Summary and conclusions

This thesis addresses three major themes within the field of spatial relation processing. The first of these themes concerned the temporal characteristics of spatial relation processing. Reports so far have been consistent in reporting a left hemisphere advantage for categorical processing and a right hemisphere advantage for coordinate processing. Yet, these advantages can be quite subtle and have shown to depend on the experimental design used to test them. Therefore, a new experimental paradigm was introduced in the first part of this thesis to carefully address this issue. With this paradigm we aimed to further explore the temporal characteristics of spatial relation processing in working memory. The second part of the thesis followed up on this by examining the topic of representational format and accompanying strategies in more detail. These findings have helped in understanding the nature and detailed definition of categorical and coordinate spatial relations. Lastly, findings about processing spatial relations of very basic and controlled stimuli have been put to the test in more lifelike and realistic stimuli in scene perception, object location memory, and spatial navigation. Each of these three parts will be discussed in more detail below. Furthermore, some suggestions provided for related fields of research that seem promising in light of the current status of spatial relation research.

Time

In part I, spatial relation processing was measured with a working memory task design; the *cross dot task*. This task entails the sequential presentation of two cross dot stimuli, with a variable retention interval. These stimuli consist of a "+" shaped cross, with a dot appearing around it. The quadrants of the cross represent the categories of the stimulus, whereas the dot could appear at four different distances, reflecting the coordinate property of the stimulus. This task has been implemented in five different experiments, using behavioural, fMRI, EEG, and neuropsychological measures.

Importantly, the cross dot task has shown that the categorical left and coordinate right hemisphere advantages are present in working memory as well. Yet, this pattern is evidently restricted by the exact temporal features of the task design; it appears to be present when the retention interval between the first and second stimulus was either 500 ms (*Chapter 1.1*, with the relatively simplest stimuli) or 2000 ms (*Chapters 1.2* and *1.3*, with more complex stimuli), but is no longer present with longer delays. The fMRI data in *Chapter 1.2* demonstrate that the superior parietal cortex in particular reflects this lateralization pattern. The outcome of the EEG study (*Chapter 1.3*) indicates that this difference can be particularly observed during the encoding of the first stimulus in the working memory task design.

Throughout this thesis various versions of the stimuli in the cross dot task have been used. In *Chapter 1.4* two versions were directly compared to empirically describe the properties of these stimuli. One important issue with testing categorical and coordinate relations has been that there is a persistent difference in difficulty between the two. In an attempt to reduce the difference in difficulty between the two, the size of the cross was either small (similar in size to a single dot) or large (extending as far as the largest distance between a dot and the centre of the cross). The outcome of *Chapter 1.4* shows that the small cross reduces this difference by relatively decreasing coordinate difficulty and increasing categorical difficulty. The patient data included in this chapter were inconclusive with regard to general lateralization, but they did indicate that the left hemisphere may specifically be involved in the construction of categories, i.e. interpreting the implications of a small cross on the categorical position of a dot.

The cross dot design has overcome some experimental problems that have been described in the past. In previous perceptual tasks that concern the responses to single stimuli, instead of a comparison of two stimuli, one particular shortcoming is that of categorization of coordinate responses, leading to a shift in lateralization from a left to a right hemisphere advantage (e.g. Baciu, Koenig, Vernier, Bedoin, Rubin & Segebarth, 1999). Such coordinate responses were dichotomous in nature, as the instruction was to decide whether something was “within” or “not within” a predefined distance, and the number of possible dot positions were generally easy to deduct. For the cross dot studies such categorization is much more difficult; participants were generally unable to identify the correct structure of the possible dot positions and the instruction concerned a continuous comparison; “same” or “different” distance. Furthermore, none of the studies offered any indication of lateralization changes with more practice, shown by data checks comparing responses to the first and last sets of trials in separate studies.

Given that differences between categorical and coordinate processing change over time, the question arises where exactly in the brain these changes take place. *Chapter 1.5* shows differences in processing categorical and coordinate information, very early in the visual cortex. It appears as though participants mainly focused on the matching region of categorical trials, whereas for coordinate trials, no difference between matching and mismatching regions was found. It was concluded that at a very basic level there are substantial differences in how categorical and coordinate information is coded and attended to.

When evaluating the use of the cross dot task, not only in part I, but also in *chapter 2.1* and *2.3*, it is clear that this design provides solid and replicable measure of categorical and coordinate processing. It is evident that spatial relation processing has some distinct temporal features; coordinate relation information decays faster than categorical information, the double dissociation of lateralization is found for intervals 500-2000 ms long, and lateralization is found most convincingly for the encoding of the first stimulus, illustrating early differences between categorical and coordinate processing. The use of different versions of the cross dot stimuli can lead to differences in difficulty and the retention interval can affect the lateralization dissociation. In conclusion, the cross dot task provides an appropriate measure to investigate spatial relation processing in working memory in more detail.

Format and strategy

Part II focused on the effect of representational format and strategy on the direction and strength of the lateralization pattern found for both categorical and coordinate spatial processing. When taking together previous studies it is evident that the right hemisphere advantage for coordinate spatial relations is strong and found often. In contrast, the left hemisphere advantage for categorical processing appears to be weaker and sometimes even absent. Explanations for this difference in strength have included the verbal versus visuospatial nature of the task.

In *Chapter 2.1* the cross dot design was adapted to allow for a comparison of a relatively more verbal and more visuospatial processing of categorical information. The original version of the cross dot task typically concerned a visuospatial version of spatial relation information. The verbal alternative was achieved by replacing the picture of the second stimulus by a word describing the category. The combined result of two experiments showed that the strength of lateralization was affected by the format of the stimuli (verbal, visuospatial), but that the suggested differences in direction of lateralization (left or right) can not be supported. Instead of a partition between verbal and visuospatial processing (Kemmerer & Tranel, 2000) it appears to be more appropriate to state that the lateralization patterns match the partition between categorical and coordinate processing as originally proposed by Kosslyn (1987). The conclusions of *Chapter 2.2* further substantiate this inference, by showing that a visuospatial secondary task (spatial tapping) interferes with both categorical and coordinate processing, whereas verbal interference (articulatory suppression) does not affect either type of processing. Furthermore, the individual differences study (*Chapter 2.3*) showed that the difference in lateralization strength of categorical processing can only be explained by spatial strategy use, not by verbal strategy use, verbal ability, or spatial ability. When a clear spatial strategy as indicated by self reports is used, the left hemisphere advantage for categorical processing is significant, whereas it is not present for low spatial strategy use.

It might seem somewhat of a paradox that the categorical left hemisphere advantage is facilitated by a spatial strategy, whereas the more verbal the categorical stimuli are, the stronger the left hemisphere advantage is (*Chapter 2.1*). Yet, these findings concern distinctly different types of processing; the first concerns the self reported, spontaneously occurring use of strategy, the second the manipulation of the format of the stimuli used and forcing of specific strategy by changing stimulus expectancy. It is likely that the effect caused by using more verbal stimuli is more reflective of verbal processing in general, and can be viewed as independent from lateralization effects linked to the type of spatial relation processed.

Context

In the third part the main aim was to focus on spatial relation processing in more natural situations. The vast amount of studies within the field of spatial relation processing have so far been restricted to very controlled, abstract experimental conditions. Given the widespread use of spatial relations in our everyday environment, it is of importance to see in how far the outcomes of these studies actually reflect spatial perception and memory in more lifelike settings. Such elaborate and complex virtual renderings present some difficulties in reflecting performance in a completely controlled manner, but as it complements the existing empirical evidence, such experiments in virtual reality can significantly add to the research field.

Chapters 3.1 and *3.2* show that both categorical as well as coordinate relation information is used to encode object locations in natural scenes in working memory and perception, respectively. Perhaps even more importantly, the typical lateralization pattern of a left hemisphere advantage for categorical processing and a right hemisphere advantage for coordinate processing has clearly been found in object location memory, and patient data (*Chapter 3.2*) suggest a similar pattern might be present in scene perception as well. Clearly, the effects found for simple stimuli are in congruence with measures of perception and working memory of lifelike scenes. First of all, both categorical and coordinate information is of importance in these processes and secondly, very similar lateralization patterns have been found.

The last *Chapter 3.3* describes the use of spatial information in navigation. Two cases with self reported impairments in navigation showed a double dissociation in impaired performance on spatial and temporal tasks. Both patients had right hemisphere lesions that were related to their navigational problems. This chapter provides a more practical outlook on how spatial information is used in a dynamic interaction with a natural environment. It confirms that navigation is a complex behaviour, and entails many different components that can be more spatial (e.g. scene memory, linking route direction to turns), or more temporal (e.g. memory of temporal order of scenes).

Related fields of research

In relation to the last part of this thesis, an interesting take on spatial relation studies would be to transfer findings in very basic settings to other fields of (spatial) cognition. Some studies have already linked spatial relation processing to features of object recognition (e.g. Laeng, Shah, & Kosslyn, 1999; Rosielle & Cooper, 2001; Laeng 2006; Lag, Hveem, Ruud, & Laeng, 2006), but also face recognition has been examined in a similar way on a few occasions (e.g. McKone, Aitkin, & Edwards, 2005). It could well be that face and object recognition show a double dissociation in hemispheric biases that could be linked directly to the type of spatial relation preferentially used to process them (Cooper & Wojan, 2001).

Another topic that can be easily related to spatial relation processing is that of the viewpoint used in the situation at hand. In particular, the distinction between egocentric and allocentric reference frames seems relevant. Egocentric reference frames are observer based and therefore linked to the viewpoint of the observer itself, whereas allocentric reference frames are environment based and independent of the observer's viewpoint. In two studies we have looked into the relation between spatial relations and reference frames (Ruotolo, Van der Ham, Iachini & Postma, in revision; Ruotolo, Postma, Iachini & Van der Ham, in preparation). These studies point towards an interaction between categorical and coordinate spatial relation processing and allocentric and egocentric reference frames, respectively.

This thesis (in particular part II) offers new information about the nature of spatial relation processing in terms of representation format and strategy, and how these interact with lateralization. The question remains however, what has caused the hemispheres to specialize in processing spatial relations in this particular way. Kosslyn (1987) stated that the left and right hemispheres' pre-existing qualities in language and navigation have led to them to develop differently resulting in an advantage is processing categorical and coordinate information, respectively. The other answer is provided by Ivry & Robertson (1998) who have proposed the "double filtering by frequency model". In this model it is suggested that all lateralization effects found in human perception are essentially based on the frequency properties of stimuli; high spatial frequencies are processed better by the left hemisphere and low spatial frequencies better by the right hemisphere. This model is based on suggested receptive field sizes differences between the hemispheres, which makes them differentially suitable to process certain types of information. This could then also explain lateralization in perceiving local and global information (e.g. Martin, 1979; Boles, 1989; Sergent, 1982; Van Kleeck, 1989), and processing categorical and coordinate spatial relations. The main objection to this idea of receptive field sizes and frequencies is that there is no physiological evidence or motivation for the differences in field sizes between the two hemispheres. At this moment, clarity is lacking to which of these two models is most realistic. As no empirical evidence supporting or rejecting the Ivry & Robertson model has been reported as of yet, it would be very informative for this debate to conduct a study addressing their proposition. If indeed all lateralization patterns in perception can be related to frequencies in the stimuli, then there should be a considerable correlation between lateralization scores on various tasks concerning local and global, and spatial relation processing.

Concluding remarks

The studies in this thesis have contributed to the field of spatial relation processing by going into its temporal characteristics, the effects of strategy, and the generalization of the results to lifelike perception and memory. As described in the general introduction there are two current alternative views on spatial relation processing. Some of the studies in this thesis specifically looked into the viability of these alternatives of task difficulty (e.g. Martin et al., 2008) and task characteristics (Kemmerer & Tranel, 2000). However, very little if any support is found for these alternative views, whereas it seems most likely that there are relative advantages of the left hemisphere for categorical processing and the right hemisphere for coordinate processing. In Kosslyn's (1987) original proposal, this lateralization pattern was proposed to be quite strong and robust, but it seems more appropriate to speak of "relative advantages" and to keep in mind the effects of temporal and stimulus related circumstances as presented in this thesis.

The reports on the cross-dot task are of importance, as they illustrate this task not only provides a suitable measure of spatial relation processing, but can also be manipulated in a number of ways to examine these processes into greater detail. Furthermore, the relative hemispheric advantages in spatial relation processing as confirmed by the cross dot task have also been found when using tasks that are more life-like. It is evident that both categorical and coordinate spatial relation information is used to perceive and memorize object locations in complex virtual environments. Evidence is presented that the lateralization pattern described above is also present in these environments. This might also be of value in other research topics, such as object and face recognition, where such differences between categorical and coordinate spatial information could play important though distinct roles.