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Review

Lateralized perception: The role of attention in spatial relation processing

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ABSTRACT

Any spatial situation can be approached either categorically – the window is to my left – or coordinately – the glass is 20 cm away from the bottle. Since the first description of the distinction between categorical and coordinate spatial relation processing, it has often been shown that they are processed by at least partially different underlying mechanisms, mainly located in the left and right hemisphere, respectively. A number of recent studies have suggested that spatial attention plays a particularly important part in the perception of space: categorical processing benefits from a local focus of attention, and coordinate processing profits from a global focus of attention. This suggests that the lateralization pattern is modified by the concurrent size of the attentional focus, and is consequently more dynamic than previously thought. Therefore, a thorough revision of earlier theories on spatial relation processing is in order. In this review, we present a new model on lateralization of spatial relation processing that explicitly describes the role of spatial attention.

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1. Introduction

When we interact with our environment, its spatial features are crucial to us. There are different ways to deal with these spatial features. If someone asks us where we left the car keys, we can respond with something like: 'I left them on the coffee table in the living room'. On the other hand, when we want to pick up those keys, it does not help much to know they are on the table; we need

to know their exact location with respect to our hand in order to plan and execute our movement. These two examples illustrate the two main types of spatial relation processing. The first example shows that we can process spatial relations between objects in an abstract, propositional way, which is termed *categorical*. We can use this type of spatial relation to give directions or memorize where we left things. In contrast, in the second example we use the precise, metric properties of spatial relations, or *coordinate* spatial relations, when we navigate or grasp objects.

The characteristics of these spatial relations are in part dictated by the type of 'coordinate system' that is used to represent spatial characteristics. Such coordinate systems can be either ego-centric (observer based) or allocentric (environment based) (see

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e.g. Klatzky, 1998; Majid et al., 2004). In an egocentric coordinate system, these spatial relations by definition concern the relation between an external object and the observer, such as ‘the car is to my left’ or ‘I am closer to the library than you are’. Neurophysiological studies on primates indicate that visual space is constructed many times over, according to a variety of frames of reference, each attached to different parts of the body and possibly subserving different functions (Graziano and Gross, 1995). Neuroimaging in humans confirms that one of the topographic maps of the parietal lobes is based on a head-centered coordinate frame (Serenio and Huang, 2006). A plurality of sensorimotor action spaces can be related to specific effectors that have the ability to move independently from the rest of the body (e.g. hand, head, and eye). In such motor-oriented frames of reference, spatial relationships between two locations can be coded in terms of the movements required to act or move from one to the other (Paillard, 1991).

In an allocentric coordinate system the relation concerns two objects or parts of objects that are defined according to a reference frame whose fulcrum is located outside of the observer’s body. Examples of spatial relations from an allocentric perspective are: ‘the church is to the North of the square’ and ‘you are 200 meters West from the library’. Crucially, both categorical and coordinate spatial relations can be applied within these different frame of reference and coordinate systems (see also Ruotolo et al., 2011a,b; Ruggiero et al., 2012). In this review we focus on the direct comparison of categorical and coordinate spatial relations, regardless of the coordinate system used. All that is discussed here can equally apply to spatial relation processing in an egocentric as well as an allocentric or object-based perspective.

The distinction between categorical and coordinate spatial relations is not only reflected by clear differences in functionality, but also refers to different underlying processing mechanisms. Although described earlier by McNamara (1986), Kosslyn (1987) provides the first elaborate theoretical framework to understand the differences between categorical and coordinate processing. He introduced the idea that the two types of spatial relations are processed by two different subsystems in the human brain, which have lateralized due to evolutionary processes. Categorical spatial relation processing is thought to be lateralized to the left, whereas coordinate spatial relation processing is argued to be right lateralized.

Over the years, many experimental studies have been performed concerning this distinction, which have enabled a fine-tuning of the original theory (see for review, e.g. Jager and Postma, 2003; Laeng et al., 2003; Laeng, 2014). Recent empirical studies have brought new evidence to the table and point toward a substantial role of spatial attention in explaining differences between categorical and coordinate processing. This offers a novel theoretical perspective. Therefore, an up-to-date review of current evidence and the impact of these findings on the theoretical framework underlying categorical and coordinate spatial relation processing is called for. In this review, we first provide an overview of the main experimental work on spatial relation processing, particularly recent work. Then we discuss what this tells us about the nature of spatial relation processing, and focus on the role of spatial attention in particular. We present a new framework to fit the experimental findings on how spatial attention affects spatial relation processing and its lateralization. Lastly, we will explore how spatial relation theory translates to human visual perception in general.

2. Empirical evidence

Soon after Kosslyn’s first publication on the topic of spatial relation processing (Kosslyn, 1987) numerous behavioral studies attempted to empirically prove the distinction (e.g. Hellige and

Michimata, 1989; Kosslyn et al., 1989; Koenig et al., 1990; Bruyer et al., 1997; Wilkinson and Donnelly, 1999; Banich and Federmeier, 1999). These studies were mainly aimed at verifying the double dissociation of type of spatial relation and hemisphere. Typically, very simple stimuli were used in these studies. The dot-bar stimuli have been used in most of these early studies. These stimuli consist of a horizontal bar with a dot presented either above or below the bar, at varying distances, as illustrated in Fig. 1. The categorical instruction in this case, was to indicate whether the dot is ‘above’ or ‘below’ the bar, regardless of distance. The coordinate instruction in turn, was to focus on the distance and indicate whether the dot is ‘within’ or ‘not within’ a predetermined distance, regardless of side. An important feature of this design was that the stimulus layout was identical and only the instruction varied between the two versions of the task.

In these behavioral studies, a visual half field design was used to assess lateralization patterns by means of response times and accuracy for stimuli presented to the left or right visual field. This approach was soon followed by studies in which lateralization was determined with more direct and precise measures of brain activity: positron emission tomography (PET), functional magnetic resonance imaging (fMRI and MEG), electroencephalography (EEG), and transcranial magnetic stimulation (TMS). In the vast majority of these studies, the lateralization pattern was further substantiated (e.g. Baciú et al., 1999; Kosslyn et al., 1998; Trojano et al., 2002, 2006; van der Ham et al., 2009; Franciotti et al., 2013). Several studies on patients with unilateral brain damage also supported these findings (e.g. Laeng, 1994; Palermo et al., 2008; van der Ham et al., 2011, 2012a,b,c). Overall, the parietal cortex seemed of particular importance; left parietal cortex was mainly linked to categorical processing, whereas the right parietal cortex was involved mostly with coordinate processing. Yet, the original theory as proposed by Kosslyn needed some attenuation. Most of the foregoing findings indicate that the lateralization pattern is not mutually exclusive: both hemispheres are involved in processing each type of spatial relations, but they show a clear bias toward one of the two types.

Aside from the many techniques that have been used to study this dichotomy, various task designs have been applied as well, facilitating different research questions. The first number of studies was designed to study spatial relation processing in perception: a response was required to a briefly presented, simple stimulus. Results from these studies illustrate how we process the spatial features of visual stimuli. Later experiments also focused on spatial relation processing in working memory task designs, in which two sequentially presented stimuli were compared (e.g. Laeng, 1994; van der Ham et al., 2007), and in a mental imagery paradigm (Michimata, 1997; Palermo et al., 2008) where clock faces had to be imagined. These studies have shown that the typical lateralization pattern reflecting separate processing mechanisms can also be generalized to visual working memory and mental imagery.

Although the double dissociation of relation type and hemisphere is found in the convincing majority of these studies, the effects have shown to be sensitive to the methodology used. For instance, Baciú et al. (1999) showed that over time, participants started to categorize the coordinate task, as reflected by a shift from a right hemisphere to a left hemisphere dominance during the experiment. This has been explained with a critical and disadvantageous feature of the dot-bar stimulus layout. The dot could only appear at a fixed number of positions and the instruction entailed a categorization of distances into ‘within’ a particular distance and ‘not within’ a particular distance. Therefore, participants could well start to realize this limitation and categorize the distances instead of encoding them as exact distances. The cross-dot working memory paradigm (see Fig. 2) in which two distances were compared later solved this problem as participants continued to encode the

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