

Editorial

New insights in categorical and coordinate processing of spatial relations

Processing of the visual world around us critically depends upon the analysis of spatial relations between objects in scenes and of the subcomponents within complex multi-part objects. For example, in order to pick up our cup of coffee, we need to be able to observe the fine-grained distance relations between our hand and fingers and the cup's position and handle's orientation. This fine-grained, metric information is what we call a coordinate spatial relation. In turn, in order to recognize the cup from an unusual perspective (e.g., viewed straight down from above) it is important to observe more abstract, invariant relations which keep constant across a great variety of situations (or in this case across multiple viewpoints): the handle is attached laterally to the cup's body. This abstract spatial relation is what we call 'categorical'. In positional terms, it offers a global code capturing the invariants in an object's structure. That is, the label 'laterally attached to' applies to a range of positions. Visual analyses crucially require processing of both categorical and coordinate spatial relations. This allows spatial inference, spatially directed motor activities and object recognition. Moreover, categorical spatial relations, by partitioning space in discrete categories and often in a binomial manner (left versus right; outside versus inside), may form the basis of many linguistic concepts and modifiers (e.g., spatial prepositions such as 'above', 'below', etc.).

Kosslyn (1987) argued that our ability to process categorical and coordinate spatial relations is the end result of a long evolutionary history, which at a neuroanatomical level has predisposed the left hemisphere for processing categorical spatial relations and the right hemisphere for coordinate relations. Evidence for this differential hemispheric lateralization in humans is provided by experimental, neuroimaging and patient lesion studies (Jager & Postma, 2003), though a number of negative findings also exist, which at least call for a qualitative refinement of the hypothesis.

The goal of this special issue is to provide exactly this qualitative refinement by tackling a number of new issues and providing new empirical findings, which will hopefully deepen our insights in categorical and coordinate processing of spatial relations. We focus on the following specific targets.

1. How did the hemispheric specializations for different spatial relation processing develop in the brain of humans and perhaps of other animals?

Kosslyn (1987) originally proposed a snowball mechanism, according to which, evolutionary pressures may favour unilateral control of some functions (action in particular), which in turn can influence the development in neighboring areas (or within the same hemisphere) of other functions, if these are closely-linked functionally to the original "seed", even in cases where they may gain no direct benefit per se from being lateralized. Specifically, one primary developmental "seed" may be that the left hemisphere in right-handed individuals is dominant for speech output control and consequently for language processing. Because of the importance of category-formation in many aspects of language, the left hemisphere may become specialized in categorical processing in general, including visuospatial categorization. Moreover, the right hemisphere may contain another primary developmental "seed" which makes it tuned for visual search and navigation mechanisms (perhaps again as the result of evolutionary pressures in favor of unilateral control of the shifts and adjustments of a single and narrow focus of attention and of the body's navigation in the physical environment). This could create the basis for a subsequent right hemisphere's specialization for coordinate spatial relations. In other words, even small initial differences between the hemispheres could ultimately end up in a larger set of asymmetries in those groups of functions that share certain properties. Alternatively, one might hypothesize that there was a continuous and early evolution of spatial relation processing within the two hemispheres. The foundation of categorical spatial relation processing and abstraction in the left hemisphere might have been an important precursor for the evolution of language. In fact, both Kosslyn and Jacobs (1994) and Ivry and Robertson (1998) have later proposed that at the basis of the hemispheric differences representation of categorical and coordinate processing may be differential low-level perceptual biases, which make it more likely for each hemisphere to attend to different spatial frequency channels (e.g., low versus high) or to the output of populations of neural cells with different receptive field sizes.

Two papers in the current special issue touch upon the issue of the evolutionary basis of spatial perception. Vauclair et al. (this issue) present an overview of the existing literature on spatial relation processing in birds and nonhuman primates. They appear to conclude that most of the available empirical evidence points to a pattern of lateralization for spatial functions in birds (e.g., pigeons) and primates (e.g., baboons) which only weakly resembles the observations made with humans. They interpret the existing findings as indications that the relational/absolute spatial distinction may need to be rephrased in terms of a global/local distinction. Admittedly, comparative empirical studies are only sparse and often the original studies were not intended as a test of the categorical–coordinate lateralization hypothesis, although the researchers found it useful to interpret their results. Hence, more empirical and directed work is needed to better understand the evolutionary history of spatial relation processing. Jellema and Perrett (this issue) provide a good example of this type of empirical evidence. They demonstrate the existence of relational categorical cells in the anterior part of the STS, supporting the recognition of body postures. Importantly, this might form an essential impetus for the evolution of social cognition at large.

It may be noted here that the phylogenetic evolution discussed in the papers of Vauclair et al. and Jellema and Perrett (this issue) might also resemble the pattern of ontogenetic (cf. Koenig, Reiss, & Kosslyn, 1990) and anthropological changes observed. Regarding the latter, Kemmerer (this issue) offers an intriguing review of both the neurocognitive basis of spatial language terms and its differentiation across language families.

2. Differences within and between objects

While intuitively the notion of spatial relation processing appears to apply to between objects relations within the whole

field of vision, we also note that parts of complex objects and limbs of biological organisms can be specified by their positional codes within the object's configuration. This issue includes several papers focusing on within-object spatial relation processing (cf. Hugdahl et al.; Jellema & Perrett; Trojano et al.; Laeng, this issue). These studies suggest there may not be an essential processing difference when describing between- or within-object relations. However, the former seem to involve more the dorsal hemispheric circuit whereas the latter could rely mostly on the ventral circuitry (cf. Carey et al., this issue). Moreover, we may speculate here that the use of categorical spatial abstractions is most prominent in the within-object case. One could speculate that, evolutionarily, this might have been the motor for its development within the perceptual system. In contrast, in linguistic communication it may be more common or relevant to specify the relations between different-objects in the physical world. The paper by Kemmerer (this issue) illustrates this function of the spatial language system. If so, it can be conjectured that the human cognition system for between-object relations may have been modified in an important way by the evolution of the accompanying language system.

3. Spatial relation processing across cognitive domains

While most of the research thus far has focused on perception of spatial relations, it should be mentioned that spatial relation processing extends into multiple domains beside perception; that is, imagery, working memory, long-term memory, action and verbal communication. It is likely that the precise characteristics of the relevant categorical and coordinate mechanisms could vary both in function and neuroanatomy with respect to the cognitive domain under scrutiny.

Table 1 presents a limited overview based on the papers included in this issue. We can see that, although the majority

Table 1
Papers in the special issue arranged by cognitive domain, neuroanatomical findings and methods

	Paper	Categorical processes and neuroanatomical circuits	Coordinate processes and neuroanatomical circuits	Methodology
(Object) perception	Jellema and Perrett	STS $\Rightarrow$ abstract object structure of flexible, animate objects		Single-cell recordings in nonhuman primates
Working memory	van der Lubbe et al.	Stronger posterior and RH activation when coding and comparing the second stimulus of a sequential comparison task	Stronger early and late posterior activation when coding the first stimulus of a sequential comparison task	ERP
Memory retrieval	Slotnick and Moo	Left prefrontal cortex (BA10) $\Rightarrow$ retrieval of categorical visual memories	Right prefrontal cortex (BA9/10) $\Rightarrow$ retrieval of coordinate visual memories	fMRI
Imagery	Trojano et al.	Left PPC $\Rightarrow$ categorical decisions on top-down generated mental images	Right PPC $\Rightarrow$ coordinate decisions on top-down generated mental images	TMS
Mental rotation	Hugdahl et al.	Bilateral inferior frontal gyrus (BA 44/45) $\Rightarrow$ presumed categorical mental rotation strategy	Right SPL (BA 7) $\Rightarrow$ presumed coordinate mental rotation strategy	fMRI
Spatially directed motor activity	Carey et al.	Preserved categorical information processing in the ventral stream in spatiomotor action tasks	Preserved dorsal stream coordinate information processing in immediate spatiomotor tasks	Brain-damaged patients
Spatial construction	Laeng	LH dorsal stream damage leads to categorical constructive errors	RH dorsal stream damage leads to coordinate constructive errors	Brain-damaged patients
Language	Kemmerer	Left supramarginal and angular gyri $\Rightarrow$ spatial language terms		Review

of these studies confirm the expected pattern of lateralization, a rather extended neural circuitry, spanning frontal and posterior (viz. parietal and ventral) hemispheric areas, may underlie the processing of categorical and coordinate spatial information. Arguably, inter- as well as intra-hemispheric differences between the various studies could derive from the specific cognitive domains being investigated. As pointed out by van der Lubbe et al. (this issue), it could be rather important to further delineate the series of cognitive operations engaged by a particular task and establish where exactly differences in categorical and coordinate processing emerge (e.g., encoding, maintenance in working memory, retrieval and decisions making). Kosslyn (this issue, 1994) also paints in more detail the various subsystems involved in visual analysis of the surrounding world, and the role of categorical–coordinate spatial properties within these systems.

While in early studies the relevance of the posterior cerebral cortex in categorical–coordinate spatial tasks had been stressed, in more recent studies we have seen that also the frontal areas play an important role, in particular in the retrieval of information from (episodic) memory (Slotnick & Moo, this issue) and when manipulating mental images (Hugdahl et al., this issue). In contrast to the latter finding, the process of generation of images would seem to be mostly a parietal function (Trojano et al., this issue).

4. Convergent neuroimaging techniques

The years following Kosslyn's original formulation of the categorical–coordinate hypothesis, the most used technique to test the presumed neural differentiation was the visual half field technique. While offering some support, visual half field studies have not always been successful, likely because they suffer inherent methodological limitations (cf. Jager & Postma, 2003); however, a metaanalysis of all of the visual half field studies available at the time (Laeng, Chabris, & Kosslyn, 2003) has confirmed the complementary dissociations between the two hemispheres proposed by the original hypothesis. As Kosslyn points out in his sharp analysis of the theoretical, heuristic potential of the categorical–coordinate distinction, the success of this particular “theory” (if not any neurocognitive theory) might increase even more, if a multitude of modern neurocognitive techniques is used. Indeed, the present special issue has made an effort to offer evidence that was gathered with a large variety of convergent observational techniques. Jellema and Perrett address the distinction by examining nonhuman primates with the use of single cell recording techniques, which provides a neurophysiological precision not obtainable by the available human neuroimaging techniques. The work by Hugdahl et al. (this issue) and Slotnick and Moo (this issue) underscores the importance of fMRI (or neuroimaging methods in general) for establishing the hemispheric locus of spatial relation processing, while van der Lubbe et al. (this issue) illustrates the strength of the ERP methodology in determining the temporal organization of spatial relation processing in the human brain. Carey et al. (this issue) and Laeng (this issue) employ the lesion method in human cases of patients

who suffered some injury to the brain, offering the possibility to go beyond simple correlational observations to more specific causal roles of particular brain areas for the task at hand. Interestingly, they also illustrate how classical interpretation of patients' syndromes might profit from a new theoretical framing which is computationally informed. Trojano et al. also present a variant of the “lesion technique” by applying with TMS reversible lesions in the target areas of normal human participants.

The categorical–coordinate distinction has not been without critics (most prominently, Sergent, 1991a, 1991b, and Ivry & Robertson, 1998; cf. Jager & Postma, 2003). Their criticisms have contributed to sharpen and refine the hypothesis and, in particular, to clarify important underlying low-level perceptual mechanisms that may be a necessary processing step for the brain in order to form higher-level representations of objects and of their relations in space. From an epistemological perspective, one could be very sceptical that a simple binary or dichotomous characterization of brain function has really the power to explain so much. Kosslyn (this issue), who proposed the dichotomy within a computational model of perception and imagery (Kosslyn, 1987) and thus initiated its study, convincingly argues that when one places a binary distinction in a larger information processing context, encompassing all levels of analysis, and relating it directly to the brain, one can indeed gain quite a lot from binary distinctions. We hope this special issue exactly offers the enriched neurocognitive context and ultimately will spur researchers to continue research on computationally inspired theory of how the brain processes where objects and their parts are, and how they relate to one another.

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