e., an object-recognition condition (i.e., assessing the ability to memorize the objects per se) and a visuo-spatial construction condition (assessing the ability to relocate object to their exact position). Since the two binding conditions required knowledge of the object identities, performance on the object-recognition condition was used as a covariate in the analyses of these conditions. The pure coordinate condition required participants to place objects to their exact position, instead of their relative positions (as the other tasks required). Since patients might be impaired in their ability to perform the precise motor movements that this condition requires, the visuo-spatial construction condition was used as a covariate. Finally, the identity task was included as well, because of its potential to demonstrate the hypothesized function lateralization (Laeng, 1994). In general, we hypothesized that encoding coordinate spatial positions would relate to the right hemisphere, whereas encoding categorical spatial positions were impaired by damage to the left hemisphere. Additionally, the same lateralization effects were expected when integrating categorical and coordinate position information with object information.

2. Methods

2.1. *Participants*

Twenty-five patients who had suffered a stroke and were admitted to the stroke unit of the neurology department of the University Medical Center Utrecht (UMCU) were tested. Thirteen patients had a lesion in the left hemisphere and 12 patients had a lesion in the right hemisphere. Lesion locations included the right frontal cortex (4 patients), left frontal cortex (6), right temporal cortex (7), left temporal cortex (6), right-hippocampal formation (4) left hippocampal formation (3), right parietal cortex (1), left parietal cortex (1). Some patients had a lesion involving more than one of these brain areas. All patients were examined at least six months after the stroke and were mobile at the time of testing, i.e., they were able to walk around and did not have problems with using the touch-screen. Patients were all between 21 and 75 years of age and did not suffer from other neurological or psychiatric diseases. The study was approved by the medical ethics committee of the UMCU and written informed consent was obtained according to the declaration of Helsinki. Importantly, it was made clear that all patients understood the task instructions and did not have any apparent language impairments. We also examined 36 age and education matched, healthy control participants who were recruited through an advertisement in the local newspaper and were paid for their participation. Characteristics of the patients and comparison group are shown in Table 1. Handedness was assessed with a Dutch version of the Annett handedness inventory (Briggs and Nebbs, 1975). Education level was measured using seven categories (1 being the lowest and 7 the highest; Hochstenbach et al., 2003). No difference was found between the three groups for education level [$F(2,62) = 2.1$], age [$F(2,63) = .1$], or gender distribution [$\chi^2(2) = 4.4$].

Standard neuropsychological tests were used to assess overall intelligence and memory performance. Verbal intelligence was assessed with the Dutch version of the National Adult Reading Task (Schmand et al., 1991); non-verbal intelligence with the 12-item short form of the Raven Advanced Progressive Matrices (Raven et al., 1993). Verbal memory was assessed with the Dutch version of the Rey Auditory Verbal Learning Test (RAVLT), (Rey, 1964; Van der Elst et al., 2005). The Letter Number Sequencing task (WAIS-III) was used as an index of verbal working memory (Wechsler, 1987).

2.2. *Material and procedure*

2.2.1. *Identity task*

This computerized version of the Identity test used by Laeng (1994) included the same 20 stimulus pairs as the original experiments with cards. Black- and-white drawings of animals (e.g., rabbit) and objects (e.g., football) were shown on a 15-inch computer-screen during 5 sec. Participant received the instruction to pay attention to the drawing and to try to

Table 1 – Characteristics and neuropsychological test results (SE) of patients with a lesion in the right hemisphere (RH), patients with a lesion in the left hemisphere (LH) and control participants separately

	RH	LH	Controls
Age	57.8 (3.1)	57.8 (2.8)	56.9 (1.8)
Education level (1–7)	4.7 (.4)	5.3 (.3)	5.5 (1.0)
Annett handedness inventory (−24/24)	15.2 (4.2)	17.8 (2.9)	15.3 (2.2)
Sex (m:f)	12:2	11:5	20:16
NLV-IQ	107.5 (6.1)	105.6 (5.6)	107.2 (3.7)
RAVLT: immediate recall	36.5 (2.8)*	37.5 (3.1)*	46.9 (1.7)
RAVLT: delayed recall	8.5 (1.1)	7.8 (1.5)	9.6 (.6)
Raven APM (short form)	7.0 (.9)	8.0 (.7)	12.0 (2.8)
Letter number sequencing task	9.5 (.8)	8.5 (.7)	9.8 (.3)
Corsi block-tapping task	45.8 (4.6)	43.6 (3.5)	42.4 (2.5)

*Significant difference with the controls ($p < .05$).

SE, Standard error; NLV, National Adult Reading Task; RAVLT, Rey Auditory Verbal Learning Test; Raven APM, Raven Advanced Progressive Matrices.

remember it. Then, after an interval of another 5 sec in which an empty screen was seen, two drawings were shown. One of these drawings was the same as the original drawing, whereas the other was slightly different. Drawings could be changed according to a coordinate relation (distance on the horizontal, vertical or both axes, distance relative to a frame, position of body parts, orientation in angle, object size) or a categorical relation (laterality, verticality, confrontation, inclusion and contact). Participants had to indicate which of the two pictures was the same as the drawing initially shown, by pressing either one of two buttons on the keyboard.

2.2.2. *Object relocation task*

The Object Relocation program was used (Kessels et al., 1999), in which everyday objects (e.g., ball, frog) were shown within a frame of 19 × 19 cm on a computer-screen (15-inch LCD touch-screen). After a presentation time of 30 sec, the objects disappeared from the display and were placed above the frame. Participants could replace them by touching the objects and touching the location they wanted to place the object. Two control conditions were used: First, the *object-recognition condition*, in which 10 objects were shown in a 2 × 5 grid. During the relocation phase 20 objects were shown and participants were instructed to place the 10 correct objects in the matrix, disregarding the correct location. Second, in the *visuo-spatial construction condition* two frames of 10 × 10 cm were shown, one of which contains 10 objects, the other was empty but had the 10 objects placed above the frame. Then, participants were instructed to copy the frame. Subsequently, four experimental conditions were used (see Fig. 1). In the *categorical positions-only condition* 10 equal objects were shown in a 7 × 7 grid. During the relocation phase the objects were placed above the same 7 × 7 grid, and participants were instructed to place the objects on the correct location. In the *coordinate positions-only condition* 10 equal objects were shown within an empty grid, and during the relocation phase participants had to replace these objects to the correct location within the same empty grid. In the *categorical object-to-position condition* 10 different objects were shown within a square. During the relocation phase the locations of the objects were marked with dots. Participants were instructed to replace the objects to their correct locations. In the *coordinate object-to-position condition* again 10 different objects were shown within a square, but now participants had to replace the objects within an empty frame. Each condition contained two different trials and was preceded by a practice condition of four objects (with a presentation time of 20 sec). A different set of objects and locations was used for each trial. A fixed task order was followed for all participants: object-recognition condition, visuo-spatial construction condition, categorical positions-only condition, coordinate positions-only condition, categorical object-to-position condition, coordinate object-to-position condition.

For the object-recognition task condition the percentage of errors was calculated. Error percentages were also calculated for the object-to-position task, based on the number of objects that were incorrectly relocated. For the categorical and

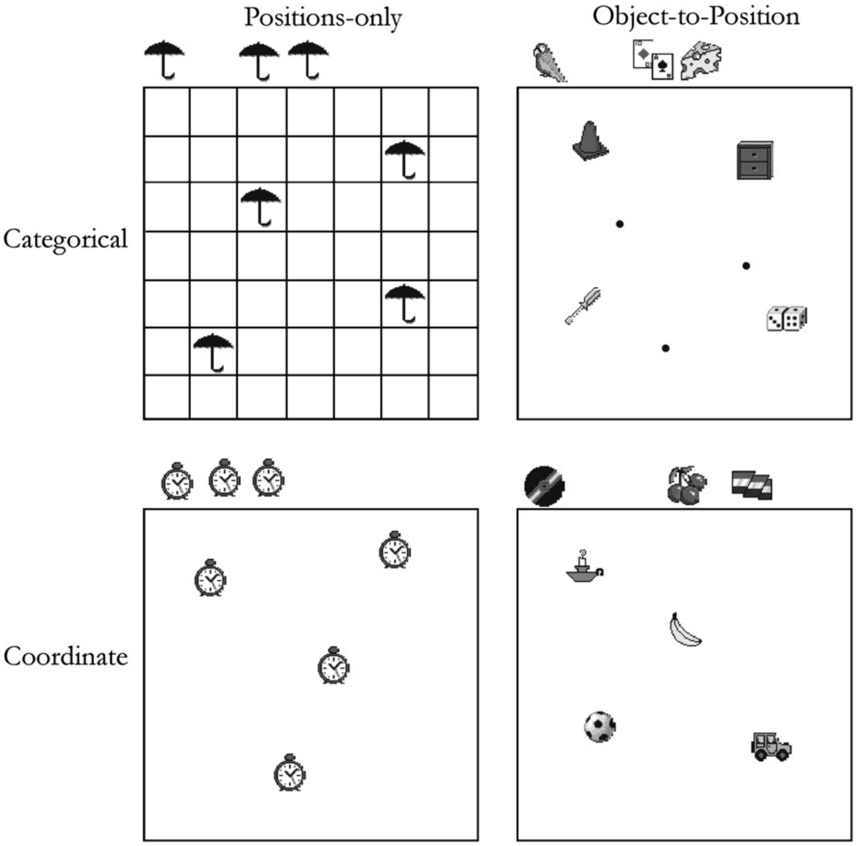

Fig. 1 – Example of a display of the four tasks conditions used.

coordinate positions-only condition and the visuo-spatial construction condition, the absolute distance between the relocated position and the original position of each object was calculated. The absolute displacement error was the total of these absolute distances in mm for the stimulus display as a whole. In the positions-only condition all objects were equal, and therefore the absolute distances could not be calculated, since it cannot be easily determined which object belongs to which position. Therefore, all possible pairings of relocated and original positions were computed. The best-fit measure in mm was based on the pairings which yielded the smallest error score for the stimulus display as a whole.

3. Results

3.1. *Neuropsychological tests*

Independent-samples' *t*-tests revealed no differences on any of the standard neuropsychological tests between the patients and controls, except on immediate reproduction of the RAVLT [$F(2,57) < 7.7$, $p = .01$]. Patients with a lesion in the right or left hemisphere performed worse than the control participants [$t(47) = 2.9$, $p = .09$, $t(46) = 3.3$, $p = .02$, respectively]; no difference was found between performance of the patients with damage to the left or to the right hemisphere [$t(24) = .2$].

3.2. *Identity task*

Performance on the Identity task (Table 2) was analysed by means of a 2 × 3 analysis of variance (ANOVA) with within-subject variable Type of error (coordinate, categorical) and between-subject variable Group (patients with a lesion in the left hemisphere, patients with a lesion in the right hemisphere, controls). No main effect was found for type of error [$F(1,63) = 2.4$] or Group [$F(1,63) = 1.1$], nor an interaction effect [$F(2,63) = 1.1$].

3.3. *Object relocation task*

Error percentages were calculated for the object-to-position condition, and displacement errors (in mm) were calculated for the visuo-spatial construction condition, the categorical and coordinate positions-only condition and the coordinate object-to-position condition (Table 3). Since the dependent measures were not directly comparable, Z-scores were computed based on the performances of the patients and control participants taken together (Fig. 2). A 2 × 2 × 3 Repeated Measures General Linear Model (GLM) analyses with within-subject variable Feature (categorical, coordinate), Binding (single feature, binding) and Group (patients with a lesion in the left hemisphere, patients with a lesion in the right hemisphere, controls) was conducted. Performance on the object-recognition condition and the visuo-spatial construction condition were used as covariates. A significant effect between Feature × Binding × Group was found [$F(2,56) = 5.2$, $p = .008$], but no main effects were found [$F(1,56) = .1$], nor other interaction effects [$F(1,56) = .9$].

Table 2 – Mean correct scores (SE) for the Identity task (categorical and coordinate) for the RH and LH patient group and control group separately

	RH	LH	Controls
Categorical trials (max. 10)	8.5 (.3)	8.2 (.5)	8.8 (.2)
Coordinate trials (max. 10)	7.9 (.3)	8.1 (.5)	8.7 (.2)

Table 3 – Mean (SE) number of errors for the two control tasks and four main tasks for the RH and LH patient group and control group separately

	RH	LH	Controls
	Mean (SE)	Mean (SE)	Mean (SE)
Object-recognition task (%)	12.3 (2.9)	5.8 (1.6)	4.2 (1.1)
Visuo-spatial construction task (mm)	102.2 (11.2)	107.5 (9.3)	84.4 (4.9)
Categorical positions-only task (mm)	223.2 (21.1)	261.5 (12.1)	227.1 (12.4)
Coordinate positions-only task (mm)	266.3 (15.6)	235.0 (13.1)	219.4 (8.4)
Categorical object-to-position task (%)	36.5 (7.5)	30.4 (4.8)	20.1 (3.7)
Coordinate object-to-position task (mm)	416 (41.2)	463.2 (42.6)	380.8 (25.8)

RH, right hemisphere patients; LH, left hemisphere patients.

To study hemispheric specialization for categorical/coordinate representations when position information had to be encoded, a 2 × 3 Repeated Measures GLM analyses was performed, with within-subject variable Feature (categorical positions-only task, coordinate positions-only task) and Group (patients with a lesion in the left hemisphere, patients with a lesion in the right hemisphere, controls). Performance on the visuo-spatial construction condition was taken as

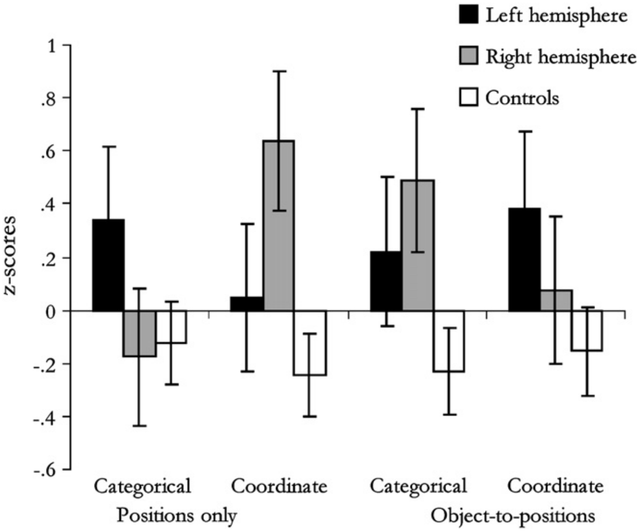

Fig. 2 – Mean Z-scores of the categorical and coordinate positions-only task and the categorical and coordinate object-to-position task.

a covariate. This indicated a significant Feature × Group effect [$F(2,57) = 4.3$, $p = .018$], but no main effects [$F(1,57) < .8$]. Subsequently, Independent-samples' *t*-tests indicated that patients with a lesion in the right hemisphere performed worse than the controls on the coordinate condition [$t(47) = 2.8$. $p = .007$], but not the categorical condition [$t(47) = .2$], also after using performance on the visuo-spatial construction condition as a covariate [$F(1,46) = 5.0$, $p = .03$]. Patients with a lesion in the left hemisphere performed worse than the controls on the categorical condition [$t(47) = 2.1$, $p = .046$], but not the coordinate condition [$t(46) = .9$].

To assess hemispheric specialization for categorical/coordinate representations when position information had to be integrated with object information, a 2 × 3 Repeated Measures GLM analyses was conducted with within-subject variable Feature (coordinate object-to-position task, categorical object-to-position task) and between-subject variable Group (patients with a lesion in the left hemisphere, patients with a lesion in the right hemisphere, controls). No main effects were found [$F(1,57) = 1.0$], nor an interaction effect [$F(2,57) = 1.2$].

3.4. *Correlations*

A double dissociation was found for the coordinate and categorical positions-only condition, but not for the coordinate and categorical object-to-position condition. This might suggest that the latter rely on the same underlying memory process, while the first do not. In order to further explore this hypothesis, two two-tailed Pearson's correlation were performed using the performances of patients with a lesion in either the right or left hemisphere. This revealed a significant correlation between performance on the categorical and coordinate object-to-position condition ($r = .52$, $p < .01$), but not between the categorical and coordinate positions-only condition ($r = .39$). However, no significant difference was found between these two correlations ($Z = .53$).

4. Discussion

The current neuropsychological study was aimed at testing the object-location model of Postma et al. (2003) in patients with various cortical and hippocampal lesions. Therefore, different task conditions were used, assessing categorical and coordinate spatial representations when position information is encoded in isolation, and when it is integrated with object information (i.e., binding). Interestingly, lateralization effects were found when only position information had to be encoded, but not when this information had to be integrated with object information in memory. That is, patients with a lesion in the left hemisphere performed worse on the categorical positions-only task, but were unimpaired on the coordinate positions-only task, whereas the reverse effect was found for patients with a lesion in the right hemisphere. Importantly, this is not the result of differences in general cognitive ability and memory function, which was assessed with standard neuropsychological tests. Although impaired memory for coordinate position information due to damage to the right hemisphere has been found previously (Kessels et al., 2002, 2004), a deficit for pure categorical position memory after damage to the left hemisphere has not yet been demonstrated within this object-location paradigm. The results are in line with the idea that categorical spatial representations are processed by the left hemisphere and coordinate spatial representations are processed by the right hemisphere (Kosslyn et al., 1989; Laeng, 1994; Laeng and Peters, 1995).

Importantly, this lateralization effect for categorical and coordinate spatial information was not found when position information had to be integrated with object information. In contrast, Kessels et al. (2004) found that patients with a lesion in the left MTL were impaired on the coordinate object-location binding task, whereas Kessels et al. (2002) found a binding deficit for object and categorical position information in patients with a lesion in the left parietal cortex. It remains unclear why this difference exists between neuropsychological studies employing comparable spatial tasks. Differential results may be due to differences in the etiology of the lesion. That is, the patients with unilateral MTL lesions (Kessels et al., 2004) suffered from chronic pre-surgical epilepsy, which may have affected the lateralization of cognitive function (e.g., Vingerhoets et al., 2004). In turn, stroke patients generally have a healthy brain prior to the occurrence of the stroke. Indeed, recent functional Magnetic Resonance Imaging (fMRI) research shows that healthy controls show right-hippocampal involvement in a task relying on coordinate object-location binding (Piekema et al., 2006). Next to differences in etiology, differences in lesion localization may also explain contrastive findings. For example, the study of Kessels et al. (2002) involved patients with damage to the parietal, frontal, occipital and temporal cortex. Importantly, it was suggested that binding categorical and object information in memory might depend on the left parietal cortex (cf. Laeng and Peters, 1995). The fact that the current study involved only few patients with damage to the left parietal cortex, might explain why no impairment was found on the categorical object-to-position task. Additionally, this might explain why no overall lateralization effects were found for the identity task, assessing memory for categorical and coordinate spatial representations. That is, Laeng (1994) suggested that the parietal cortex might be particularly involved in processing categorical and coordinate spatial relation. Moreover, the data of the identity task show that in absolute terms both patients and controls make only few errors, indicating that the task might not be sensitive enough to reveal differences in the present patient group, in contrast to the categorical and coordinate positions-only task. Another important difference is that the identity task of Laeng (1994) contains manipulations related to both within-object and between-object spatial relations.

Interestingly, performance on the categorical and coordinate object-to-position task was highly correlated, whereas no correlation was found between performance on the categorical and coordinate positions-only task. One possibility is that this correlation is due to the involvement of object memory in both tasks. Alternatively, the binding conditions might reflect to some extent a single underlying functional process. Possibly, to remember the locations of multiple objects, the objects serve as 'landmarks' characterizing the positions. Subsequently, the relative (categorical) relations between the objects are remembered (e.g., 'the ball and lizard are in the right upper corner, whereas the calculator and orange are in the left upper corner'). Accordingly, Alexander et al. (2002) indicated that the exact coordinate location might only be remembered when objects are presented individually, whereas multiple simultaneously presented objects are always processed categorically. This notion is partly in line with the finding of Kessels et al. (2002), who showed that patients with a lesion in the left hemisphere are impaired on both a categorical and coordinate object-to-position task including multiple objects, whereas no deficit was found in the right hemisphere group with respect to object-to-position memory. Note that although the authors feel confident that the categorical task conditions tap on categorical spatial memory, the scoring procedures that are used take no account of the relative positions, since relative scoring methods are particularly difficult for the categorical positions-only condition.

The results of the current study have important implications for the object-location memory model. As was hypothesized by Postma et al. (2003), two distinct processes are involved in remembering categorical and coordinate position information, which clearly rely on brain areas in the left and right hemisphere, respectively. However, no evidence was found supporting the hypothesis that a similar hemispheric specialization for categorical and coordinate information processing is found when spatial information is integrated with object information. That is, the current results point more towards a shared, single mechanism responsible for integrating object and location information. In sum, it can be argued that object-location memory rests on a distributed network of different areas in the frontal, medial temporal and parietal cortex. While the current study as one of the first reveals this network as a whole, more neuropsychological cases are needed to fully reveal the working and details of the presumed neural circuitry.

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