

CHAPTER 3:

THE QUESTION OF EARLY-ONSET BLINDNESS

Introduction

Over the last 20 years, converging evidence have suggested that numerical and spatial representations are strongly linked (see, for reviews, Fias & Fischer, 2005; Hubbard et al., 2005). Indeed, as shown in the first chapter of the present thesis, many behavioural data have revealed the existence of a close connection between numbers and space by the recurrent observation of the SNARC effect, leading to the postulate that the numerical magnitudes are spatially organised along a mental continuum oriented from left to right. Additionally, many neuropsychological and neuro-imaging data, reviewed in the first section of the current third chapter, give further support to the assumption of the existence of spatial-numerical associations.

In neuroscience, the environmental input, and more particularly the visual modality, has been considered to be crucial in the emergence of human numerical representations and abilities (e.g., Simon, 1997, 1999), but also in the emergence of spatial representations and abilities (Fraiberg, 1977; Hartlage, 1969; Von Senden, 1960). As it will be presented in the second section of this chapter, the role of vision has been addressed in the development of spatial processing (see Collignon et al., 2006; Thinus-Blanc & Gaunet, 1997), by the study of the impact of early visual deprivation on spatial behaviour. But what about the role of vision in numerical cognition?

One way to investigate this question is, like in spatial cognition, to study how people who have lacked vision since birth or early childhood represent and process numbers. Indeed, by examining how congenitally or early blind people represent and process numbers, the question of the necessary role of vision in the development of numerical representations and abilities will be indirectly answered. Therefore, in the third section of this chapter, two exploratory opposite hypotheses that can be drawn on the impact of early visual deprivation on the elaboration of numerical representations and abilities, based on theoretical postulates and observations made in the literature, will be presented. Finally, the unique recent study conducted on this issue so far will be described.

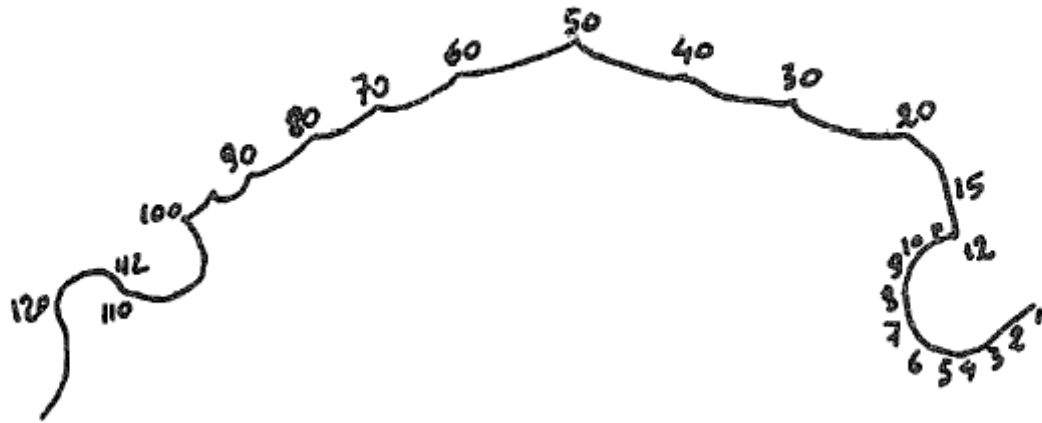
1. Interactions between space and number

A large part of the literature has demonstrated that spatial and numerical processing are deeply and intimately connected. Firstly, the repeated observation of the SNARC effect in many behavioural studies, as shown in the first chapter of our thesis, suggests the existence of a close link between numbers and space. Indeed, as postulated by several authors (Dehaene et al., 1983; Fischer, 2003; Hubbard et al., 2005; Lavidor et al., 2004; Zorzi et al., 2006), the SNARC effect reflects the fact that numerical magnitudes are spatially coded in most people. Therefore, following its observation, in addition to the distance effect, the semantic numerical representation itself has been spatially defined as a mental continuum oriented from left to right. Moreover, additional behavioural, developmental, neuropsychological and neuro-imaging data further support the assumption of a relationship between numbers and space.

1.1. Behavioural data

One of the first evidence of the existence of interactions between spatial and numerical representations came from the observation that a certain portion of the human adult population report seeing numbers mentally on different spatial supports. Galton (1880a, b) and Seron, Pesenti, Noel, et al. (1992) found that 15% of normal adults report visuo-spatial representations of numbers: they represent numbers as occupying precise locations in space, forming two- or three-dimensional objects of different shapes, colours and orientations (see Figure 13). This phenomenon, called number-form synaesthesia, corresponds to the integration of number representations into visuo-spatial coordinates. According to Hubbard et al. (2005), the number-form synaesthesia probably arises from similar brain mechanisms of genetically-mediated cross-activation between spatial and numerical representations in the parietal lobe.

a)



b)

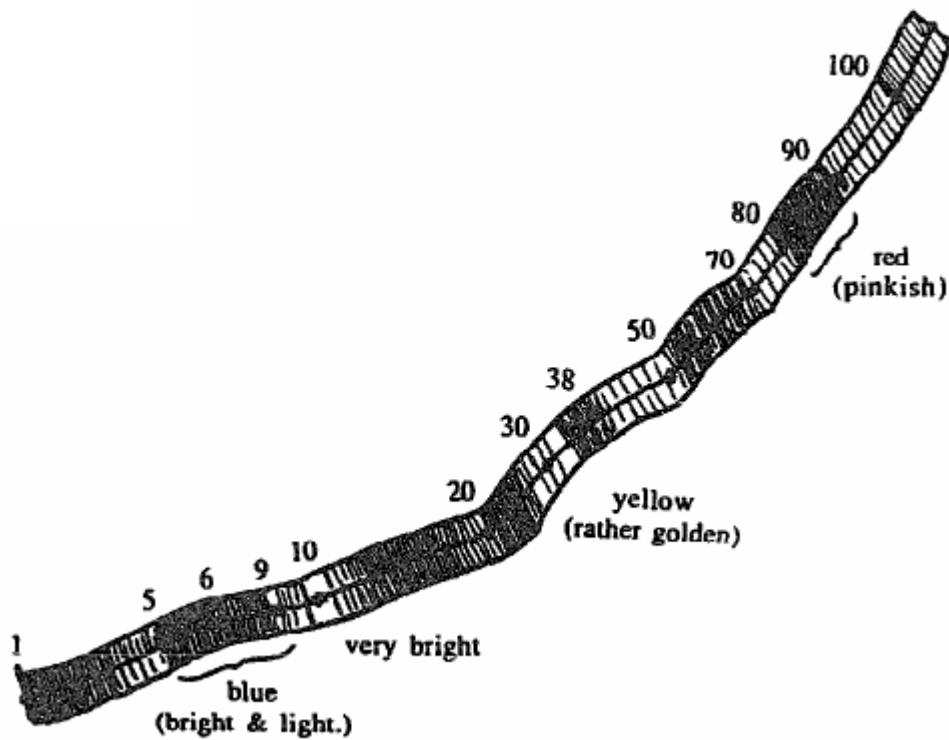


Figure 13: Number-form synaesthesia: illustration of different number-forms with a clock-like from the beginning (a) or with change in luminosity or colours at same locations (b) (Galton, 1980a).

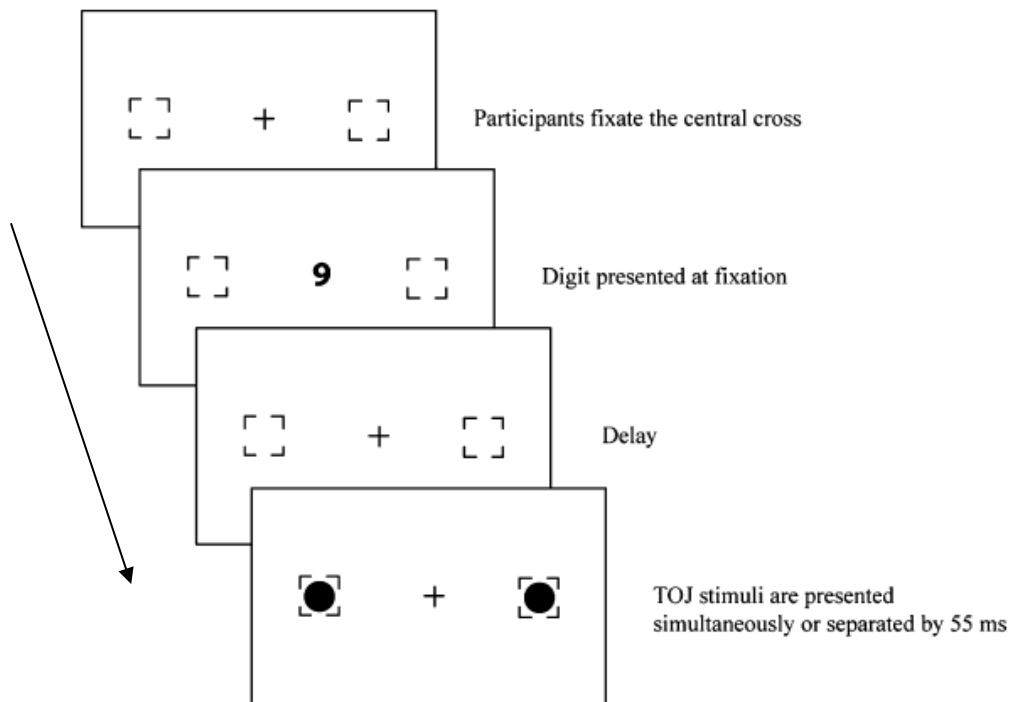
Furthermore, several behavioural studies demonstrated the link existing between numbers and space by the investigation of the relation between numbers and spatial attention. In their study, Fischer, Castel, Dodd and Pratt (2003) submitted human adults to a simple detection task, in which participants had to detect as fast as possible a target presented either in the left or right visual field. The particularity of the task was that the target was preceded by the presentation at fixation of an irrelevant numerical cue, a single Arabic digit of small (1 or 2) or large magnitude (8 or 9). The aim of this study was to examine whether, considering that numbers are associated with space, the mere perception of numbers in a task in which their processing was irrelevant could induce a shift of attention to the left or right visual field. The results indicated that the presentation of small magnitude numbers, such as 1 and 2, facilitated the detection of the target in the left visual field, while the presentation of large magnitude numbers, such as 8 and 9, facilitated the detection of the target in the right visual field. These findings demonstrated that the simple perception of numbers induced an automatic access to their semantic representation having spatial properties that caused a shift in covert attention to the left or right side according to the magnitude of the numerical stimuli.

Casarotti, Michielin, Zorzi, and Umiltà (2007) conducted a set of experiments in order to further investigate the relation between numbers and spatial attention using a temporal order judgement (TOJ) paradigm to index attentional allocation. It is well-known that the perception of temporal order is influenced by attentional allocation: when two stimuli are presented at a same time, the attended stimulus is perceived to occur before the unattended one (Stelmach & Herdman, 1991). Therefore, Casarotti et al. (2007) submitted human adults to temporal judgement tasks in which two brief flashes of light (TOJ stimuli) were presented on both sides of a fixation cross either simultaneously (synchronous condition) or separated by a short delay (asynchronous condition). Before the presentation of the TOJ stimuli, an irrelevant digit cue of small (1, 2) or large (8, 9) magnitude appeared centrally on the screen. The participants had to report which of the TOJ stimuli occurred first. In addition, they had also to report the cued digit after performing the TOJ task (see Figure 14a). The results demonstrated that the processing of the irrelevant numerical cue produced an automatic shift of the participants' visuo-spatial attention, which affected the perception of the temporal order of visual events (see Figure 14b): when a small numerical

magnitude is processed, given equal onset time, left-sided stimuli are perceived to occur before right-sided stimuli, whereas when large numerical magnitude is processed, right-sided stimuli are perceived to occur before left-sided stimuli¹. Additionally, in order to investigate whether the attentional allocation observed previously might be linked to the ordinal character of numbers rather than quantity information, the participants also undertook TOJ tasks with non-numerical ordinal irrelevant cues (letters the alphabet). The results indicated that the spatial attentional effect observed in the TOJ tasks is specific to the numerical quantity processing, as it did not generalise to non-numerical ordinal sequences.

¹ In the first experiment of this study, the participants did not have to report the irrelevant digit cue after performing the TOJ task. However, in this case, contrary to Fisher et al.'s (2003) results, the number magnitude did not appear to affect TOJs, suggesting that the simple perception of irrelevant cues did not necessarily cause an automatic shift of visuo-spatial attention. Nevertheless, according to the authors, this result might be due to the fact that the irrelevant digit numbers in this experiment constituted a weak cue for the automatic triggering of attentional shifts. Moreover, it is possible that the participants fully allocated their attention to the lateral markers and did not pay attention to the irrelevant numerical cue in order to increase the processing of the TOJ stimuli.

a)



b)

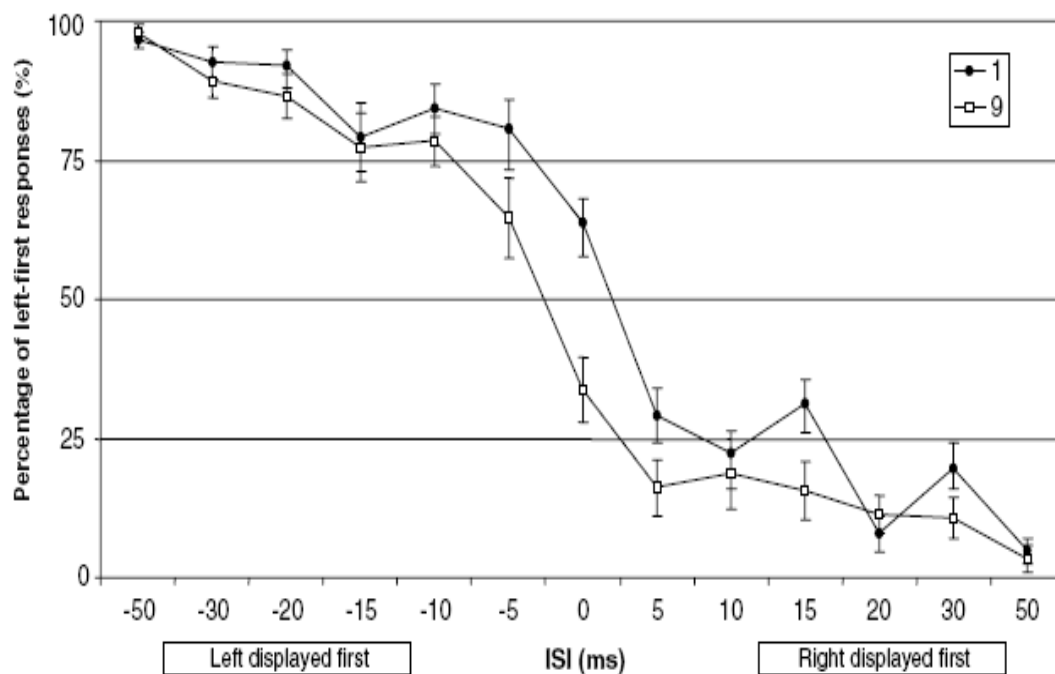


Figure 14: Numerical-spatial attentional effect: illustration of (a) the experimental display sequence used in Casarotti et al. (2007) and (b) the observation that numerical processing induced an automatic allocation of spatial attention, which in turns affected the perception of the temporal order of the visual stimuli presented: mean percentage of left-first responses as a function of number magnitude and ISI between the TOJ stimuli.

Further evidence of an automatic shift of visuo-spatial attention due to numerical irrelevant information arose from Calabria and Rossetti's (2005) and Fischer's (2001) bisection task studies. When human adults had to bisect lines composed of numbers in Arabic or verbal formats, they deviated to the right when the lines were composed of large numbers (9 or NINE) and to the left when lines were composed of small numbers (2 or TWO) (see Figure 15). These results demonstrated again that numbers biased spatial attention automatically to the left or right according to their magnitude, even in tasks in which their processing was completely irrelevant.

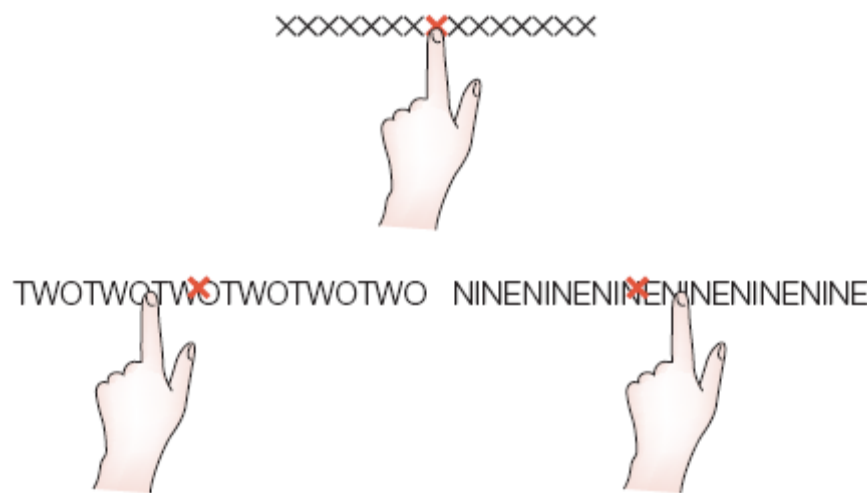


Figure 15: Numerical-spatial attentional effect: illustration of the bisection task used in Calabria and Rossetti (2005). When subjects had to point to the midpoint of a line composed of “x”, they were approximately accurate. But, when the line is composed of number words, the performance was biased from the midpoint according to numerical magnitude (*reproduced from Hubbard et al., 2005*).

1.2. Developmental data

The assumption of the existence of a close link between numerical and spatial processing is reinforced by the observation in several behavioural developmental studies of a tight correlation between mathematical and visuo-spatial skills. For example, Rourke and Conway (1997) showed that visuo-spatial learning disorders generally correlate with a delayed or abnormal development of mathematical abilities. In addition, the same correlation was found in children having genetic disorders, such as the chromosome 22q11.2 deletion syndrome (Simon, Bearden, McDonald-McGinn, & Zackai, 2005) or the

Williams syndrome (Ansari, Donlan, Thomas, et al., 2003): visuo-spatial deficits correlated with numerical disorders. Therefore, these findings confirm the important role of visuo-spatial abilities in number processing.

1.3. Neuropsychological data

Neuropsychological data further confirm the connection between visuo-spatial and numerical processing, by showing the co-occurrence after parietal lesions of spatial and numerical deficits. A basic and classical example is observed in the Gerstmann syndrome characterised by the presence of joint deficits in spatial processing (i.e., left-right confusion) and in numerical processing (i.e., dyscalculia) (Gerstmann, 1940; Mayer, Martory, Pegna, et al., 1999).

A long time ago, Spalding and Zangwill (1950) also found in a patient, who experienced number-form synaesthesia before having a gunshot wound of the left temporo-parietal cortex, the co-occurrence of spatial problems and difficulties in calculation tasks. This patient also complained about the fact that his spatial forms for numbers, letters of the alphabet, months of the year and days of the week were no more distinct.

Recently, Zorzi et al.'s (2002, 2006) studies on numerical bisection task with patients suffering from neglect following right parietal damage demonstrated that the patients' spatial neglect affected the left side of external space, but also the left side of the semantic numerical representation. Indeed, following parietal brain damage in the right hemisphere, patients present hemi-spatial neglect, but also distortions in number processing. These findings reflect a purely representational form of neglect and suggest that numerical bisection involves an internal stage of representation on a spatially oriented number line. In addition, they were supported by Vuilleumier, Ortigue, and Brugger's (2004) study, in which patients with spatial neglect undertook several number comparison tasks. On the one hand, when asked to judge whether a single number presented at fixation was smaller or larger than "5", patients with neglect were selectively slower to respond to "4". On the other hand, when they were asked to compare numbers to "7", they were selectively slower to respond to "6". It seems then that patients with unilateral spatial neglect show

difficulty to orient their attention toward the left side of a relevant reference point along the mental representation of numbers. These results give evidence that spatial neglect may cause a representational deficit that affects the mental manipulation of numbers based on positional proximity on the semantic numerical representation. According to the authors, their findings support the assumption that spatial codes are automatically activated in numerical processing tasks (Dehaene, 1992, 1997), but also strengthen the postulate that certain mental operations on numbers involve literal shifts of attention acting on a spatially-organized internal representation (Zorzi et al., 2002, 2006)².

In consequence, this set of neuropsychological data gives further evidence to the existence of a functional link between the representation of numerical quantity and visuospatial processes mediated by right parietal cortex.

1.4. Neuro-imaging data

Functional imaging studies also reinforce the postulate of a strong connection between numbers and space, by showing that similar parietal networks are activated in tasks involving either numerical or spatial processing (Dehaene, Piazza, Pinel, & Cohen, 2003; Milner & Goodale, 1995; Walsh, 2003). Indeed, the neural circuitry in the parietal cortex involved in the processing of numerical quantity appears to overlap with the neural circuitry involved in spatial processing.

In numerical cognition, several studies have shown that a distributed network of areas, including the frontal and the left and right parietal cortex, is activated when

² In Vuilleumier et al.'s (2004) study, neglect patients were also asked to classify numbers as indicating hours earlier or later than six o'clock. In this task, they showed a reverse pattern of performance: slower reaction times to numbers larger than "6". This result is consistent with a representational deficit for hour numbers located on the left side of an imagined clock-face (i.e., numbers smaller than 6 on the right side, numbers larger than 6 on the left side). Therefore, it reinforces Di Luca et al.'s (2006) and Wood et al.'s (2006) results, indicating that the small-left/large-right association does not constitute the only mental spatial-numerical association existing and that the spatial-numerical code activated when participants are submitted to a numerical task depends on the nature of the task and its relevant frame of reference.

individuals perform numerical quantity treatment (Dehaene, Spelke, Pinel, et al., 1999; Eger, Sterzer, Russ, et al., 2003; Pesenti, Thioux, Seron, & De Volder, 2000; Pinel, Dehaene, Riviere, et al., 2001; Pinel, Piazza, LeBihan, & Dehaene, 2004). Recently, Dehaene, Piazza, Pinel, and Cohen (2003) made a meta-analysis on a large set of fMRI experiments on numerical processing and they found that the bilateral horizontal segment of the intra-parietal sulcus (IPS) might be particularly important in the representation of numerical magnitudes. Moreover, physiological recordings in animals and fMRI in humans showed that humans (Piazza et al., 2004) and macaque monkeys (Nieder & Miller, 2004) share a similar population of intraparietal number-sensitive neurons, responding selectively to numbers.

In spatial cognition, recent electrophysiological and neuro-imaging studies indicated that the neural basis for spatial representations interfere with number processing. Using fMRI, Simon, Mangin, Cohen, et al. (2002) investigated the topographical relationship of calculation-related activation to other spatial areas in the parietal lobe. They observed that calculation activated the fundus of the IPS, while all visuo-spatial tasks (grasping, pointing, saccades and spatial attention) activated closely surrounding areas (a large overlapping region in the anterior parietal cortex and the posterior parietal cortex). Therefore, it appears that numerical and spatial tasks entail the activation of a similar posterior-anterior parietal organisation (see Figure 16). Moreover, further studies confirm that the IPS is involved in spatial processing in macaque monkeys (e.g., Colby, Duhamel, & Goldberg, 1995; Lewis & Van Essen, 2000), as well as in humans (Orban, Van Essen, & Vanduffel, 2004).

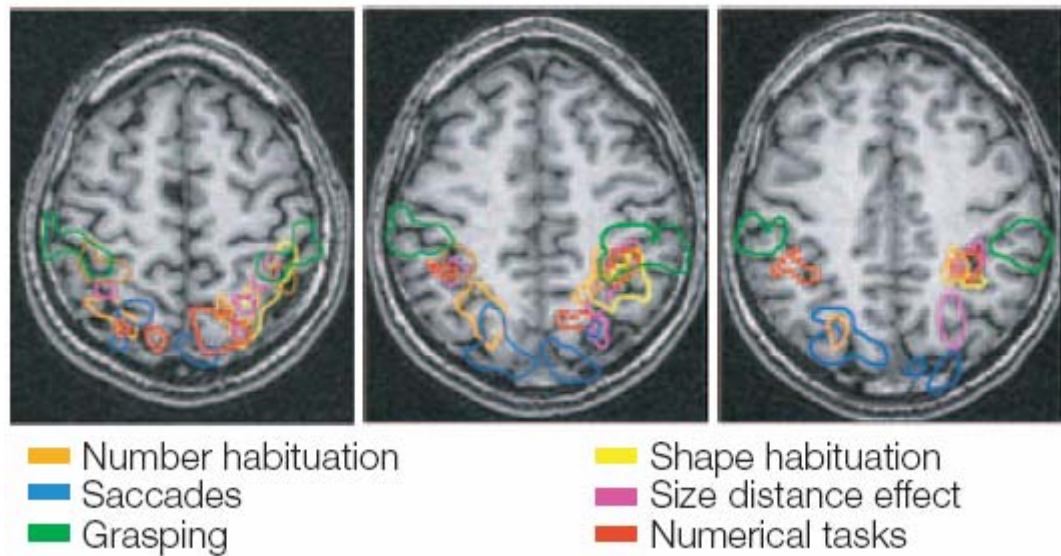


Figure 16: Illustration of the same posterior-anterior parietal organisation across numerical and spatial tasks in humans. The most anterior area is activated during grasping, while the most posterior area is activated during saccades. Between these regions, many areas are involved in visuo-spatial and numerical tasks. Each colour outline represents the extent of activation for the different tasks in each study: activation observed in number and shape habituation tasks in Piazza et al. (2004); activation reflecting a size distance effect in physical size comparison of numerical stimuli in Pinel et al. (2004); activation observed during grasping and saccades in Simon et al., (2002); activation in several visuospatial and numerical tasks reviewed in Dehaene et al. (2003) (*reproduced from Hubbard et al., 2005*).

Finally, using repetitive transcranial magnetic stimulation (rTMS) in healthy human adults, Göbel, Walsh, and Rushworth (2001) demonstrated directly that a similar cerebral network is involved in numerical and spatial processing. Indeed, they showed that the stimulation of the left and right parietal cortices leads to decreased performance in both visuo-spatial search and number comparison tasks. In other words, virtual lesions caused by rTMS stimulations lead to joint deficits of space and number. In consequence, this finding clearly indicates that both processing of numerical magnitude and visuo-spatial information are functionally connected.

2. The role of vision in spatial knowledge

For a long time, vision has been considered to be a genuine spatial modality, necessary in the elaboration of our spatial representations and abilities. This strong intuition has led psychologists to ask whether all the modalities (audition, olfaction, touch and kinaesthesia) have the same status as vision in spatial knowledge. Therefore, the role of environment, and especially of the role the visual input modality, has been largely taken into consideration in the domain of spatial cognition, by examining whether blind people could ever come to have the same understanding of space as do sighted people.

Von Senden (1960) was the first to propose an extreme empiricist view according to which vision is necessary for the development of spatial knowledge, and in consequence blind people could not have a sense of space whatsoever. According to Von Senden (1960), blind people environment is determined by time rather than space, as the awareness of space can only be elaborated via visual perception and not via tactile perception. From then on, Hartlage (1969) observed that blind children produced more errors than sighted controls in answering spatial questions and he concluded that vision is a pre-requisite for the development of spatial abilities. Furthermore, Fraiberg (1977) and Bower (1977) postulated that congenitally blind children are unable to construct a spatial world, as the lack of vision causes widespread and severe deficits in the development of various spatial concepts. According to these authors, because of their lack of vision, blind children cannot acquire a spatial framework, but they use spontaneously a temporal framework to deal with their environment.

These primary theoretical perspectives on the role of vision in the elaboration of spatial knowledge clearly appear to be extreme. Moreover, they have been disconfirmed rapidly by the repeated observation of efficient spatial abilities in blind people. Indeed, several studies allowed rejection of Von Senden's (1960) theory by showing that blind people present similar, verily enhanced, spatial abilities compared to sighted people. Similar patterns of performance on spatial knowledge between blind and sighted subjects were observed, for example, in Haber, Haber, Levin, and Hollyfield's (1993) study. In this study, a group of blind and a group of sighted participants were familiarised with a room

and 10 well-known and salient objects placed in it. Then the subjects had to estimate the distance between every pair of objects using an absolute distance metric (feet or meters). The results indicated that the spatial representations of the blind were similar to those of the sighted. Therefore according to the authors, these findings suggest that visual experience is not necessary for the development of spatial knowledge, such as high level spatial organisation, the concept of spatial layout, the notion of a person's view point and a metrical knowledge of the environment.

Several studies using a similar experimental procedure as in Haber et al. (1993) came to a similar but balanced conclusion. Carreiras and Codina (1992) submitted a group of congenitally blind, blindfolded sighted and sighted participants to spatial tasks, in which they had to learn the location of different relevant and non-relevant places (i.e., utility and physical importance of the places for spatial orientation)³ on a scale model with either a regular grid-shaped (i.e., straight-line) or an irregular (i.e., curved-line) street configuration. In the learning phase of the scale model, the experimenter guided participants' index finger across the model following a fixed route which included 12 places. During the route, participants were given the location and a description of each place with varying number of perceptual and functional features according to its relevance. Once the learning was over, participants were asked to follow the route on the scale model on their own and to name each place. If they failed to do so, the training was repeated as many times as needed to satisfy the learning criterion (i.e., being able to follow the route while naming each of the places in the same order as in the learning phase). Then in a test phase without the scale model, participants had to estimate route and straight-line distances for all possible pairs of relevant and non-relevant places. These experiments allowed examining the internal spatial representation abilities of the participants with a regular and an irregular structure. The results showed the absence of important differences between the three groups of participants. In the three groups, some environmental features, such as the place relevance and the regularity of the model had a positive influence on spatial representation: fewer errors were observed for relevant places and regular scale model.

³ The relevance of the places was defined in a previous study conducted with other blind participants.

However, the blind participants were slightly less efficient than sighted participants with the irregular environment. Therefore, it seems that in the absence of vision, irregular structure makes tougher their sequential knowledge. Sighted participants had also shorter response latencies than the blind and blindfolded sighted participants, suggesting that they possess a more accessible representation and/or that they are more efficient in recalling information. In addition, the sighted participants needed fewer learning sessions to study the maps than the blind and the blindfolded sighted participants. In conclusion, these results demonstrated that vision is not necessary for the elaboration of spatial abilities, but the visual modality still shows some predominance in spatial representation, as it seems to facilitate spatial representation in complex environments.

Morrongiello, Timney, Humphrey et al. (1995) and Ochaita and Huertas (1993) strengthened this conclusion. In their study, Morrongiello et al. (1995) examined spatial knowledge in congenitally and blindfolded sighted children with the use of a large-scale four-location navigation task. The children were first trained in a spatial layout with four landmark locations (i.e., a “home” location and three “test” locations) in a test room. The training consisted in leading the children by hand from the “home” table to a “test” table, and back. When arrived at a “test” table, children had to touch a toy positioned on it. A different toy was placed on each “test” table. The training procedure was repeated for each of the three “test” tables. The complete training sequence was executed two or three times to ensure that each participant could point toward each toy (i.e., test table) on command when positioned at the home table (i.e., training criteria). Then children undertook a navigation task, in which they had to follow familiar and novel paths between the four landmarks learned. For each trial, children were told where they were starting from (e.g., “you are at the table with the hammer on it”) and where they had to go (e.g., “please, go to the table with the bear on it”). Following this navigation task, each child was asked to create tactile maps with the four landmarks. The performance of the blind children was similar to that of the sighted on all measures, except accuracy at final position reached relative to the goal position in the navigation task, for which their performance was worse than that of the sighted. Therefore, these results also indicate that visual experience is not necessary for establishing a system of spatial knowledge. Nevertheless, vision appears to play a facilitative role. Indeed, the blind children’s cognitive maps of the spatial layout

learned seemed to be less accurate than those of their sighted peers, as suggested by their poorer accuracy than sighted children for final position scores. Ochaita and Huerta (1993) by the examination of the effect of development on spatial knowledge and representation in blind children drew the same conclusion. In their study, a group of 40 early and late blind children from 9- to 17-year-old were firstly submitted to training sessions to learn a route formed by seven landmarks. Then the children knowledge and spatial representation were evaluated with a cartographic technique (construction of a scale model of the learned route) and a verbal procedure involving the estimation of distance between the different landmarks on the route. No difference in results was observed between the early and the late blind children, as both groups presented abilities to organize a known and simple space in an abstract and coordinated manner. Thus the blind children appear to be able to represent an easy route learned in a successive and sequential manner. However, according to the authors, previous visual experience may still facilitate the representation of complex environments.

Several studies conducted on spatial auditory location tended to support the idea that blind people present similar, verily enhanced abilities compared to sighted people. Voss, Lasseonde, Gougoux, et al. (2004) submitted early and late blind participants to a sound location discrimination task. The results demonstrated that the blind participants showed enhanced spatial auditory skills compared to sighted participants. Indeed, the blind participants showed normal or supra-normal abilities to discriminate the relative positions of two sounds presented in far-auditory space, as well as to determine the relative distance between them. According to the authors, this supra-normal spatial auditory ability in early- and late-onset blind individuals might be critical for the development of their ability to navigate through their environment. Superior spatial auditory ability in the blinds has also been observed in Lessard, Paré, Lepore, and Lasseonde's (1998) study, in which participants had to localize a sound source presented on the horizontal plane randomly through 16 loudspeakers under monaural and binaural conditions. Indeed, in this study, early blind individuals showed the ability to map the auditory environment with equal or better accuracy than sighted participants. In another study, Röder, Teder-Sälejärvi, Sterr, et al. (1999) compared behavioural and electrophysiological indices of spatial tuning within central and peripheral auditory space in congenitally blind and blindfolded sighted

participants. The participants' task was to detect infrequent deviant sounds either at a central or at a peripheral speaker. Again it appeared that blind participants displayed better sound localisation abilities than sighted participants, but only when attending to sounds in peripheral auditory space, that is at spatial positions where auditory localisation is the poorest in sighted individuals. In addition, the electrophysiological data recorded in this study indicated sharper tuning of early spatial attention mechanisms in the blind participants and a different scalp topography distribution, suggesting the existence of a compensatory cerebral reorganisation in the blind that might contribute to the improved spatial abilities observed here.

Taken together these last data tend to indicate that blind people are particularly good in spatial processing in the auditory modality. However, these findings might simply reflect better auditory abilities in blind participants compared to sighted participants, rather than superior spatial abilities per se. Indeed, this particular modality plays an important role in blind people's daily life locomotion. In addition, for a long time, it has been assumed that blind people develop stronger ability in their remaining senses, such as audition, as compensatory mechanisms. Recently, Collignon et al. (2006) investigated spatial attentional performance of blind participants compared to sighted participants, independently of any possible sensory influence. They submitted a group of congenitally blind and blindfolded sighted participants to four different tasks using auditory and tactile modalities: a sensory acuity test, a simple reaction task, a selective and a divided spatial attention task (see Figure 17). The results indicate no difference between the two groups of participants in either sensory sensitivity or simple reaction times for both modalities. However, the congenitally blind participants demonstrated enhanced spatial attention performance in both tactile and auditory selective spatial attention task and also in bimodal divided spatial attention task. These findings then suggest that following visual deprivation, blind people develop compensatory mechanisms in non-visual spatial attention that might play an important role in their daily life. Indeed, thanks to these compensatory mechanisms, blind people present high abilities to focus their attention on an auditory or tactile space location, that allow identifying and quickly reacting to the events occurring in their environment. Furthermore, these results clearly indicate that blind people show

enhanced spatial attention abilities that cannot be attributed to better sensory abilities in their remaining senses.

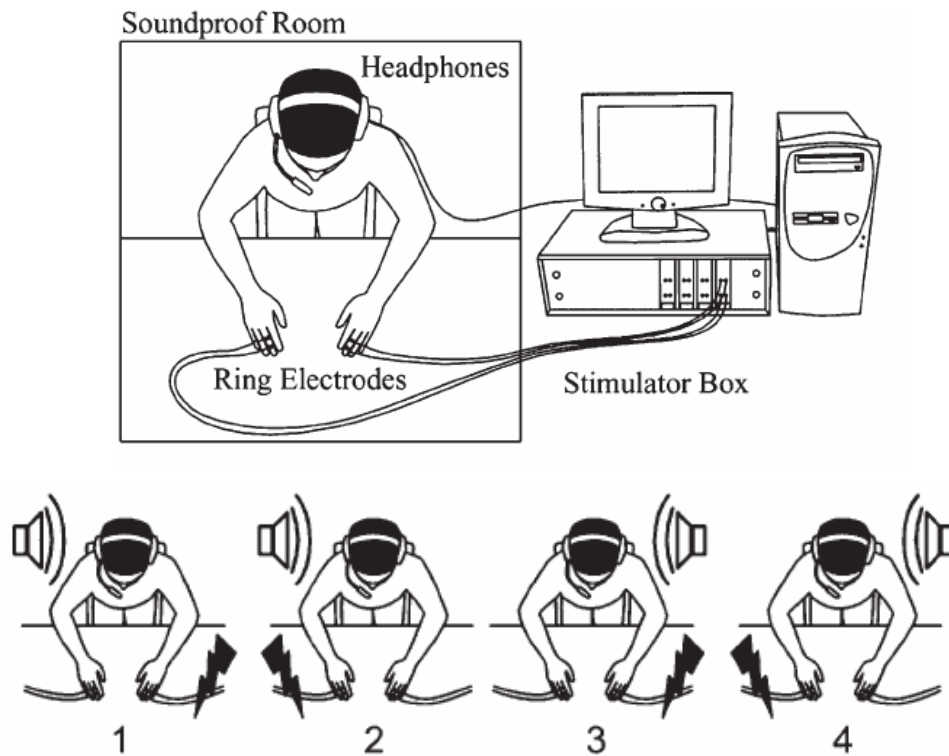


Figure 17: Experimental set up and the four auditory-tactile stimulus combinations used in Collignon et al. (2006). In the simple reaction time task, participants had to detect and respond orally to every stimulus. In the attentional tasks, they had to detect and respond orally either to the right-sided sounds (selective auditory condition – 1 or 2) or to the left-sided pulses (selective tactile condition – 1 or 3), or to the combination of a right-sided sound and a left-sided pulse (divided bimodal condition – 1).

All these studies demonstrate that blind people present similar, verily enhanced, spatial abilities compared to sighted people, suggesting that vision is not crucial in the elaboration of spatial cognition as postulated by Von Senden (1960). Nevertheless, no straightforward conclusion can be drawn yet as: 1) as we have already noticed, several studies drew balanced conclusion on the role of vision in spatial knowledge (i.e., blind people spatio-cognitive competence can be limited as a function of task's complexity)(e.g., Carreiras & Codina, 1992); 2) several studies also show that congenitally and early blind people were seriously impaired compared to sighted participants when performing spatial tasks (see, for review, Thinus-Blanc & Gaunet, 1997). For example, Rieser, Guth, and Hill (1986) addressed the role of visual experience in the development of sensitivity to

occluded changes (e.g., changes in the network of directions and distances spatially relating the observers to fixed objects in the surrounding environment) in the perspective structure. They submitted sighted, late and early blind participants to navigation tasks. When participants were asked to judge perspective while imaging a new point of observation on the learned structure, the three groups presented similar performance. But when they had to reach this new point, the sighted and the late blind participants presented better performance than early blind participants, indicating that visual experience plays an important role in the development of sensitivity to changes in perspective structure when walking without vision. Therefore according to the authors, early visual experience is crucial for setting up an optimal spatial-processing system.

This conclusion was further supported by Gaunet and Thinus-Blanc's (1996) and Gaunet, Martinez, and Thinus-Blanc's (1997) results. In their study, Gaunet and Thinus-Blanc (1996) investigated the impact of the lack of visual experience on the detection of the rearrangement of objects after a free exploration in the locomotor space. In their study, a group of congenitally, late blind and blindfolded sighted participants were firstly submitted to a familiarization phase with a spatial arrangement of four objects in a large room. In a second phase, the participants undertook several trials, each one consisting of exploration and test. During the exploration stage, they had to freely explore the room in order to memorize the respective locations of the four objects. Then the experimenter modified the spatial layout of the objects (i.e., swap between two objects, displacement of one object, reduction of the spatial arrangement by 20%, or no change). During the following test phase, the participants had to explore, detect and identify the new spatial arrangement as quickly as possible (i.e., change-detection task). The early blind group showed significant worse performance (i.e., percentage of correct responses, latencies) than the two visually experienced groups. Their patterns of exploration were significantly different from those of the late-blind and sighted participants, suggesting, like Rieser et al.'s (1986) results, that early visual deprivation has effects on spatial cognition and that vision plays an important role in the elaboration of optimal spatial processing systems. In a second study, Gaunet et al. (1997) investigated the effects of early visual deprivation on the detection and identification of a spatial change in the configuration of objects displayed in the manipulatory space. A group of congenitally, late blind and blindfolded sighted

participants were firstly familiarized with a set of ten objects. Then, they undertook several trials in which they explored firstly a spatial arrangement of the ten familiarised objects; secondly, the experimenter modified this spatial arrangement (i.e., exchange of two objects, dislocation of one object by few centimetres, or no change in the configuration); and thirdly, in a following test phase, they had to detect and react to a change of the spatial arrangement. The results indicated that early visual deprivation affects both exploratory patterns and performance levels (i.e., accurate detection of spatial changes). Therefore, these results also strengthen Rieser et al.'s (1986) conclusion that early blindness seems to have deleterious effects on high-level spatial processing.

In view of the discrepant results observed on spatial cognition in blind people, it seems then impossible to formulate a general theory to account for the effect of blindness on spatial knowledge. Currently, the only possible conclusion that could be drawn is that early visual deprivation does not lead to consistent effect on spatial behaviour. Recently, Gaunet and Rossetti (2006) provided within the same study a good illustration of these different effects of visual deprivation on spatial behaviour. They submitted congenitally, late blind and sighted participants to a pointing task at proximal memorised proprioceptive targets (see Figure 18). Several measures were made to examine the spatial representation involved with proprioception: absolute distance estimation, surface area and ellipse elongation, amplitude and direction estimates, orientation of pointing distribution (see Figure 19). The blind participants' results demonstrated different results according to the different pointing parameters explored: increased capacity in absolute distance estimation, but also unaltered organisation for surface area and ellipse elongation, and altered organisation for amplitude and direction estimates and orientation of pointing distribution. Following these findings, the authors concluded that sensory deprivation probably entails both increased and altered abilities within the same cognitive processing, as blindness necessarily involves the development and use of particular compensatory strategies that lead to specific patterns of performance (errors, accuracy, variability) according to the task and the measures made.

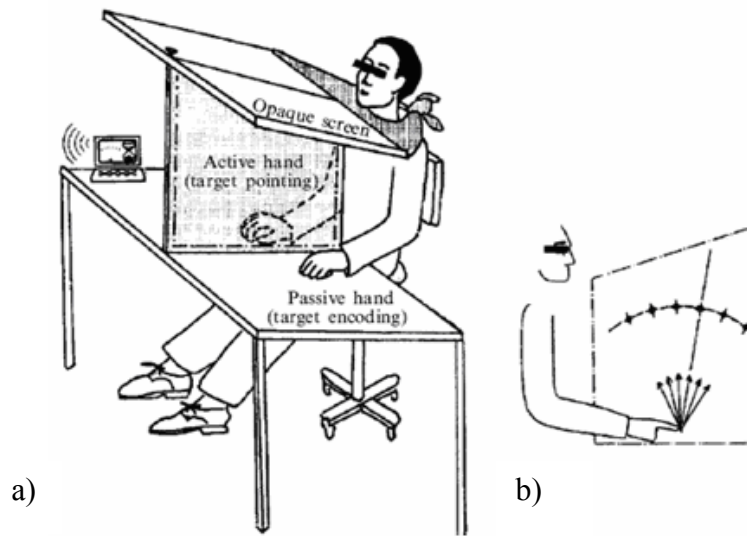


Figure 18: a) Apparatus used in Gaunet and Rossetti (2006): the passive left hand was placed on the table while the active right hand was placed on a tactile mark affixed to the bottom of the panel and which corresponds to the starting position. The experimenter put the subject's index finger of the left hand on the target and then back on the table. An auditory signal indicated to the subject the moment when he had to point toward the memorised target. b) Representation of the spatial configuration of the targets arranged along an arc centred on the finger's starting position.

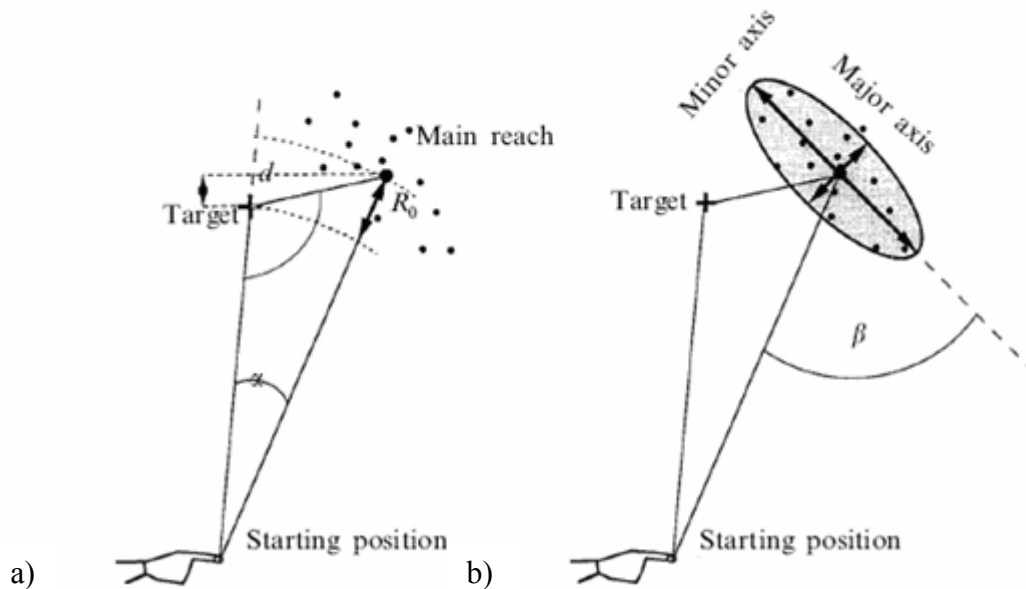


Figure 19: a) Dependent variables measured in Gaunet and Rossetti's (2006) study: d = absolute distance error between pointing distribution and target; α = movement amplitude error of pointing distribution; R_0 = movement direction error of the pointing distribution. b) Minor and major axes length of pointing distribution; β = orientation of the ellipse major axis.

To sum up, discrepant results have been collected on spatial processing in blind people. Therefore, no clear conclusion can currently be drawn and no general model on the effect of early visual deprivation and on the role of vision in spatial cognition can be formulated. Several factors could account for the fact that blindness does not seem to have consistent effects on spatial behaviour: individual factors, such as the level of sensorimotor and intellectual stimulation during childhood; the variety of spatial tasks used in the literature; the size of the groups and the matching criteria between experimental groups of participants, etc. Moreover, as Gaunet and Rossetti (2006) pointed out, early visual deprivation may have also discrepant effects on spatial behaviour because of the complexity of the mechanisms underlying spatial representation and processing. Nevertheless, the fact that blind people have demonstrated spatial abilities on several occasions clearly proves how extreme were the early theories according to which vision was considered as the supreme spatial sense. In consequence, it can at least be concluded that, visual experience appears not to be necessary for establishing a system of spatial knowledge, even if some results still indicate that vision could play a facilitative role in some circumstances.

3. The role of vision in numerical cognition?

To date, the visual modality has been predominant in the domain of numerical cognition. Indeed, the majority of the studies on numerical cognition have been conducted in this particular modality. Moreover, as for spatial cognition, some authors suggested that vision plays a critical role in the emergence of the numerical representations and skills (e.g., Simon, 1997, 1999). Now, numbers and space appear to be intimately linked, bearing in mind that the semantic numerical representation itself has been spatially defined. Therefore, it seems particularly pertinent and important to start studying the role of vision in the elaboration of the numerical representations and skills.

One original way to address this question is to explore numerical representations and abilities in people who have lacked vision since birth or early childhood. We have seen that in the domain of spatial knowledge, this experimental approach has already been used, and has led to the observation of discrepant results that did not allow drawing a general

model on the impact of early visual deprivation on this particular cognitive domain. But what can be the impact of early blindness on the development of numerical representations and skills?

According to the new theoretical proposals made in numerical cognition questioning the numerical processing's necessary obedience to Weber's law, experience and exposure to numbers and numerosities have an impact on the way we represent (e.g., Siegler & Opfer, 2003; Verguts et al., 2005) or access numerical magnitudes (e.g., Lipton & Spelke, 2005). Now, given the absence of vision, people suffering from early onset blindness have necessarily experienced numbers and numerosities in a different way compared to sighted people. Therefore, one may wonder whether this particular experience could have repercussions in the way blind people represent numerical magnitudes.

The aim of the current thesis is to address this question: what is the impact of early visual deprivation on the elaboration of the semantic numerical representation, in its spatial framing and its obedience to Weber's law. Indeed, as the study of numerical cognition in blind people is only at its premises, it seems relevant to start exploring this issue by examining whether blind people's numerical processing has the same characteristics to that of sighted people (i.e., spatial-numerical association, Weber's law), suggesting that their mental representation of numerical magnitudes has the same properties. Therefore, based on several theoretical proposals and observations made in the literature, two opposite exploratory hypotheses can be drawn on the impact of early visual deprivation on the elaboration of the numerical representations and skills: the sensory limitation hypothesis and the cognitive compensatory mechanisms hypothesis.

3.1. The sensory limitation hypothesis

Early visual deprivation involves the impossibility for blind people to experience numbers and numerosities through vision. Could this lack of visual experience preclude the elaboration of a semantic numerical representation with the same properties to those postulated for sighted people's numerical representation?

According to Simon's (1997, 1999) assumption, the lack of vision since birth or early childhood should have detrimental consequences on the elaboration of numerical representations and abilities. In addition, although vision does not appear to be essential in the elaboration of spatial knowledge, it seems to play a facilitative role. Hence, a similar particular role of vision could be postulated in numerical cognition, as it has been clearly demonstrated that numerical and spatial processing are linked. Moreover, the visual modality appears to present advantages over the other senses. These advantages are the following:

- vision constitutes a privileged sensory modality in allowing maintenance of information about one item, while another one is being examined, especially in the distal space;
- vision presents a larger precision compared to the other senses;
- vision allows subtle attentional modulations: visual attention can be sharply focused and easily solicited, while for example audition can only be easily solicited and touch can only be easily focused;
- vision overcomes the other sensory modalities in case of sensorial conflict situations (see for a review, Thinus-Blanc & Gaunet, 1997).

Vision presents then a much higher information capacity compared to the other senses. In other words, the visual modality shows a quantitative advantage: greater amount of information and more precision (Thinus-Blanc & Gaunet, 1997).

Therefore, because of visual deprivation, blind people are always limited in their perceptual reach of the environment. When no external stimulation reaches them, they necessarily have to take action to maintain contact with their environment. They cannot rely on sight to construct landmarks or references in their surroundings. Because of their perceptual limitations, they are constrained to collect information by fragments and sequentially. As a result, vision could play an important role in the development of numerical cognition. Moreover, new theoretical perspectives in numerical cognition pointed out that experience with numbers and numerosities has an impact on the way numerical magnitudes are presented or accessed (e.g., Lipton & Spelke, 2005; Siegler & Opfer, 2003; Verguts et al., 2005). Now, early visual deprivation necessarily leads to a particular experience with numbers and numerosities; an experience different from that of

people who have the benefit of vision. In addition, Mix (1999) demonstrated that children numerical abilities are limited by the features of the target sets: the discrimination of sequential sets of objects and events is more complex than the discrimination of static sets. In her study, Mix investigated whether 3- to 5-year-old children can recognize numerical equivalence for comparisons involving sequentially presented sets, and whether accurate numerical-equivalence judgments correlate with the acquisition of a conventional counting system. The results indicated that children recognized numerical equivalence for static sets earlier than for sequential sets and that memory for the number of objects presented sequentially emerged earlier than memory for the number of sequential events. Now, in blind people, numerical auditory and tactile discrimination usually rely on events and objects in the sequential mode.

In consequence, the sensory limitation hypothesis can be postulated in view of: 1) the role attributed to vision in numerical cognition by some authors; 2) the facilitative role of vision in spatial cognition and the link existing between spatial and numerical processing; 3) the quantitative advantage of vision over the other senses; and 4) the role of experience on the way numerical magnitudes are represented or accessed. According to this hypothesis, vision constitutes the principal cue from which the semantic numerical representation is elaborated. People suffering from early visual deprivation should not be able to handle with numerosities and to discriminate them as do sighted people. In consequence, early visual deprivation should have repercussions on the apprehension and processing of numerosities and should preclude the elaboration of a semantic numerical representation with the same properties to those of sighted people. When submitted to numerical tasks, such as numerical comparison, blind people should not show the classical behavioural effects (distance and SNARC), reflecting the spatial layout of the semantic numerical representation. Given that the SNARC effect appears to be culturally determined by the reading habits (Dehaene et al., 1993), if blind people do not show this effect, this would indicate that it is the visuo-spatial aspect of the reading habit that is determinant in the elaboration of the spatial orientation of the semantic numerical representation. Finally, according to the sensory limitation hypothesis, because of their lack of vision, blind people should have less proficient experience with numbers and numerosities. Therefore, in view of the recent theoretical proposals on the impact of numerical experience, their numerical

processing should be more prone to obey Weber's law, resulting in more approximate and imprecise numerical abilities than sighted people.

3.2. The cognitive compensatory mechanisms hypothesis

Because of early blindness, blind people have to use alternative approaches compared to sighted people to deal with their environment. Recent studies conducted on early visual deprivation in spatial knowledge indicated that blind people develop cognitive compensatory strategies to make up for their lack of vision (Collignon et al., 2006; Gaunet & Rossetti, 2006). However, these compensatory mechanisms following blindness may probably extend to other cognitive domains (Collignon et al., 2006), notably to cognitive domains that are linked with spatial cognition, such as numerical cognition. Therefore, a second opposite hypothesis on the impact of blindness on the elaboration of numerical representations and skills can be postulated: the cognitive compensatory mechanisms hypothesis.

In their daily life, blind people cannot rely on sight to process numerosities, but on the other side, they might have gained a more extended experience with numerosities than sighted people via hearing, touch and proprioception. In other words, they might have access and represent numerical magnitudes more often than sighted people through their remaining senses.

According to the compensatory mechanisms hypothesis, there is no reason to believe that blind people should have elaborated a semantic numerical representation with different spatial properties to those postulated in sighted people. In consequence, they should present, like sighted people, a distance and a SNARC effect, when submitted to numerical tasks, such as comparison or parity judgement tasks. Concerning the SNARC effect, reflecting the small-left/large-right spatial-numerical association, blind people should have been able to develop a similar spatial-numerical association from the tactile-spatial aspect of their Braille reading habits. Moreover, this particular spatial-numerical association might emerge in blind children, like in sighted children, from early training in school with left-to-right number lines to learn numbers and arithmetical principles. The

observation of a distance and a SNARC effect in classical numerical comparison or parity judgement tasks in blind people would then indicate that the visual modality is not necessary to elaborate a semantic numerical representation with the same spatial properties to those usually postulated in sighted people: a mental continuum oriented from left to right.

As assumed by the new theoretical proposals developed recently on numerical cognition, the experience individuals have with numbers and numerosities has a particular impact on the third property of the semantic numerical representation: its obedience to Weber's law (e.g., Lipton & Spelke, 2005; Siegler & Opfer, 2003; Verguts et al., 2005). Therefore, blind people's particular experience with numbers and numerosities due to their lack of vision should be reflected predominantly on this property of the semantic numerical representation. To handle and deal with numerical information, blind people cannot rely on sight to keep numbers and numerosities in mind or to apprehend them. Therefore, according to the compensatory mechanisms hypothesis, they might have developed compensatory strategies to access and represent numerical magnitudes more often than sighted people, and in situations in which sighted people are not used to manipulate numbers and numerosities as they can rely on sight. For example, when they go shopping, it is likely that they manipulate mentally the products' prices (i.e., particular experience with numbers) and their related magnitudes in working memory much more than sighted people. Regarding their locomotion abilities, blind people cannot rely on sight to move themselves from one place to another. To compensate, they might rely on numerical information provided by their own proprioceptive movements in order to constantly estimate the distance they have walked, the number of footsteps they have done between two landmarks on the pavement, the number of stairs covered before reaching the first floor, etc (i.e., particular experience with numerosities). Therefore, with the development of numerical compensatory mechanisms, blind people might have acquired more efficient experience with numbers and numerosities compared to sighted people, leading to less sensitivity to Weber's law and to more precise numerical skills.

3.3. Previous results

To our knowledge, only one study has been dedicated to the investigation of the role of vision in numerical cognition, and more particularly of the impact of early visual deprivation on the elaboration of the semantic numerical representation. To address this issue, Szűcs and Csépe (2005) submitted a group of eight congenitally blind and eight blindfolded sighted participants to an auditory numerical comparison task to 5. They examined whether the blind participants demonstrate the classical behavioural distance and SNARC effects generally observed in numerical comparison. In addition, electroencephalographic (EEG) data were collected in order to investigate whether the blind participants show, like sighted people, the amplitude modulations of electroencephalographic parameters, in function of numerical distance in the parietal electrode sites (Dehaene, 1996). The results indicated that both groups of participants presented robust distance and SNARC effects, suggesting that blind and sighted participants used a semantic numerical representation with similar spatial properties: a mental continuum oriented from left to right. In addition, similar brain circuits appeared to be recruited in both groups, as no apparent morphological or distribution discrepancies were observed between them. Indeed, the blind and sighted participants' EEG recording showed similar parietal and frontal ERP deflections at around 200 ms and a similar distance effect. No divergence in the ERP topographies and the ERP distance effect were found between the two groups, indicating that number comparison relies on similar neural circuits in the blind and the sighted participants. However, the analyses of the event-related spectral perturbation (ERSP) transformed from the EEG showed some discrepancies between the blind and the sighted group in the overall ERSP landscape, electrodes and in the frequency ranges demonstrating distance effects. The main difference found from the ERSP analyses relied in both groups in the initial topography of the distance effect determined by the authors (see Figure 20). In the initial phase of the number comparison processing, the sighted participants presented parietal and frontal cerebral activation, while the blind participants only showed a parietal activation. It was only in the later phase of the number comparison processing that both groups showed similar parietal and frontal activations. According to the authors, these differences observed with the ERSP between both groups suggest the existence of a general and specific functional reorganisation in the

blind participants. Therefore, they suggested that the discrepancies observed in the primary stage of numerical comparison between the blind and the sighted groups might be due to the fact that the blind participants used a unique compensation network, involving a possible initial translation of numbers into somatosensory representations. And it is only in the following stage of numerical comparison that they would have used a similar parietal network as sighted participants for representing and processing numerical magnitudes. In conclusion, it seems that in the absence of vision and visual experience with numerosities, a normal phenomenological number representation can be elaborated and a partially normal number processing network can be shaped.

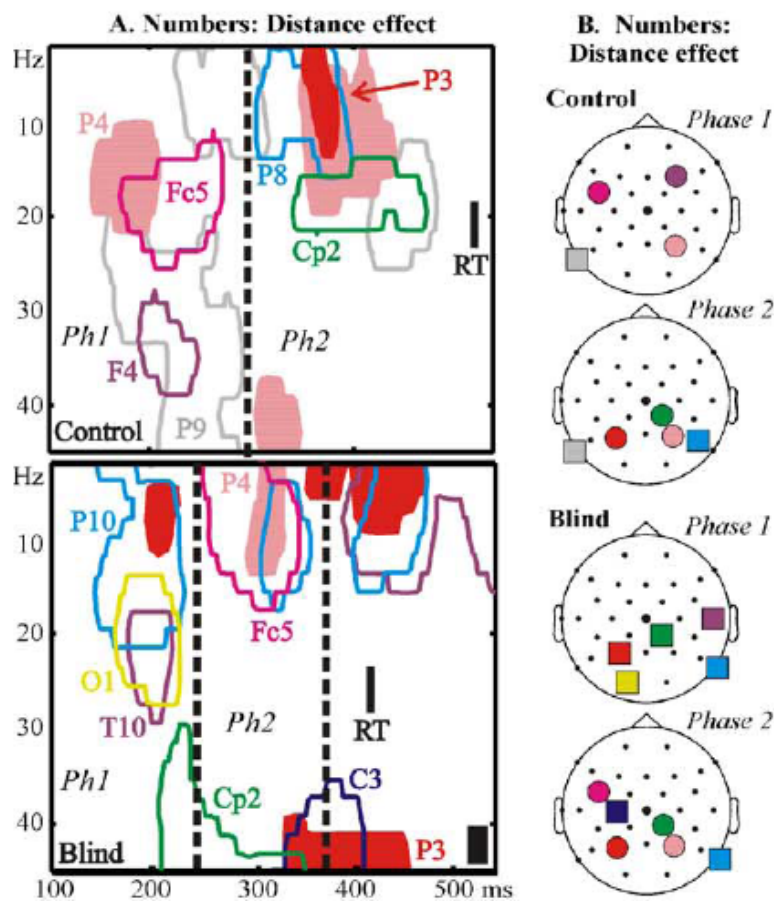


Figure 20: The distance effect in the ERPS landscape observed in Szűcs and Csépe (2005). A) Significant numerical distance effects are indicated by contour lines at different electrodes. The numerical comparison process is divided into two phases marked by the long dashed vertical lines crossing the landscapes. B) Topography of electrodes sites indicating distance effects in the two phases. Squares indicate different effects in both groups, circles stand for similar effects.

These primary findings constitute the premises to the investigation of numerical cognition in blind people and to the study of the role of the visual input in the elaboration of numerical cognition. Nevertheless, following the authors' warning, this issue needs further research, including different numerical tasks, larger group of participants, but also a larger range of numerosities. Indeed, it is possible that the quantitative advantages of vision compared to the other senses have mainly repercussions in the handling of large numerosities, while small numerosities might be handled without particular limitations by all perceptual cues. It would be then worthy to examine whether the absence of vision has an impact on the elaboration of numerical representations and skills in wider numerical range.

Conclusion

A large part of the literature on numerical cognition has demonstrated that numbers and space are closely linked. Firstly, at a behavioural level, an important set of evidence suggested that numerical magnitudes are spatially coded in most people. Secondly, behavioural developmental and neuropsychological data showed the existence of a tight correlation between numerical and spatial skills, as spatial learning disorders in children or deficits in patients have been found to co-occur with numerical disorders. Finally, neuro-imaging data clearly established that close parietal networks are involved in numerical and spatial processing.

In addition, vision has been considered as crucial for both numerical and spatial processing. The role of this particular modality has been investigated in the domain of spatial cognition, by the study of the impact of early visual deprivation on spatial knowledge. Actually, a large set of studies has been devoted to this issue. Taken together, all these studies lead to discrepant results making impossible the formulation of a straightforward conclusion on the impact of blindness on spatial processing. Nevertheless, as at several occasions congenitally or early blind people showed spatial abilities, it can be concluded that early visual experience is not necessary for the development of spatial knowledge, but may still play a facilitative role.

Regarding numerical cognition, what is really the role of vision in the elaboration of numerical representations and skills? Based on several observations (i.e., vision's advantages, Mix's results) and theoretical postulates (i.e., role of vision in numerical and spatial cognition, role of experience with numbers and numerosities on numerical processing) made in the literature, two opposite exploratory hypotheses can be made on the impact of early visual deprivation on the development of the semantic numerical representation and its postulated properties: the sensory limitation and the cognitive compensatory mechanisms hypotheses. On the one hand, according to the sensory limitation hypothesis, vision is important in the elaboration of the numerical representations and skills and early visual deprivation should lead to less proficient experience with numerosities to that of people who benefit from sight. In consequence, when submitted to classical numerical tasks, blind people should present different patterns of results than those usually observed with sighted people: no similar behavioural effects reflecting the spatial framing of the semantic numerical representation, more sensitivity to Weber's law. On the other hand, according to the cognitive compensatory mechanisms hypothesis, vision is not necessary for the development of numerical representations and skills. Early blindness could even lead to more efficient experience with numbers and numerosities than sighted people by the elaboration of compensatory numerical strategies to deal in daily life with the environment in the absence of vision. In consequence, when submitted to classical numerical tasks, blind people should present the same patterns of performance as sighted people regarding the spatial framing of the semantic numerical representation, but they might also show better numerical skills as their numerical processing should be less sensitive to Weber's law.

To our knowledge, only one recent study has investigated this issue (Szűcs & Csépe, 2005). This study examined if congenitally or early blind participants' numerical representation has the same spatial properties to those of sighted participants' numerical representation, and if a similar cerebral network is recruited in both groups. These primary results showed that the absence of vision has no effect in the elaboration of a semantic numerical representation with the same spatial properties as those postulated in sighted people: a mental continuum oriented from left to right; and that a partially normal number processing network can be shaped. However, these findings need to be further investigated

in order to be supported. Moreover, several issues remain unresolved at this very first point: 1) can these primary results be replicated on small numbers; 2) what about the impact of early visual deprivation in the elaboration of the semantic numerical representation in the range of large numbers?; 3) what about the impact of the absence of vision on the third property of the semantic numerical representation: its obedience to Weber's law?

The aim of the present thesis is to try to provide answers to these different questions and to bring light to the study of numerical cognition in blind people, and in consequence to the study of the role of vision in this particular cognitive domain.