

Constructional apraxia after left or right unilateral stroke

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Abstract

The present study re-assesses the question whether deficits, after brain damage, in constructional tasks can be partitioned in different types of disorders of spatial cognition. Based on a current cognitive neuroscience account, originally proposed by Kosslyn [Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148–175], that posits two complementary lateralized systems for the encoding of (categorical and coordinate) spatial relations, it is here proposed that two qualitatively different types of “constructional apraxia” can occur and that the nature of the constructional impairment after unilateral lesions closely reflects the loss of lateralized components for the perceptual processing of differing types of spatial relations. New evidence is presented, based on the study of two groups of patients with unilateral posterior brain lesions, which supports such a bipartition of constructional apraxia. In addition, past evidence is reviewed in the light of this new cognitive neuroscience account.

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1. Constructional apraxia after left or right unilateral stroke

For about a century it has been common practice to demonstrate and assess the devastating effects of brain damage on spatial cognition by asking patients to copy a drawing or reconstruct a model from memory. Indeed, one key symptom of spatial neglect is provided by a patient's omission of elements from the side on the model to be reproduced (McFie, Piercy, & Zangwill, 1950). However, the modern techniques of neuroimaging have greatly reduced the value and use of constructional and other bedside tests. Moreover, the lack of clarity and contradictory findings between many studies on constructional apraxia in patients with unilateral lesions (cf., De Renzi, 1982, chapter 9) might have contributed to the current lack of focus of cognitive neuroscientists on what patients can draw or build as a way to investigate – for example – deficits of spatial processing and their neural basis.

The goal of this study was to re-assess whether deficits in constructional tasks, or as it came to be called “constructional apraxia”, could be partitioned in two different types of disorders of spatial cognition. Kleist originally used the term “apraxia” in 1934 and this was meant to indicate an “inability to do” (in

this case, an inability to do a construction; e.g., re-arrange letter blocks to compose words or build patterns with sticks; cf., Benton, 1984). The term turned out to be somewhat misleading because it tended to suggest the deficit might not be due to distortions of spatial processing but, more literally, to problems in motor control. Kleist's view was that the parietal lobe of the left hemisphere (LH) had a perceptual processing capacity that was specifically dedicated to the analysis space in the service of the organization of action or movements planning or, in more recent terms, a “manipulospacial” subsystem (cf., LeDoux, Wilson, & Gazzaniga, 1977). Within the contemporary research community, there is still skepticism that a patient's constructional errors can derive from a disorder of spatial processing (especially when the patient has suffered damage to the left hemisphere; e.g., Warrington, James, & Kinsbourne, 1966). However, such a skeptical stance might be avoided by positing a division of labor in spatial processing between the cerebral hemispheres. In fact, such a perspective has the potential to capture important aspects of the effects of unilateral lesions on the human brain on constructional tasks. Hence, the present study proposes a re-assessment of past conclusions about the neural basis of constructional apraxia in the light of a contemporary theory of the neural basis of spatial cognition. Hopefully, the present attempt may help to resolve some of the contradictions and doubts that the research conducted on the topic seems to have accumulated.

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Interestingly, one of the original observations of constructional apraxia was a single-case study by [Liepmann \(1912\)](#). As described by [De Renzi \(1982\)](#), Liepmann's patient had right hemiplegia and language impairments as well as a complete failure of writing skills. There was considerable impairment in block constructions, despite the fact that the patient could imitate gestures and actions and handle actual objects. The patient was unable to place a block "beside" another, when instructed to do so. Interestingly, he confused the vertical with the horizontal plane, the top with the bottom and the right with the left. Liepmann suggested that the deficit could indicate a specific impairment in analyzing and assembling objects in space. Liepmann's patient had suffered left hemisphere's damage. Twenty years later, Kleist proposed that constructional apraxia derived from damage to structures of the LH, particularly to the region of the angular gyrus. These early German neurologists' seminal observations were later often dismissed as due to the left-sided patients being forced, by their right hemiplegia, to use the non-dominant left hand. However, use of the non-preferred hand cannot possibly lead to the spatial confusions described in, for example, Liepmann's case (in fact, as shown by [Dee & Fontenot, 1969](#), the drawing performance of normal individuals is remarkably similar in terms or errors whether they use either the preferred or non-preferred hand). More damaging to the idea that constructional apraxia was determined by lesions to the posterior regions of the LH was the observation that constructional deficits would also appear after lesions to the other side of the brain ([Black & Strub, 1976](#); [Ettlinger, Warrington, & Zangwill, 1957](#); [Hécaen, Ajuriaguerra, & Massonet, 1951](#); [Hécaen, Penfield, Bertrand, & Malmö, 1956](#); [McFie et al., 1950](#)). [Piercy, Hécaen, and De Ajuriaguerra \(1960\)](#) proposed that, after left-sided lesions, constructional apraxia was due to these patients' problems with manipulating objects (i.e., an impairment in executive functions); whereas only right-sided lesions would reveal a genuine form of spatial perceptual impairment (cf., [Arenia & Gainotti, 1977, 1978](#); [Carlesimo, Fadda, & Caltagirone, 1993](#); [Costa & Vaughn, 1962](#)). Such a conclusion seemed highly consistent with the field's consensus at the time (yet, still pervasive today) that the right hemisphere (RH) is the one specialized for spatial function.

However, according to an original formulation by [Kosslyn \(1987\)](#), there is an early split within the "dorsal" stream of visual information into two subnetworks that process qualitatively different types of spatial information. These two networks within the dorsal system are each concerned with a single type of computation, and each type produces a representation of a different kind of spatial relation. Both formats may uniquely enrich our analysis of space. One type of spatial relations representation captures "coordinate relations". These sorts of relations occur within a metric space; that is, an order or collection of points on which distances between points are defined. An order of such points creates a continuum, thus two spatial forms can transform into one another through intermediate orders of points. The ability to encode coordinate relations would allow the perception and expression of space in a quantitative sense and this coordinate mode of coding interrelations would be most suit-

able for the control of action (cf., [LeDoux et al., 1977](#)) and for navigation.

In addition, [Kosslyn \(1987\)](#) proposed an alternative and qualitatively different mode of perception from the one necessary to guide action. Specifically, some problems of object recognition would seem to require integration of visual information about shape with spatial information about the arrangement of the object's parts. Specifically, this type of spatial information is defined as "categorical", consisting of groupings of locations that define an equivalence class. At the root of such representations is the ability to delineate patches of space or to discover boundaries or limits that separate bins of space. Categorical representations are abstract compared to coordinate ones. The categorical type of spatial representations would seem most adequate to capture an object's "structural description"; that is, a representation made of the object's parts primitives and the way these parts spatially relate or inter-connect to one another (as proposed by several theories of object recognition; e.g., [Biederman's, 1987](#); [Marr's, 1982](#)). These categorical spatial relations would amount to abstract spatial relations, like those usually captured by prepositions or locatives (e.g., "inside", "on top", "beside", "between", "left of", etc.).

Finally, [Kosslyn \(1987\)](#) (see also [Kosslyn & Koenig, 1995](#)) hypothesized that, although both hemispheres embody computational subsystems that encode the two types of spatial relations representations, the subsystem that encodes categorical spatial relations is more efficient in the LH; whereas the one that encodes coordinate spatial relations is more efficient in the RH. This hypothesis is grounded on the idea that the two types of spatial relations are most efficiently computed by separate subsystems, a hypothesis that has been independently supported by computational simulations ([Kosslyn, Chabris, Marsolek, & Koenig, 1992](#)). Some of the computational models have been developed in quite some detail ([Kosslyn & Jacobs, 1994](#)). In the current version of the theory different processes accomplish the two kinds of spatial encoding, but these processes in turn regulate attention to facilitate encoding the appropriate aspects of the input. Specifically, the efficiency with which spatial relations are encoded depends critically on the receptive fields of the neurons that are being preferentially attended by each hemisphere. The simulations showed that categorical spatial relations are encoded more effectively if the outputs being attended come from neurons with relatively small, non-overlapping receptive fields, as opposed to relatively large, overlapping receptive fields ([Jacobs & Kosslyn, 1994](#)). For categorical relations, an observer can attend to one object and group the receptive fields for the surrounding space into "bins", whereas outputs from neurons with large, overlapping receptive fields allow a system to localize a stimulus precisely. Interestingly, the same account predicts that the ventral areas of each hemisphere will use two distinct mechanisms to encode shape, one that attempts to categorize objects as members of basic-level categories (e.g., dogs and cars), on the basis of their structural description ([Laeng, Carlesimo, Caltagirone, Capasso, & Miceli, 2002](#)), and one that labels specific exemplars (poodle and sedan), on the basis of metric information about shape ([Laeng, Zarrinpar, & Kosslyn, 2003](#)).

Most of the evidence garnered for the complementary laterality hypothesis of spatial relations processing relies on divided visual field studies (e.g., Hellige & Michimata, 1989). Specifically, the theory predicts an interaction between the visual field in which stimuli are presented and the way in which spatial relations must be encoded to perform the task: subjects should be faster and more accurate when stimuli are presented in the left visual field (LVF), or to the RH initially, when coordinate spatial relations must be encoded, and faster and more accurate when stimuli are presented in the right visual field (RVF), or to the LH initially, when categorical spatial relations must be encoded. A recent meta-analysis (Laeng, Chabris, & Kosslyn, 2003, chapter 9) of the divided visual field experiments on the topic has considered the response times (RTs) results of 24 experiments. This analysis showed that in the categorical judgments, RTs were 8 ms faster when stimuli were presented initially to the LH than to the RH, whereas for coordinate judgments the RTs were 14 ms faster when stimuli were presented initially to the RH than to the LH. The overall effect size for this interaction was $d=0.47$, the combined Z-value was 6.93 and the associated p -value was smaller than 0.0001. In sum, the hypothesized hemispheric asymmetries have been supported by the divided visual fields studies, although (at least with this method) they appear to be small in absolute terms. Recent neuroimaging research (some of which is presented in this same issue) has generally confirmed the proposed pattern of relative specialization of each hemisphere for each type of spatial function (e.g., Kosslyn, Thompson, Gitelman, & Alpert, 1998).

Laeng (1994) also provided converging evidence for the lateralization between the two types of spatial relations by studying patients with brain lesions. If categorical spatial relations are computed primarily in the LH, then damage to this hemisphere should cause the patient to become insensitive to changes in categorical relations between objects; in contrast, if coordinate spatial relations are computed primarily in the RH, then damage to this hemisphere should cause the patient to become insensitive to changes in the metric relations among the same objects. Indeed, this study documented a “double dissociation” between these types of deficits, which supported to the idea that the human neural substrate separates the computations underlying each spatial encoding into split “neural networks”, each in one cerebral hemisphere.

Interestingly, the most comprehensive definition of constructional apraxia (provided by Benton, 1967) implies the “impairment in combinatory or organizing activity in which details must be clearly perceived and in which the relationship among the component parts of the entity must be apprehended”. Given that the LH is also specialized in perceiving details or local features of a pattern (Bradshaw & Nettleton, 1983; Delis, Robertson, & Efron, 1986; Van Kleeck, 1989) and that a pattern’s structural description is made of these parts description and how they spatially relate in abstract (categorical) terms (Laeng, Shah, & Kosslyn, 1999), it would seem that the definition of constructional apraxia given above would specifically identify a constructional deficit as resulting from the disruption of the LH’s perceptual functions (incidentally, this would be in line with Liepmann’s and Kleist’s original accounts of constructional

apraxia). However, one is led to expect constructional disorders also after damage to neural substrates that support the perception and expression of space in a quantitative sense (and of patterns in a global sense, given the RH’s specialization in global shape processing; Schatz, Ballantyne, & Trauner, 2000). Hence, one would expect that RH damage would also lead to constructional apraxia, but the deficits resulting from such lesions should lead to types of constructional errors that are qualitatively different from those after lesion to the LH.

The current proposal is that two types of constructional apraxia can occur and each is characterized by disruption of one of the two lateralized spatial perceptual system. In other words, there may exist a “coordinate” form of constructional apraxia, most often observed after RH lesions, and a “categorical” form of constructional apraxia, most often observed after LH lesions. In this perspective, although motor control problems, most often observed after LH lesions, can complicate the assessment of constructional apraxia, they are not in themselves sufficient for characterizing a separate form of the disorder (cf., Arrigoni & De Renzi, 1964; Roncato, Sartori, Masterson, & Rumiati, 1987). In reviewing the constructional apraxia research, De Renzi (1982, 1997, chapter 23) has pointed out the lack of converging evidence between several studies with groups of unilaterally brain-damaged patients in revealing qualitative differences in their constructions; nevertheless, as remarked by De Renzi, in such studies the search for alleged signs distinguishing hemispheric groups was typically conducted with ‘post hoc’ analyses of previously collected data (e.g., Gainotti & Tiacci, 1972; McFie & Zangwill, 1960) and no theoretically-grounded hypothesis of what to look for in each hemispheric group’s performance (cf., De Renzi, 1982, p. 245). Specifically, there was a lack of a perspective that would differentiate spatial function into (relatively) separate (and lateralized) spatial subsystems (as subsequently proposed by Kosslyn’s account). Instead, the underlying assumption of these past studies appeared to be that there is only one type of spatial processing (the metric or coordinate one) and either there is dominance of one hemisphere for it or both sides of the brain support it. Instead, constructional problems after LH lesion are explained away as a problem with executive functions (e.g., Zacharias & Kirk, 1998). Perhaps, an approach that is sufficiently grounded in modern cognitive theory might provide new insights on spatial processing and distortions in constructional tasks.

In the present study, tasks that reduce the possibility of confounds due to motor awkwardness were chosen (hence graphomotor tests, such as copying drawings, were avoided). Instead, patients had to re-arrange spatially separate components of a pattern or array without having to construct these as well in the first place. Although, no constructional tasks can be entirely free from use of some degree of dexterity, tasks that require re-arranging elements without the requirement of a prior reproduction of the elements themselves should greatly reduce the influence of motoric factors. Specifically, a version of one classic constructional task (Butters and Barton’s “Stick Test”) was used as well as a new test consisting in re-locating figures of animals within a scene (see Figs. 1 and 2). Two groups of patients with posterior unilateral lesions and their matched controls were



Fig. 1. Re-location of Object Test. (Top panel) sample array, (middle panel) same array with two missing objects and (bottom panel) four token images (only two can be selected and re-located in the original position on the array shown in the middle panel).

then evaluated in these tasks. [Crichtley \(1953\)](#) and [Newcombe \(1969\)](#) have pointed out that constructional apraxia is associated with parietal damage or, generally, posterior (caudal) lesions ([De Renzi & Faglioni, 1967](#)). In addition, in the present study, the patients' performance in the constructional tasks was compared to their performance in a computerized version of a perceptual test ([Laeng, 1994](#)) that had previously shown robust dissociations in spatial abilities, of the categorical and coordinate kind, in groups of patients with unilateral lesions (see [Fig. 3](#)).

One test consisted of arrays of color drawings of animals (varying in number from three to seven) presented together on a

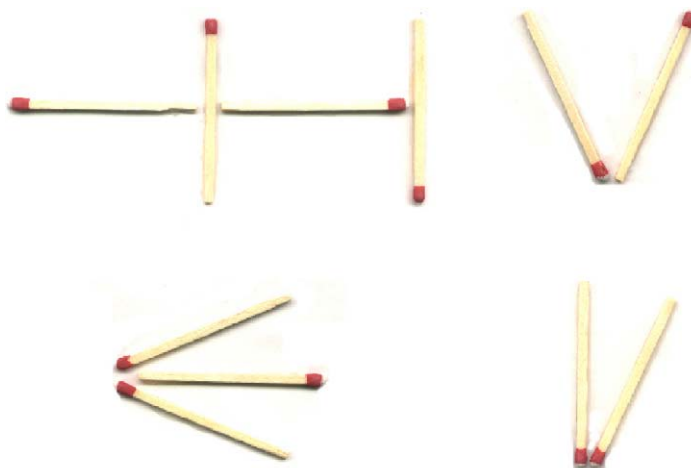


Fig. 2. The Stick Test: examples of four arrays of matchsticks to be reproduced from memory.

page. The patients viewed one set for a few seconds, and after a short delay the previously viewed scene was presented again but without two of the original objects. The remaining objects were always shown in their original spatial positions (both in coordinate and categorical terms). The patients were then given four chips, each one depicting one of the two missing objects in the same or mirror image orientation. The task was to re-locate the correctly oriented pair of drawings in the same positions as originally seen (cf., [Kessels, Kappelle, de Haan, & Postma, 2002](#)). Categorical errors were measured by distortions of the original array, like changes of positions within regions of space (e.g., above or below another object), mirror reversals, and exchanges of position. Instead, the distance of the re-located objects from the originally occupied metric locations (regardless of the identity of each object) measured the coordinate errors.

A similar scoring method was applied to the second test, which consisted of a version of the standard "Stick Test" ([Benson & Barton, 1970](#); [Butters & Burton, 1970](#)). In this test patterns made of a few matchsticks (glued on a piece of paper) is shown to the patients for a few seconds. After a short delay they are requested to reproduce with loose matchsticks the previously seen pattern. Specific attention was paid to categorical and coordinate distortions as the one described for the previous test, plus some additional ones, like disconnection of parts (mainly a categorical error) and angular deviations (mainly a coordinate error).

2. Method

2.1. Participants

Patients with single posterior lesions (confirmed by brain imaging analyses; i.e., CT and MRI), confined to either the left or right hemisphere, were recruited from a variety of health institutions within a time period of approximately 10 years (i.e., 24 patients were recruited from the Massachusetts General Hospital and the Spaulding Rehabilitation Center in Boston, USA; three patients from the San Giovanni Hospital of the Università Cattolica in Rome, Italy; two from the I.R.C.C.S. S. Lucia Hospital, also in Rome; one patient from the University Hospital of Northern Norway in Tromsø, Norway). There were an equal number ($N=15$) of patients with LH and RH patients (total $N=30$); all patients had lesions affecting the parietal lobes but only subcortically in two

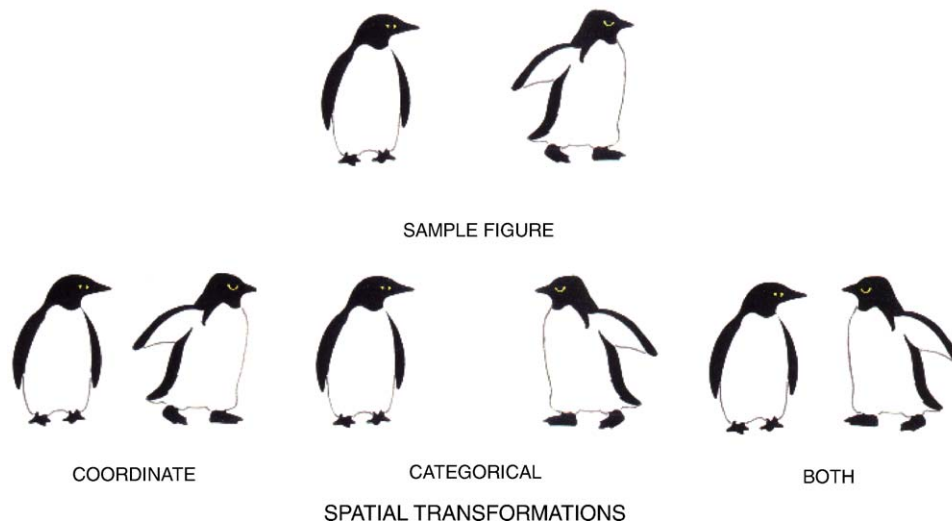


Fig. 3. Perceptual Categorical/Coordinate Test. (Top panel) sample figure and (bottom panel) spatial transformations (from left to right: coordinate, categorical, and both coordinate and categorical, spatial transformations).

patients (one with LH and the other with RH damage). Two patients with LH damage and three with RH damage had lesions encroaching also areas of the temporal lobe. Two patients in each hemisphere group had lesions affecting the frontal lobe. The two groups of patients did not differ in terms of age (LH: mean age = 62.1, S.D. = 8; RH: mean age = 63.2, S.D. = 9), $F(1, 29) = 1.2$, $p < 0.44$. They also did not differ in terms of educational level or time elapsed from the onset of the lesion and the test sessions. All patients were right-handed. Six of the RH patients and one LH patient had shown signs of neglect in the acute stage following their stroke in either cancellation tasks or line bisection tasks but they had recovered by the time they participated in the experimental sessions. There was also an additional group ($N = 15$) of control participants who were matched to the patients by age range (mean age = 59.6, S.D. = 12), percentage of the two sexes (i.e., 60% males), and educational level. The controls subjects were recruited in Boston, Rome and Tromsø.

Patients older than 70 years were excluded, this to reduce complicating factors between the aging process and the effects of brain damage. None of the patients suffered from general mental impairment or dementia (as assessed by subtests of the Wechsler batteries as well as the Mini-Mental State examination). All patients were included if the brain-imaging (CT or MRI) showed evidence of lesions confined to the posterior of the brain and with involvement of the parietal lobe (either cortically or subcortically). The reason for the inclusive criterion of parietal lobe involvement was based on previous evidence (either from patients' studies or neuroimaging studies of normal individuals) of the relevance of this region of the brain in spatial relation processing (e.g., Baciú et al., 1999; Laeng, 1994). Moreover, damage to either parietal lobe has been specifically implicated as a cause of constructional apraxia (Villa, Gainotti, & De Bonis, 1986). Lesions confined to subcortical structures were also included, given that Kirk and Kertesz (1993) have shown that constructional apraxia symptoms do not differ significantly between large groups of patients with cortical or subcortical strokes.

2.2. Procedure

2.2.1. The Animals' Re-location Test

This test consisted of arrays of color drawings of animals (varying in number from three to seven). The patients viewed each array (a sheet of paper showing the animals printed in color) for 5 s, after which the sheet was removed. After a 5 s delay, a similar array on a sheet of paper of the same size was presented in the same position on the table. In this second array, two of the original objects were missing while the others remained in their original positions and orientations. The patients were given four tokens, each one depicting one of the two missing objects. For each missing item there was a version in the same orientation of the original (e.g., a dog oriented towards the left) and another one with its mirror image (i.e., the same dog oriented towards the right). The task was to choose the two correct tokens and to re-locate them in the exact positions as originally

seen. There were a total of 12 trials in this task, each trial presenting a different array to be reproduced.

2.2.2. The "Stick Test"

This test has been designed by Butters and Barton (1970) and consists of meaningless patterns made of two to five matchsticks (glued on a piece of paper) that are shown individually to the patients. In the present version of the task, each array is shown for 5 s, after which the sheet of paper with the sample pattern is removed from sight. After a delay of approximately 5 s, the patients are given a box of matches and blank sheets of paper of the same size of those where the sample patterns were presented and in the same orientation and position on the table. The patients are then requested to reproduce with loose matchsticks the previously seen pattern. Once a patient is satisfied with its rendition of the original model, the experimenter fixes the matchsticks in the positions chosen by the patients with some transparent tape. There were a total of 10 trials in this task, each trial presenting a different pattern to be reproduced. There were no practice trials in either task. Subjects sat upright at a distance of about 50 cm away from the sheets. For a few RH patients, who had evidence of spatial neglect from independent neurological testing (e.g., line cancellation and bisection), the sheets were moved about 40 cm towards the right side of the patient's body midline.

2.2.3. The Perceptual Categorical/Coordinate Test

This test consisted of a computerized matching-to-sample task in which two-dimensional shapes (depicting 3D objects and animals) forming a simple visual scene with two to four elements were shown across several types of spatial transformations. The "sample" items appeared within a box centered on the computer screen for 5 s. A blank screen followed for the duration of another 4 s. Then the same sample box was presented together with a "match" box containing the same items but in a different spatial configuration. The two boxes were arranged vertically and the position of the original box was randomly varied between the top and bottom positions. The patients' task was to press one of two keys (either 'M' or 'K') re-labeled to indicate the position (top/bottom) that corresponded to drawing that was identical to the one seen previously. In the task, there was the same number of trials in which either categorical or coordinate spatial relations were manipulated in the alternative or match drawing. In these drawings, no items were omitted or new ones added to the array, so that only the spatial relations changed between the match and the sample. Each class of spatial relations included several subtypes of spatial relations. For the categorical spatial relations these were: inside/outside; in front/behind; on/off (or also connected/unconnected); above/below; left/right (the latter two types were further subdivided in transformations where two items would exchange their absolute position, e.g., the dog to the left takes the place of the cat to the right and the cat takes the dog's original place, or an item would keep its absolute position but its orientation towards the other item would invert, e.g., the dog that originally

faced the cat would be re-oriented giving its back to the cat). In addition, 20% of the trials showed transformations of both types of spatial relations together (e.g., distance plus left/right orientation). Fig. 3 illustrates the three types of transformations. There were a total of 140 trials in the task (Figs. 2 and 3).

3. Results

3.1. Re-location of objects

It was predicted that patients with LH damage would make more categorical position errors (i.e., the object's location being

displaced over another object's position either vertically or horizontally) and pattern inversions (left/right reflections) of the two re-located objects than the patients with RH damage. Whenever a patient would place an object in a region of space that would cross a boundary established by the imaginary lines (one horizontal and one vertical) centered on the two nearest neighbors of a missing object, this re-location error was scored as a categorical position error. Note that only boundary crossings would lead to a re-location error, whereas any location within the same region would count as a correct response (although the object could be incorrectly position in terms of its absolute metric location). The purpose of this measure was to selectively assess categorical spatial distortions regardless of the patient's performance in coordinate spatial information.

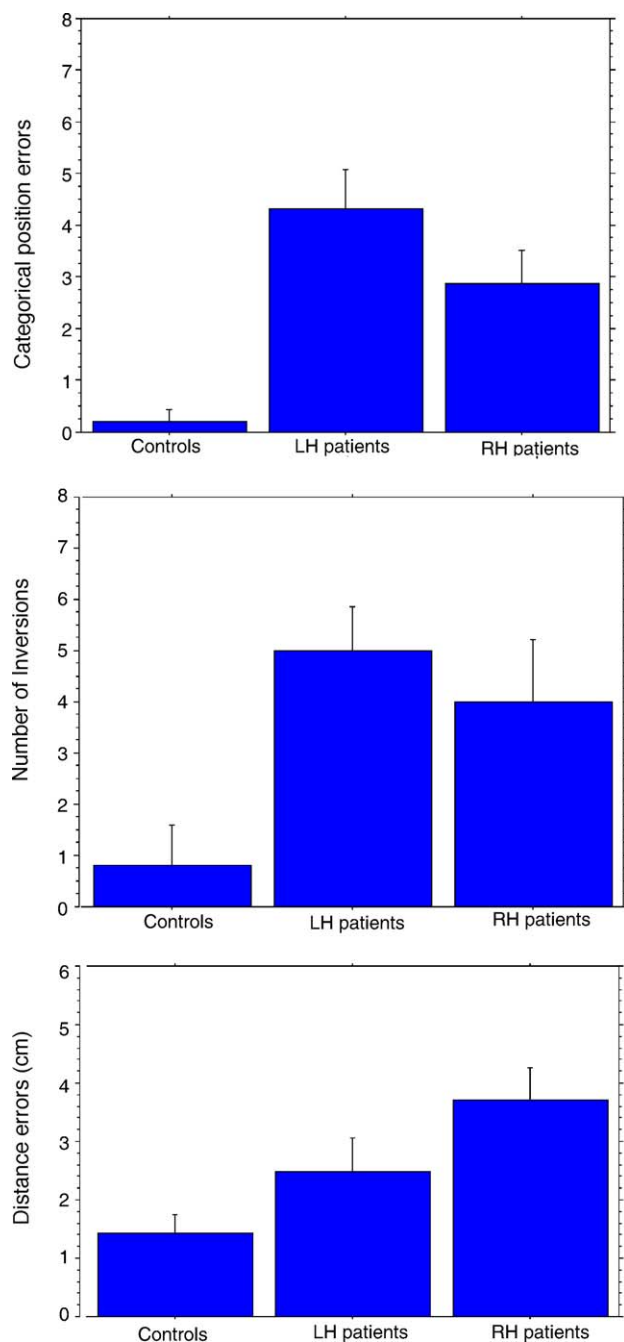


Fig. 4. Re-location Test: columns show the performance of the controls, LH patients and RH patients; bars show 95% confidence intervals. (Top panel) categorical position errors, (middle panel) inversion errors and (bottom panel) distance errors.

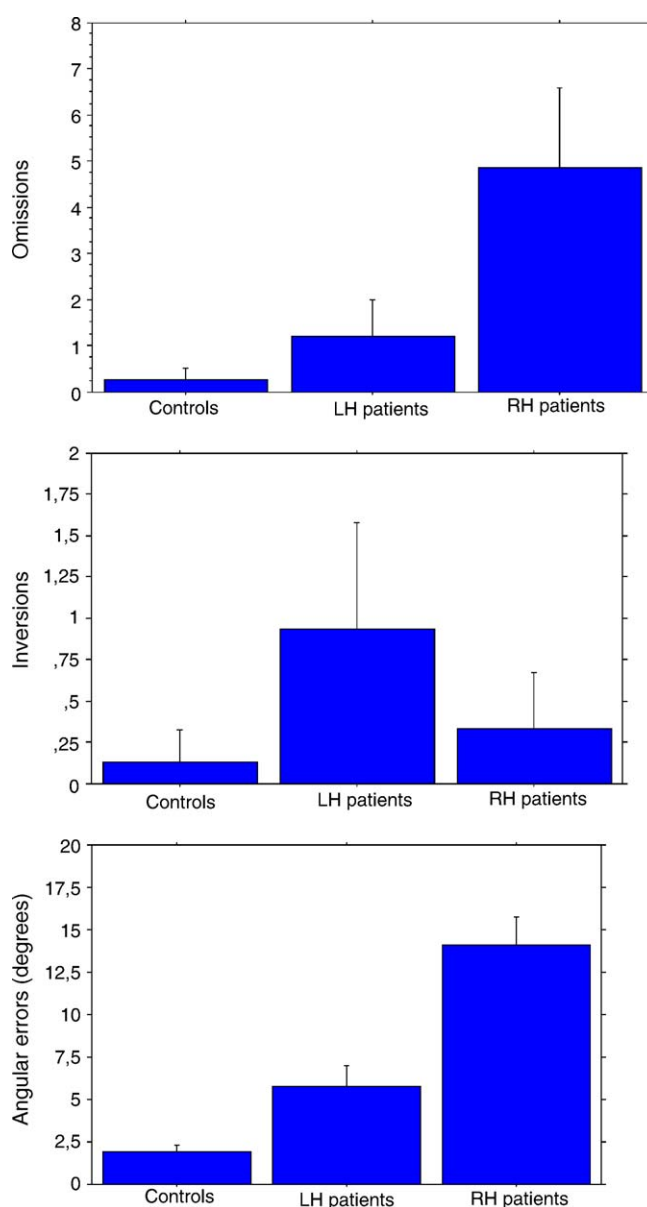


Fig. 5. Matchsticks Test: columns show the performance of the controls, LH patients and RH patients; bars show 95% confidence intervals. (Top panel) omission errors, (middle panel) inversion errors and (bottom panel) angular errors.

There were significant differences between groups (matched controls, LH patients, and RH patients) in both measures, according to separate ANOVAs (re-location categorical errors: $F(2, 42) = 58.2$, $p < 0.0001$; inversion errors: $F(2, 42) = 30.5$, $p < 0.0001$). However, while the two patients groups (LH: mean error = 4.33, S.D. = 1.4; RH: mean error = 2.87, S.D. = 1.2) differed significantly from one another in categorical position errors, the number of inversions shown by the two patients groups (LH: mean error = 5.0, S.D. = 1.6; RH: mean error = 4.1, S.D. = 2.2) differed from those of the matched controls (controls: mean error = 0.8, S.D. = 1.4) but not from one another (see Fig. 4). Interestingly, some of the categorical position errors (37% of all position errors made by the LH and 11% of the RH patients) consisted in the exchange of the positions of an item “A” with the position of “B” while simultaneously placing “B” in “A’s” original position. This type of error indicates confusions about cardinal relations like north/south (above/below) and east/west (left/right) in the presence of appropriate encoding of the absolute coordinates occupied by the two missing objects.

A coordinate error was scored in terms of distance of a re-located object from the center of the nearest empty position. Importantly, it was ignored whether the nearest empty position was in fact originally occupied by the re-located item or by the other one. In this manner, the measure dealt exclusively with memory for coordinates, regardless of whether the bindings of a specific pattern to that coordinate position occurred or not. Moreover, given the likelihood described above of exchanges of position between two items (especially after LH damage), it would be incorrect to consider such re-location errors as coordinate errors (as opposed to confusions between bounded regions and cardinal directions). This coordinate measure of distance also showed a reliable difference between the two patient groups and the controls, $F(2, 42) = 23.6$, $p < 0.0001$. As predicted, there were more distortions of distance among the original locations and those occupied by the re-located chips for the RH patients (mean distance = 3.69, S.D. = 1.02) than the LH patients (mean distance = 2.46, S.D. = 1.03). Both patient groups made more errors than the matched controls (mean distance = 1.43, S.D. = 0.58) (see Fig. 4).

3.2. Stick constructions

It was predicted that the LH patients would show more distortions, like inversions of parts (left/right or above/below reflections), reflections of the whole construction, and omission of parts than the RH patients (although neglect for left-sided elements might be an additional complication factor for the latter group; cf., Gainotti, Miceli, & Caltagirone, 1977). In contrast, the RH patients were expected to show more distortions in the angular orientation of parts than the LH group. In assessing inversion errors, only inversions of parts in relation to other parts were considered (e.g., a horizontally oriented matchstick that could be end-connected to the bottom end of a vertically oriented matchstick would be considered inverted if positioned to the right of the vertical stick when the original position was

to the its left). Inversions of the head of the match were ignored in the present analyses. Scoring of errors was similar to that described for the re-location task; however, whereas the previous construction task consisted of an array of separate elements, the present task is better described as a single pattern made of connected elements, which allows the scoring errors regarding the disconnection of parts or failures of the spatial aspect of a structural description.

The results of this task confirmed most of the predictions. There were more inversions of parts (see Fig. 5) in the LH patients’ constructions (mean errors = 0.93, S.D. = 1.2) than in those of the RH patients (mean errors = 0.33, S.D. = 0.6) or controls (mean errors = 0.13, S.D. = 0.3), $F(2, 42) = 4.2$, $p < 0.02$. Moreover, reflections of the whole construction were rare (five times in total) but they occurred exclusively in the LH group. However (see Fig. 5), the RH patients made more omission errors (mean omissions = 4.9, S.D. = 3.1) than the LH patients (mean omissions = 1.2, S.D. = 1.4) and the controls (mean omissions = 0.3, S.D. = 0.5). There were more left-sided omissions (6.2) than right-sided omissions (3.6) in the RH patient group but the RH patients’ right-sided omissions were more common than those of the LH group (1.3). The analysis on the distortions of the angular orientation of parts was significant, $F(2, 42) = 130.9$, $p < 0.0001$. As expected (see Fig. 5), the RH patients made more angular distortions (mean degrees = 14.1, S.D. = 2.9) than the LH patients (mean degrees = 5.8, S.D. = 2.1) and the matched controls (mean degrees = 1.9, S.D. = 0.7).

3.3. Perceptual categorical/coordinate task

We obtained descriptive statistics for each participant by calculating means of percent errors and response times for each combination of the factor of spatial transformation (categorical versus coordinate). RTs from trials on which errors occurred were excluded from computation of the RTs. Moreover, trials with RTs longer than three standard deviations from each individual’s mean RT for that condition were excluded from all the statistics (on average 1.5% of data were discarded for each of the control subject and 6% of data for either type of patients). The results were then analyzed with two separate repeated-measures analyses of variance, one with the percent error rate and another on the RTs as dependent variables and both with spatial transformation (categorical versus coordinate) as the within-subjects factors and group (controls, LH and RH) as the between-subjects factor.

The analysis of variance on the error rates revealed a reliable difference between the groups, $F(2/42) = 348.7$, $p < 0.001$. The control subjects committed fewer errors (mean error = 3.9, S.D. = 2.9) than either the LH stroke group (mean error = 24, S.D. = 14) or the RH stroke group (mean error = 28, S.D. = 16). The main effect of spatial transformation was significant, $F(2/84) = 201.4$, $p < 0.001$. Importantly, as expected, there was a significant interaction between the factors of group and spatial transformation, $F(2/84) = 72.7$, $p < 0.0001$. As shown in Fig. 6 (top panel), the LH patients (mean error = 40.1, S.D. = 7.1) showed more difficulty than the RH patients (mean error = 29.8, S.D. = 5.7) and controls (mean error = 4.1, S.D. = 2.7) in match-

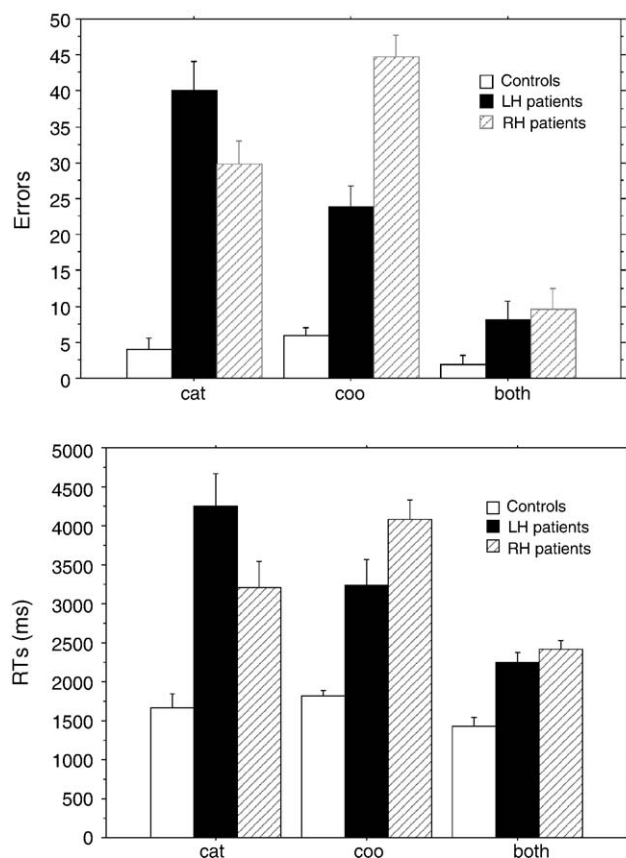


Fig. 6. Perceptual Categorical/Coordinate Test: columns show the performance of the controls, LH patients and RH patients when spatial relations among the items (categorical, coordinate or both) were transformed; bars show 95% confidence intervals. (Top panel) errors and (bottom panel) response times (RTs).

ing correctly categorical spatial transformations. In contrast, RH patients (mean error = 44.7, S.D. = 5.7) showed more difficulty than LH patients (mean error = 23.9, S.D. = 5.2) and controls (mean error = 5.8, S.D. = 2.2) in matching correctly coordinate relations. When both spatial relations were transformed together, error rates decreased significantly in all groups (see Fig. 6).

The analysis on the RTs revealed, once again, a difference between groups, $F(2, 42) = 181.8$, $p < 0.0001$. As the confidence intervals around the means in Fig. 6 (bottom panel) show the controls differed reliably from both the LH group and the RH group and, as predicted, LH patients (mean RTs = 4253 ms, S.D. = 739) were slower than RH patients (mean RTs = 3203 ms, S.D. = 624) and controls (mean RTs = 1662 ms, S.D. = 331) in matching categorical transformations; whereas RH patients (mean RTs = 4081 ms, S.D. = 449) were slower than LH patients (mean RTs = 3230 ms, S.D. = 603) and controls (mean RTs = 1817 ms, S.D. = 136) in matching coordinate transformations. Again, when both spatial relations were transformed together, error rates decreased significantly in all groups (see Fig. 6).

Three separate univariate regression analyses were performed on all participants' errors and RTs in each of the three conditions ("categorical", "coordinate" and "both" spatial transformations); these showed highly significant correlations between the accuracy and efficiency measures (categorical errors and RTs:

$R = 0.58$; coordinate errors and RTs: $R = 0.66$; both transformations' errors and RTs: $R = 0.67$).

3.4. Correlations between the patients' performance in the perceptual tasks and in the constructional tasks

Finally, we performed separate univariate linear regression analyses of the patients' accuracy in matching each type of spatial relations with their accuracy in the constructional tasks. Specifically, categorical and coordinate accuracy scores were regressed with each one of the accuracy scores measured in the Re-location Test (i.e., re-location categorical errors, inversions and distance error) and in the Stick Test (i.e., inversions, reflections, omissions and distortions); thus yielding a total of 14 separate regression analyses. The present account posits that there is a causal relation between the ability to perform a specific type of spatial processing and the ability to use such information in constructional problems. Hence, if the theory is correct, performance in each theorized spatial function (categorical versus coordinate) should predict performance in re-constructing a pattern or array. In other words, we expect to see a positive relation between impairment in the categorical condition of the perceptual tasks and the categorical errors of the two constructional tasks; whereas, either a reduced correlation or no relationship should be observed between the categorical impairment in perception and the coordinate errors in constructional tasks. In contrast, we expect to see the opposite pattern of relations when comparing performance in the coordinate condition of the perceptual task and coordinate distortion in the constructional tasks.

The separate regression analyses yielded results that were consistent with the predictions. First of all, it was found that the number of categorical errors in the perceptual tasks was positively related to the number of categorical position errors in the re-location task, $t(29) = 2.2$, $p < 0.03$, $R = 0.38$. In contrast, the number of coordinate errors in the perceptual tasks was positively related to the distance errors in the re-location task, $t(29) = 3.6$, $p < 0.001$, $R = 0.56$. Similarly, the number of categorical errors in the perceptual tasks was positively related to the number of matchsticks inversions, $t(29) = 3.3$, $p < 0.003$, $R = 0.53$; and the number of coordinate errors in the perceptual tasks was positively related to the angular errors in the matchsticks task, $t(29) = 6.2$, $p < 0.0001$, $R = 0.76$. None of the other regression analyses yielded significant relationships. Importantly, neither the categorical errors in the perceptual task did predict coordinate errors in the constructional tasks nor the coordinate errors in the perceptual task predicted categorical errors in the constructional tasks.

4. Discussion

The value of a new theory must be measured by its ability to provide a systematic framework for organizing findings and making new predictions that in turn lead to additional empirical observations. To the extent that those predictions are novel and counterintuitive, the theory accrues greater value. The present

theory (Kosslyn & Koenig, 1995; Laeng, Chabris et al., 2003) posited an early split within the “dorsal” stream of visual information into two subnetworks that process qualitatively different types of spatial information, each concerned with a single type of computation, and each producing a representation of a different kind of spatial relation. As proposed, the theory appears to have the benefit of being sufficiently general to allow us to make sense of a wide range of findings. The present study is an example of the generality of the theory, given its ability to throw new light on a classic neurological syndrome as well as bring some order into controversial and apparently contradictory earlier findings (cf., De Renzi, 1982).

On the basis of the distinction between categorical and coordinate spatial relations subsystems and their complementary lateralization to the left and right hemispheres, respectively, it was predicted that patients with unilateral brain damage would make constructional errors that reflect the relative loss of one of the types of spatial representations. In the present study, patients with unilateral strokes were requested to re-construct from memory visual arrays of objects (i.e., figures of animals or patterns of matchsticks) that were shown in predetermined spatial relations for a brief period of time. The patients were then asked to reposition the same elements as previously seen in the original display. Their performance was then scored as separate types of spatial errors or as demonstrating categorical versus coordinate distortions. As expected, LH patients made more errors of the categorical type (e.g., reversals of the patterns or its elements and exchanges of position between elements), whereas RH patients made more errors of the coordinate type (i.e., metric distance and angular distortions).

A look at the literature on constructional apraxia would reveal that construction distortions that can be, in hindsight, interpreted as “categorical” had already been described rather clearly; indeed, these were also described as more common after LH than RH damage. The earliest observations of Liepmann (1912) and Kleist (1934) are particularly interesting. Liepmann’s patient was unable to position objects according to prepositional definitions (e.g., one block “beside” another) and showed inversions of items between the above/below or right/left categorical relations. Kleist proposed that constructional apraxia derived from damage to the LH’s angular gyrus. Interestingly, Baciú et al. (1999) reported a fMRI study in which normal subjects performed categorical (above/below) and coordinate tasks (near/far), using the dot-bar stimuli developed by Hellige and Michimata (1989). Throughout the categorical task, the left angular gyrus was more active than the right. These results are also consistent with the characteristics of left-sided lesions that cause Gerstmann’s syndrome (cf., Heilman & Valenstein, 1985), in which right/left confusion is a landmark symptom.

The ability to re-construct a figure inside a figure (e.g., in the Gottschaldt Test or Rey-Osterrieth Complex Figure; see Teuber & Weinstein, 1956) also seems to depend more on the LH than the RH. However, a recent fMRI study in which two fragments were presented and male and female normal subjects had to decide whether they could match to form a perfect square (Georgopoulos et al., 2001) has shown that the cortical mechanisms for processing visual object construction involve mostly

the LH in women, but the RH was mostly involved in men. Thus, it is possible that future studies of patients will reveal that the effects of the laterality of lesions on constructional apraxia may be influenced by the different spatial strategies that are preferentially used by each sex.

Piercy et al. (1960) examined drawings made by patients with either LH or RH lesions and concluded that the types of errors made by the two group of patients appeared qualitatively different: LH patients produced oversimplified drawings (perhaps a sign of the loss of the local elements of the pattern; see also McFie & Zangwill, 1960) whereas RH patients produced more complex drawings but disorganized (perhaps a sign of the loss of the precise coordinates of the elements in a pattern). Several studies have been based on the “post hoc” analysis of patients’ drawings; for example, Gainotti and Tiacci (1972) and Warrington et al. (1966). Curiously, these studies generally failed to achieve converging evidence on types of drawing distortions and describe a similar set of qualitative differences between the LH and RH groups. An fMRI study by Makuuchi, Kaminaga, and Sugishita (2003) showed that both parietal lobes are involved when normal individuals draw; however, this study also showed that there were more individuals with left-greater-than-right parietal lobe activations. However, despite its first glance appeal, drawing might not be the best method to assess spatial distortions of the categorical and coordinate types because not only this task requires an adequate representation of the spatial arrangements of the elements (e.g., angles between the lines, inter-relations of the parts) but also the prior correct reproduction of the elements or parts of the pattern themselves (i.e., the line elements).

Some studies have requested patients to copy models by using landmarks or parts of the model already drawn on the paper (Villa et al., 1986); however, fragments of drawings provide, not just a few elements, but also some of the spatial relations and parts’ connections (which might particularly benefit the LH patients by reducing the number of parts and relations to encode). Thus, studies (like the present one) that allow patients to re-assemble predetermined elements might be relatively free from several confounding factors that a drawing task can involve.

A study by Mack and Levine (1981) required groups of LH and RH patients to assemble elements made of plastic that differed in length and angle size into the form of a square (see also the Kohs Block Design Test; cf., Lezak, 1995; Luria, 1966). Given the weight given in this type of test to the ability to appreciate metric aspects like length and angular differences, it might not be too surprising (in the light of the present study’s account) that all but one of the RH patients performed poorly, whereas 63% of the LH patients scored within normal range (see also Ruessman, Sondag, & Beneicke, 1988). Moreover, the RH patients’ constructional scores (but not those of the LH patients’) were significantly correlated with the scores in two perceptual discrimination tasks of line length and size of angles. More recently, Angelini, Frasca, and Grossi (1992) observed that both left and right brain lesions can produce impairment of visuo-spatial abilities and that the patients’ performances in different constructional tasks (e.g., drawing objects from models, assembly of objects from parts and maze navigation) tend to be closely

correlated. In addition, Kessels et al. (2002) presented to LH and RH patients pictures of everyday objects within a square frame appearing on the computer screen, which was then emptied of objects. The patients were subsequently asked to re-locate each object, by dragging its image from outside of the frame, onto its original position. Patients with RH lesions had difficulties in remembering the positions occupied by the items, whereas the LH patients showed better memory of which locations were occupied by the items but committed errors in re-locating the correct objects onto these locations. Notably, Kessels et al. (2002) pointed out that the different deficits shown by the two patient groups were highly consistent with Kosslyn's (1987) account of cerebral lateralization for spatial information.

In split-brain patients, it is the left hand that typically outperforms the right hand in the WAIS-R Block Design Test (e.g., Gazzaniga, Bogen, & Sperry, 1965; LeDoux et al., 1977). Again, this laterality difference is consistent with a view that re-arranging multiple items that are identical in shape (and share colors) requires a coordinate representation of the matrix of the design or array (cf., Kessels et al., 2002).

Some studies, but not all, have reported the tendency of RH patients in committing rotational errors, a finding that is highly consistent with the present study's findings that RH patients made more errors in the accurate reproduction of angles. Benson and Barton (1970) showed that in a condition of the Stick Test where the pattern has to be reproduced rotated 90°, posterior LH patients made more errors than the posterior RH patients or patients with anterior lesions of either hemisphere. Consistently, in the present study, the angular errors of LH patients consisted mainly of reversals of the canonical positions or vectorial direction of the angles (e.g., a horizontal element positioned at a 90° angle to the left of a vertical one could be repositioned at a right-sided 90° angle).

Luria (1966) observed that patients with left-sided posterior lesions have particular trouble in understanding adverbial clauses as “to the left of” and that these patients showed, more markedly than patients with RH posterior lesions, of mistaking mirror image relationships (in letters, patterns, and clock reading), reversals of east/west in the drawing of maps and confusions between the right and left hands. Riddoch and Humphreys (1988) have described a single case with posterior LH damage with a highly selective spatial deficit in constructional tasks for left/right but not other spatial orientations.

The present study might be the first to show that the degree of impairment in the perceptual encoding of specific subtypes of spatial relations is specifically related to the degree of impairment in the use of the same type of relation in constructional tasks. Indeed, the regression analyses of errors in the perceptual and constructional tasks revealed that the performance in the perceptual tasks accounted for a significant portion of the variance in the constructional tasks (from 15 to 58% of the variance). This finding strongly suggests a perceptual basis of constructional apraxia in both hemispheric groups (cf., Dee, 1970); a point that has been long contested in the literature on constructional apraxia (see De Renzi's review, 1982).

An interesting, and unexpected, finding of the present study appeared in the matching-to-sample perceptual tasks. In one con-

dition the match figure presented spatial transformations of the original array that occurred simultaneously in the categorical and coordinate domain (see Fig. 3). One would expect that error rates and RTs should not have differed in each unilateral lesion group from those showed from the “spared” single spatial transformation. In other words, if the unilateral lesion would result in “blindness” for one form of spatial transformation, then its presence should have no sensible effect on the performance on the other. Instead, for the control group, one would expect that the “both” transformations condition should show an advantage compared to the single transformation conditions. Interestingly, also the patient groups appeared to show a “redundancy gain” effect from the trials with double transformations. Together with the finding that each hemispheric group is also abnormal (albeit to a less degree) in the processing of the spatial relation for which the other group is most impaired, the faster and more accurate performance of both patient groups with parallel transformations of categorical and coordinate relations suggests that the neural subsystems encoding the two spatial relations are only relatively independent. In fact, they would seem to mutually interact and facilitate each other's processing. In other terms, a constraint satisfaction process may underlie spatial information encoding. In Marr's (1982, p. 356) terms, modularity or isolability of functional systems depends on how “small” the amount of interaction is between the two subsystems. Therefore, modularity is a matter of degree; that is, there exists, at least theoretically, a continuum from “strong” to “weak” modularity. The “weak lateralization” of the categorical and coordinate subsystems, as it seems to be indicated by both divided fields studies and neuroimaging studies of normal individuals, would also suggest that the split between the two subsystems is of the weak modular type. Thus, depending on the type of computation, the degree of separation between the processing of the subsystems might entail different amounts of costs and benefits and the optimal split among networks might occur somewhere between the endpoints of the modularity continuum. On one hand, complete lateralization (or fully “split networks”) might offer the benefit of greater computational efficiency than more distributed forms, similarly to the benefits shown by artificial networks like those implemented by Kosslyn et al. (1992) or Kosslyn and Jacobs (1994). On the other hand, it might also be beneficial for the subsystems to share some of the computational work and influence each other to a certain degree; moreover, the costs entailed by completely encapsulated subsystems in the event of damage should be obvious. Thus, the brain might have opted, in the case of spatial representations, for a strategy of partially dividing the processing between the two hemispheres, so as to “divide and conquer” but also “defend” itself from possible attacks and “survive the loss” of parts of the processing system.

In conclusion, the present findings support the view that constructional apraxia cannot be considered a unitary syndrome resulting from a specific type of brain damage (Guérin, Ska, & Belleville, 1999) and they specifically suggest that the nature of this impairment after unilateral lesions can closely reflect the loss of lateralized components for the perceptual processing of differing types of spatial relations.

References

- Angelini, R., Frasca, R., & Grossi, D. (1992). Are patients with constructional disorders different in visuo-spatial abilities? *Acta Neurologica*, 14, 595–604.
- Arena, R., & Gainotti, G. (1977). Constructional apraxia in left brain-damaged patients: Planning disorder. *Cortex*, 13(2), 109–118.
- Arena, R., & Gainotti, G. (1978). Constructional apraxia and visuo-perceptive disabilities in relation to laterality of cerebral lesions. *Cortex*, 14(4), 463–473.
- Arrigoni, G., & De Renzi, E. (1964). Constructional apraxia and hemispheric locus of lesion. *Cortex*, 1, 180–197.
- Baciu, M., Koenig, O., Vernier, M.-P., Bedoin, N., Rubin, C., & Segebarth, C. (1999). Categorical and coordinate spatial relations: fMRI evidence for hemispheric specialization. *Neuroreport*, 10, 1373–1378.
- Benson, D. F., & Barton, M. I. (1970). Disturbances in constructional abilities. *Cortex*, 6, 19–46.
- Benton, A. L. (1967). Constructional apraxia and the minor hemisphere. *Confinia Neurologica*, 29, 1–16.
- Benton, A. L. (1984). Constructional apraxia: An update. *Seminars in Neurology*, 4, 220–222.
- Biederman, I. (1987). Recognition-by-components: A theory of human image understanding. *Psychological Review*, 94, 115–147.
- Black, F. W., & Strub, R. L. (1976). Constructional apraxia in patients with discrete missile wounds of brain. *Cortex*, 12(3), 212–220.
- Bradshaw, J. L., & Nettleton, N. C. (1983). *Human cerebral asymmetry*. Englewood Cliffs, NJ: Prentice Hall.
- Butters, N., & Barton, M. I. (1970). Effect of parietal lobe damage on the performance of reversible operations in space. *Neuropsychologia*, 8, 205–214.
- Carlesimo, G. A., Fadda, L., & Caltagirone, C. (1993). Basic mechanisms of constructional apraxia in unilateral brain-damaged patients: Role of visuo-perceptual and executive disorders. *Journal of Clinical and Experimental Neuropsychology*, 15, 342–358.
- Costa, L., & Vaughn, H. G. (1962). Performance of patients with lateralised cerebral lesions: (1) Verbal and perceptual tests. *Journal of Nervous and Mental Disease*, 134, 162–168.
- Critchley, M. (1953). *The parietal lobes*. London: Arnold.
- Dee, H. L. (1970). Visuoconstructive and visuo-perceptive deficit in patients with unilateral cerebral lesions. *Neuropsychologia*, 8, 305–314.
- Dee, H. L., & Fontenot, D. J. (1969). Use of the non-preferred hand in graphomotor performance. *Confinia Neurologica*, 31, 273–289.
- Delis, D. C., Robertson, L. C., & Efron, R. (1986). Hemispheric specialization of memory for visual hierarchical stimuli. *Neuropsychologia*, 24, 205–214.
- De Renzi, E. (1982). Constructional apraxia. In E. De Renzi (Ed.), *Behavioral neurology and neuropsychology* (pp. 297–307). New York, NY: McGraw-Hill.
- De Renzi, E. (1997). Visuospatial and constructional disorders. In T. E. Feinberg & M. J. Farah (Eds.), *Behavioral neurology and neuropsychology* (pp. 297–307). New York, NY: McGraw-Hill.
- De Renzi, E., & Faglioni, E. (1967). The relationship between visuo-spatial impairment and constructional apraxia. *Cortex*, 3, 327–342.
- Ettlinger, G., Warrington, E., & Zangwill, D. L. (1957). A further study of visual-spatial agnosia. *Brain*, 80, 335–361.
- Gainotti, G., & Tiacci, C. (1972). Sui rapporti fra aprassia costruttiva, agnosia visuo-spaziale e negligenza spaziale unilaterale. *Rivista di Patologia Nervosa e Mentale*, 93, 103–116.
- Gainotti, G., Miceli, G., & Caltagirone, C. (1977). Constructional apraxia in left brain-damaged patients: A planning disorder? *Cortex*, 13, 109–118.
- Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1965). Observations on visual perception after disconnection of the cerebral hemispheres in man. *Brain*, 88, 221–236.
- Georgopoulos, A. P., Whang, K., Georgopoulos, M.-A., Tagaris, G. A., Amirikian, B., Richter, W., et al. (2001). Functional magnetic resonance imaging of visual object construction and shape discrimination: Relations among task, hemispheric lateralization, and gender. *Journal of Cognitive Neuroscience*, 13(1), 72–89.
- Guérin, F., Ska, B., & Belleville, S. (1999). Cognitive processing of drawing abilities. *Brain & Cognition*, 40, 464–478.
- Hécaen, H., Ajuriaguerra, J., & Massonet, J. (1951). Les troubles visuoconstructifs par lésions pariéto-occipitales droites: Rôles des perturbations vestibulaires. *Encéphale*, 1, 122–179.
- Hécaen, H., Penfield, W., Bertrand, C., & Malmö, R. (1956). The syndrome of apractognosia due to lesions of the minor cerebral hemisphere. *Archives of Neurology and Psychiatry*, 75, 400–434.
- Heilman, K.M., & Valenstein, E. (1985). *Clinical neuropsychology*. Oxford: Oxford University Press.
- Hellige, J. B., & Michimata, C. (1989). Categorization versus distance: Hemispheric differences for processing spatial information. *Memory & Cognition*, 17(6), 770–776.
- Jacobs, R. A., & Kosslyn, S. M. (1994). Encoding shape and spatial relations: The role of receptive field size in coordinating complementary representations. *Cognitive Science*, 18(3), 361–386.
- Kessels, R. P. C., Kappelle, L. J., de Haan, E. H. F., & Postma, A. (2002). Lateralization of spatial-memory processes: Evidence on spatial span, maze learning, and memory for object locations. *Neuropsychologia*, 40, 1465–1473.
- Kirk, A., & Kertesz, A. (1993). Subcortical contributions to drawing. *Brain & Cognition*, 21, 57–70.
- Kleist, K. (1934). *Gehirnpathologie*. Leipzig: Barth.
- Kosslyn, S. M. (1987). Seeing and imagining in the cerebral hemispheres: A computational approach. *Psychological Review*, 94, 148–175.
- Kosslyn, S. M. (1994). *Image and brain: The resolution of the imagery debate*. Cambridge, MA: MIT Press.
- Kosslyn, S. M., Chabris, C. F., Marsolek, C. J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulations. *Journal of Experimental Psychology: Human Perception and Performance*, 18(2), 562–577.
- Kosslyn, S. M., & Jacobs, R. A. (1994). Encoding shape and spatial relations: A simple mechanism for coordinating complementary representations. In V. Honavar & L. M. Uhr (Eds.), *Artificial intelligence and neural networks: Steps toward principled integration* (pp. 373–385). Boston: Academic Press.
- Kosslyn, S. M., & Koenig, O. (1995). *Wet mind*. New York: The Free Press.
- Kosslyn, S. M., Thompson, W. T., Gitelman, D. R., & Alpert, N. M. (1998). Neural systems that encode categorical versus coordinate spatial relations: PET investigations. *Psychobiology*, 26(4), 333–347.
- Laeng, B. (1994). Lateralization of categorical and coordinate spatial functions: A study of unilateral stroke patients. *Journal of Cognitive Neuroscience*, 6(3), 189–203.
- Laeng, B., Carlesimo, G. A., Caltagirone, C., Capasso, R., & Miceli, G. (2002). Rigid and non-rigid objects in canonical and non-canonical views: Hemisphere-specific effects on object identification. *Cognitive Neuropsychology*, 19, 697–720.
- Laeng, B., Chabris, C. F., & Kosslyn, S. M. (2003). Asymmetries in encoding spatial relations. In K. Hugdahl & R. Davidson (Eds.), *The asymmetrical brain* (pp. 303–339). Cambridge, MA: The MIT Press.
- Laeng, B., Shah, J., & Kosslyn, S. M. (1999). Identifying objects in conventional and contorted poses: Contributions of hemisphere-specific mechanisms. *Cognition*, 70, 53–85.
- Laeng, B., Zarrinpar, A., & Kosslyn, S. M. (2003). Do separate processes identify objects as exemplars versus members of basic-level categories? Evidence from hemispheric specialization. *Brain & Cognition*, 53, 15–27.
- LeDoux, J. E., Wilson, D. H., & Gazzaniga, M. S. (1977). Manipulospacial aspects of cerebral lateralization: Clues to origin of lateralization. *Neuropsychologia*, 15, 743–750.
- Lezak, M. D. (1995). *Neuropsychological assessment*. New York: Oxford University Press.
- Liepmann, H. (1912). Anatomische Befunde bei Aphasischen und Apraktischen. *Neurologisches Zentralblatt*, 31, 1524–1530.
- Luria, A. R. (1966). *Higher cortical functions in man*. New York: Basic Books.
- Mack, J. L., & Levine, R. N. (1981). The basis of visual constructional disability in patients with unilateral cerebral lesions. *Cortex*, 17, 515–532.

- Makuuchi, M., Kaminaga, T., & Sugishita, M. (2003). Both parietal lobes are involved in drawing: A functional MRI study and implications for constructional apraxia. *Cognitive Brain Research*, 16, 338–347.
- Marr, D. (1982). *Vision*. San Francisco, CA: Freeman.
- McFie, J., Piercy, M. F., & Zangwill, O. L. (1950). Visual spatial agnosia associated with lesions of the right cerebral hemisphere. *Brain*, 73, 167–190.
- McFie, J., & Zangwill, O. L. (1960). Visual-constructive disabilities associated with lesions of the left cerebral hemisphere. *Brain*, 83, 243–260.
- Newcombe, F. (1969). *Missile wounds of the brain*. Oxford: Oxford University Press.
- Piercy, M., Hécaen, H., & De Ajuriaguerra, J. (1960). Constructional apraxia associated with unilateral cerebral lesions: Left and right sided cases compared. *Brain*, 83(2), 225–242.
- Riddoch, M. J., & Humphreys, G. W. (1988). Description of a left/right coding deficit in a case of constructional apraxia. *Cognitive Neuropsychology*, 5, 289–315.
- Roncato, S., Sartori, G., Masterson, J., & Rumati, R. (1987). Constructional apraxia: An information processing analysis. *Cognitive Neuropsychology*, 4, 113–129.
- Ruessman, K., Sondag, H.-D., & Beneicke, U. (1988). On the cerebral localization of constructional apraxia. *International Journal of Neuroscience*, 42, 59–62.
- Schatz, A. M., Ballantyne, A. O., & Trauner, D. A. (2000). A hierarchical analysis of Block Design errors in children with early focal damage. *Developmental Neuropsychology*, 17, 75–83.
- Teuber, H. L., & Weinstein, S. (1956). Ability to discover hidden figures after cerebral lesions. *Archives of Neurology and Psychiatry*, 76, 369–379.
- Van Kleeck, M. H. (1989). Hemispheric differences in global versus local processing of hierarchical visual stimuli by normal subjects: New data and a meta-analysis of previous studies. *Neuropsychologia*, 27(9), 1165–1178.
- Villa, G., Gainotti, G., & De Bonis, C. (1986). Constructive disabilities in focal brain-damaged patients: Influence of hemispheric side, locus of lesion and coexistent mental deterioration. *Neuropsychologia*, 24, 497–510.
- Warrington, E. K., James, M., & Kinsbourne, M. (1966). Drawing disability in relation to laterality of lesion. *Brain*, 89, 53–82.
- Zacharias, S., & Kirk, A. (1998). Drawing with the non-dominant hand: Implications for the study of construction. *Canadian Journal of Neurological Science*, 25, 306–309.