GENERAL CONCLUSION

As we have seen in our introduction and throughout our thesis, numbers are far away from being insignificant and they have gathered a lot of attention in neuroscience research. In addition in our everyday life, vision seems, at first glance, to play an important role in the processing of numbers and numerosities. Indeed daily, we encounter numbers and numerosities on many occasions and most of the time we apprehend them through our vision. Furthermore, in experimental research, this modality has been predominantly used and some authors have even emphasized its importance in the elaboration of our numerical representations and abilities (e.g., Simon, 1997, 1999). Therefore, one may wonder how people suffering from congenital or early blindness manage to handle with numerosities in the absence of the visual modality; how do they represent and process them. In other words, what is the impact of early visual deprivation in the development of numerical representations and skills?

Surprisingly, until recently, this question of the role of vision in numerical cognition has never been addressed in the literature. In consequence, the purpose of the present thesis was to bring light to this particular and new issue, by investigating whether congenitally or early blind people show similar behavioural effects to those generally observed in sighted people, effects that are largely considered to reflect the access and use of the semantic numerical representation, usually conceptualized as a mental continuum oriented from left to right and obeying Weber's law. Eight experiments were conducted and gathered in two main papers. All these experiments were undertaken by the same categories of participants (i.e., congenitally or early blind and matched blindfolded sighted participants); they were also in the same modality (i.e., the auditory modality) and on similar numerical ranges (i.e., small and large numbers and numerosities).

In the following sections of our conclusion, we will firstly review our findings and their implications regarding the issue of the role of vision in the elaboration of numerical knowledge. Secondly, we will further explore from our results the question of the role of experience in numerical processing abilities. Thirdly, the implications of sighted participants' results will be presented. Fourthly, the possible limitations of our findings will be discussed, as well as the future research that could be envisaged. Finally, we will present a brief summary of our main results and conclusions.

1. The role of vision in the elaboration of the semantic numerical representation

The principal aim of our thesis was to investigate the role of vision in numerical cognition, by studying the impact of early visual deprivation on the elaboration of numerical representations and skills.

Our first study was conducted to explore the potential role of vision in the development of the spatial framing of the semantic numerical representation generally postulated in the literature. We submitted congenitally or early blind and matched sighted participants to classical numerical tasks on small (i.e., comparison task to 5 and parity judgement task on small numbers) and on large (i.e., comparison task to 55) numbers. Both groups presented similar patterns of performance in both ranges of numbers in the auditory modality: the distance and the SNARC effects in the comparison and the parity judgement tasks on small numbers, the distance effect in the comparison task on large numbers. These findings, in addition to those of Szücs and Csépe (2005), give evidence that early visual deprivation does not prevent the elaboration of a numerical representation with similar spatial properties to those usually postulated for sighted people's semantic numerical representation in the range of small and large numbers: 1) numerical magnitudes are organized along a mental continuum (distance effect) (e.g., Moyer and Landauer, 1967; Dehaene, 1992, 1997); 2) this mental continuum is oriented from left to right (SNARC effect) (e.g., Deheane, 1997; Dehaene et al., 1993; Fias et al., 1996).

However, the semantic numerical representation has also been defined by a third property, following the observation of the size effect in combination with the distance effect: its obedience to Weber's law. According to the two predominant theoretical models made on the semantic numerical representation, numerical processing necessarily obeys Weber's law (Dehaene, 1992, 1997; Gallistel & Gelman, 1992, 2000). In other words, an asymmetry between small and large numbers, with approximate processing for large numbers, should be systematically observed when participants are submitted to a task involving the access to the semantic numerical representation. But, recently, new proposals have been made questioning this obligatory obedience to Weber's law of numerical processing, by pointing out that the experience individuals have with numbers and numerosities could have a positive impact on their numerical abilities (e.g., Booth & Siegler, 2006; Lipton & Spelke, 2005; Verguts et al., 2005).

We conducted our second study to investigate the consequences of early visual deprivation and its following experience with numbers and numerosities on the third characteristic of the semantic numerical representation. To study this issue, we formulated two exploratory hypotheses. According to the first hypothesis, called the sensory limitation hypothesis, people suffering from early visual deprivation are not able to handle with numerosities and to discriminate them like sighted people, as their remaining senses present some limitations compared to vision in the apprehension and processing of numerosities (see Thinus-Blanc & Gaunet, 1997). Consequently, congenitally or early blind people should have less proficient experience with numerosities than sighted people. Their numerical processing should then be more prone to obey Weber's law, resulting in worse numerical estimation skills. On the contrary, according to the second hypothesis, the cognitive compensatory mechanisms hypothesis, early visual deprivation leads to the development in blind people of numerical compensatory strategies to access and represent numerical magnitudes more often than sighted people via their remaining senses. As a result, blind people might have more experience with numbers and numerosities than sighted people, involving less sensitivity to Weber's law and better numerical estimation skills. To explore these hypotheses, a group of congenitally or early blind and matched sighted participants undertook two numerical estimation tasks: 1) a key-press estimation task; 2) an auditory events estimation task. The results showed that congenitally or early blind participants accessed and used a semantic numerical representation obeying Weber' law, like sighted participants. However, blind participants demonstrated also better numerical estimation performance compared to sighted participants, especially in a numerical context involving proprioception (i.e., key-press estimation experiment). These results suggest then that although blind participants have a semantic numerical representation with obedience to Weber's law like sighted participants, they are able to compensate for this law, thanks to better mapping abilities between the symbolic representations of numbers and their corresponding magnitudes.

Taken together our findings show that early visual deprivation does not preclude the elaboration of a semantic numerical representation with the same properties to those generally postulated for sighted people's semantic numerical representation: 1) numbers are represented on a mental continuum (distance effect in comparison task to 5 and 55); 2) oriented from left to right (SNARC effect in the comparison task to 5 and the parity judgement task); 3) obeying Weber's law (size effect in the comparison task to 5 and constant coefficients of variation in the two numerical estimation tasks). Therefore, it clearly appears that vision is not necessary in the elaboration of numerical representations and skills as suggested by some authors (e.g., Simon, 1997, 1999). Our findings indicate that early visual deprivation might even have a positive impact on numerical processing. Indeed, congenitally or early blind participants' astonishing results in our second study, and more particularly in the key-press estimation task, suggest that early blindness does not imply less proficient numerical experience and more sensitivity to Weber's law, as it was assumed in the sensory limitation hypothesis. On the contrary, blindness seems to lead to the development of numerical compensatory mechanisms, as postulated in our second hypothesis, involving a particular and more efficient experience with numbers and numerosities, that allows the development of abilities to compensate for Weber's law. Thus, the results of our second study also provide new evidence supporting the assumption made in the recent theoretical proposals in the literature according to which the experience individuals have with numbers and numerosities has an impact on their numerical skills (e.g., Booth & Siegler, 2006; Lipton & Spelke, 2005; Verguts et al., 2005). But to what extent can blind people's particular numerical experience have repercussions on their numerical processing abilities?

2. The role of experience in numerical processing abilities

There is no doubt that the blind participants' results in our second study give further support to the common assumption made in the three new theoretical proposals, according to which experience with numbers and numerosities has an impact on numerical abilities. More precisely, blind participants' patterns of performance are essentially in accordance with the hypothesis of the development with numerical experience of better mapping abilities (e.g., Lipton and Spelke, 2005), rather than multiple semantic numerical representations (e.g., Siegler & Opfer, 2003), or an exact small-number representation (Verguts et al., 2005). Indeed, although in the key-press experiment blind participants' numerical estimates were precise and accurate, they also showed the signature of Weber's law (i.e., constant coefficients of variation). Now, this finding is inconsistent with Siegler and Opfer's (2003) and Verguts et al.'s (2005) hypotheses, as both of them are equivalent at a functional level and assumed that accurate numerical estimates reflects the access and use of an exact representation of experienced numbers without scalar variability - either on an acquired linear mental number line (Siegler & Opfer, 2003) or on a linear portion of the mental number line (Verguts et al., 2005). Therefore, according to these hypotheses, the signature of Weber's law should not be observed, especially with symbolic numerical input as in the key-press estimation task (Verguts et al., 2005).

Additionally, the results of our second study allowed us bringing new developments to the hypothesis of the elaboration of better mapping abilities following numerical experience, 1) by conceptualizing the symbolic representations of numbers; 2) by adding the statement that these mapping abilities can be used depending on the numerical context. Firstly, the mental representations of symbolic numerals (i.e., Arabic digits and number words) have never been really explicitly conceptualized in the literature. In his triple-code model, Dehaene (1992, 1997) postulated the existence of symbolic representations for verbal and Arabic numerals. But he did not mention how these codes can be mentally organized. To our point of view, with the learning of the symbolic numerical codes (i.e., Arabic digit and number words), linear symbolic representations of them are elaborated. This linear coding of the symbolic numerical representations, implicitly suggested in the model of better mapping abilities (Huntley-Fenner, 2001;

Lipton & Spelke, 2005), is necessary to allow the mental representation of the progression existing in the symbolic Arabic and verbal numerical systems. We used then the metaphor of the number line to conceptualize the symbolic representations of numbers, as it is helpful to capture linear coding (see Figure 11 in our second study).

Secondly, the use of better mapping abilities appears to depend on the numerical context, as throughout our experiments, blind participants did not show constant abilities to compensate for Weber’s law. In our primary study, their results tended to indicate more sensitivity to Weber’s law compared to the sighted participants, as they showed a size effect in the comparison task to 5, while the sighted participants did not. In addition, in both comparison tasks on small and large numbers, the distance effect was similar in both groups. Now, this effect, in addition of reflecting a spatial property of the semantic numerical representation, is also considered as a signature of Weber’s law (e.g., Dehaene, 1997). In our second study, in the key-press estimation task, blind participants showed better numerical estimation abilities than sighted participants, indicating the use of better mapping abilities between the symbolic representations of numbers and their corresponding magnitudes. But in the auditory events estimation task, their ability to compensate for Weber’s law was limited to a much smaller numerical range. Consequently, it seems that the blind participants do not present better mapping abilities in general, but rather in particular contexts, namely regarding our results in those involving a symbolic to non-symbolic numerical translation through proprioception (i.e., key-press estimation task).

These findings raise the following question: Why were blind participants able to compensate for Weber’s law only in such a particular context and not in general? As Gaunet & Rossetti (2006) emphasized, early visual deprivation results in the use of specific compensatory strategies, leading to specific patterns of performance. Now, according to our cognitive compensatory mechanisms hypothesis, blind people might use numerical compensatory strategies especially in their locomotion, so in contexts close to the one encountered in our key-press estimation task, as they also involve proprioception and symbolic to non-symbolic numerical translation. Indeed, when a blind adult has to be taught a new route, he/she has to learn by heart how many steps he/she has to cover between two landmarks on the pavement, how many stairs there are to reach the platform at the station, etc. In other words, he/she has to learn to map a symbolic numeral (e.g., “fifteen” stairs to reach the platform) to its corresponding magnitude. In the first stage of this learning process, he/she might use a counting strategy. Then, with habit, he/she might develop automatic numerical estimation compensatory mechanisms to move easily on a familiar route, leading to the acquisition of better mapping abilities in this particular context.

Thus, according to these primary findings, it can be postulated that blind people present like sighted people a semantic numerical representation obeying Weber’s law. However, following early visual deprivation, they have necessarily experienced numbers and numerosities in a different way compared to sighted people; in a way that has enabled them to develop the capability to compensate for Weber’s law, thanks to better mapping abilities between the symbolic representations of numbers and their corresponding magnitudes. However, the use of better mapping abilities might essentially occur in contexts related to the individuals’ experience with numbers, rather than in general, so for blind people, in contexts involving similar modality and numerical mapping to those of the contexts in which they have acquired numerical experience (i.e., locomotion).

The conclusion that better mapping abilities cannot be observed in general, but according to numerical context, seems to be relevant for sighted people too. Indeed, several data in the literature demonstrate that sighted people also show different patterns of results according to the task, to the numerical context. For example, in our second study, as well as in Whalen et al.’ (1999) study, sighted participants presented inaccurate and approximate numerical estimates with constant coefficients of variation, reflecting the signature of Weber’s law, while in Siegler and Opfer’s (2003) number line tasks (i.e., position-to-number and number-to-position tasks), a group of sighted adults showed accurate numerical estimation, reflecting the ability to compensate for Weber’s law. Therefore, it might be possible that, in Siegler and Opfer’s (2003) study, sighted participants’ ability to compensate for Weber’s law was observed in these particular numerical contexts, because they were close to the contexts in which numbers and their corresponding magnitudes are taught at school (i.e., number lines support).

Taken together, our data combined with previous observations made in literature with sighted participants lead us to draw the following conclusion: thanks to their experience with numbers and numerosities, individuals are able to compensate for Weber's law, because of the acquisition of better mapping abilities between the symbolic linear representations of numbers and their corresponding magnitudes. However, these better mapping abilities cannot be used in general, but rather in contexts close to the situations in which the individuals have experienced numbers.

3. Implications of sighted participants' results

The sighted participants' data further support the postulate that the semantic numerical representation is modality-independent. Indeed, the fact that sighted participants showed in the auditory modality the effects (the distance and the SNARC effects, constant coefficients of variation) commonly observed in the visual modality strengthens this theoretical assumption (e.g., Dehaene et al., 1998) and indicates that auditory symbolic and non-symbolic numerical stimuli map onto numerical magnitude in the same way as do visual symbolic and non-symbolic numerical stimuli. Nevertheless, as pointed out in our first study, only a few studies have directly addressed this postulate. So, this line of research still needs to be further documented, notably by the use of cross-modal paradigms.

In our second study, another interesting finding arises from the sighted participants' results in both numerical estimation tasks, as we found that according to the kind of numerical input (symbolic vs. non-symbolic), their patterns of performance were different. Indeed, in the key-press estimation task with symbolic inputs, the sighted participants presented a growing tendency to overestimate the target magnitude, while in the auditory events estimation task with non-symbolic inputs, they showed a growing tendency to underestimate the target magnitude. To account for this last finding, which occurs to be recurrent in the literature, we emitted a new hypothesis, called the bi-directional mapping hypothesis. But this possible theoretical interpretation needs further investigation in the future to be clearly supported.

4. Notices and future research perspectives

4.1. Notices

Throughout our thesis, we have examined a new issue in numerical cognition via the study of a particular population. Our findings provided some evidence on the role of vision and experience in numerical cognition. However, we have to be cautious in drawing our conclusions, as our results are only primary results, which are based on relatively small and heterogeneous (e.g., age) samples of participants, as it was difficult to constitute a sufficiently large group of congenitally or early blind participants. Nevertheless, our studies present an advantage in comparison to the studies conducted, for example, on spatial cognition with blind people that have led to discrepant results. This advantage is that in all our experiments, the blind group was generally constituted of the same participants. Indeed, during our thesis, we had the chance to meet blind people who were keen to take part in all our experiments. Therefore, the possible impact of individual factors, such as the level of sensorimotor and intellectual stimulation during childhood, etc, on our results is limited between our experiments. And consequently, we can consider the different data collected throughout our thesis as being complementary. However, having the same participants in all our studies can also present a disadvantage, as it constrains the possibility to generalize our conclusion.

Our tasks are also conducted in modalities in which for a long time it was assumed that blind people present superior sensitivity compared to sighted people. Even if several studies demonstrate that blind people do not show tactile or auditory superiority compared to sighted people (e.g., Collignon et al., 2006), it would be useful in the future to make sensory measurements additionally to numerical tasks, in order to make sure that blind participants' performance cannot be accounted by enhanced sensory abilities.

As to date the study of numerical cognition in blind people is poor, we had to make exploratory hypotheses on the impact of early visual deprivation in the elaboration of numerical representations and skills. Our results, as well as those of Szücs & Csépe (2005), tended to support these hypotheses. However, further research needs to be conducted in the future to make sure that these postulates are relevant and can account for blind people's numerical abilities and performance.

Finally, recently a debate was raised in the literature on the question of the spatial nature of the semantic numerical representation. As presented in this thesis, several authors assume that numerical magnitude and its associated spatial code are integrated in a unique shared representation: the mental number line oriented from left to right (e.g., Dehaene et al., 1993; Zorzi et al., 2006). On the contrary, according to Gevers et al. (2006), magnitude information and its associated spatial code are not incorporated in the same mental representation. These authors formulated a computational model of the SNARC effect with dual route architecture, in which they assume that upon the presentation of a number, magnitude information is coded automatically, but the SNARC effect departs after numerical magnitude have been accessed, rather than in the same time, following the automatic activation of its corresponding spatial code on a different representational level (see Figure 21).

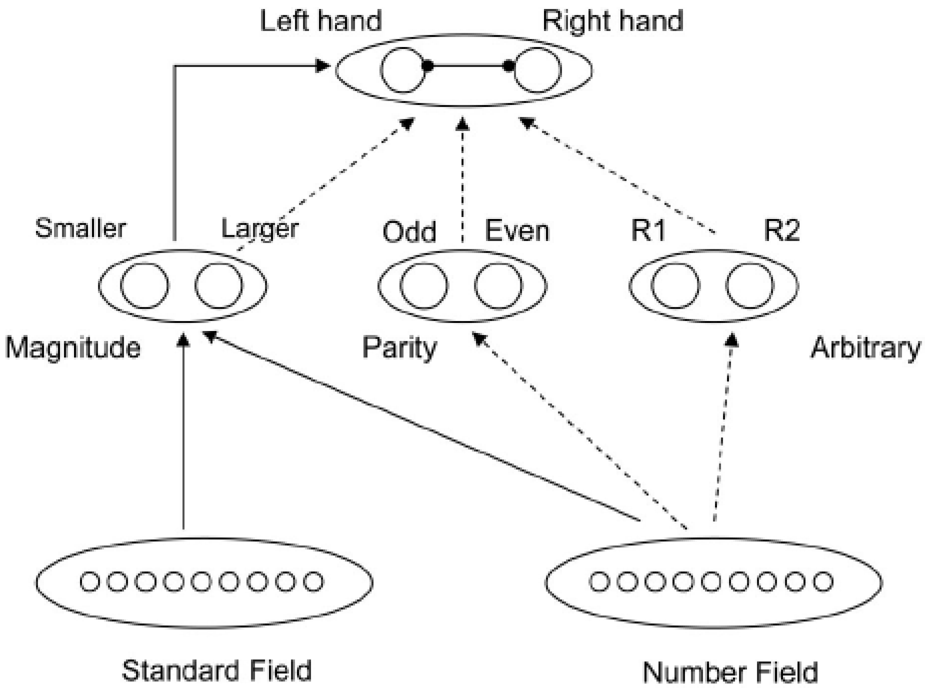

Figure 21: Computational model of the SNARC effect. The bottom layer represents the mental number line (Dehaene et al., 1990) and consists in two fields: 1) a number field coding the magnitude of the target numerals; 2) a standard field having a task-dependent function (e.g., in a comparison task to 5, it codes the magnitude of the standard 5; in a parity judgement task, it codes the mean magnitude of the target numerical range). The middle layer receives input from each of the 2 previous fields. At this layer, regardless of the task, the magnitude field is always activated with the coding of a number as either small or large, while additional fields can be activated on the basis of the task. The third top layer accounts for the SNARC effect with its response-side spatial field. In this field, spatial responses are defined (i.e., left or right). The connection between magnitude and response-side (i.e., small-left/large-right) is based on automatic long-term memory association *(reproduced from Gevers et al., 2006)*.

Throughout our thesis, we based our experiments and interpretations on the idea that the spatial-numerical association reflected in the SNARC effect occurs because of the existence of a spatial framing of the semantic numerical representation. However, although this claim has for a long time being defended in a large part of the literature, the debate is now open. On the one hand, some electrophysiological and behavioural data, suggesting that the SNARC effect arises during the response-selection stage, tend to support Gevers et al.'s (2006) dual route model (Keuz, Jenks, & Schwarz, 2005; Müller & Schwarz, 2006; Notebaert, Gevers, Verguts & Fias, 2006). But, on the other hand, as pointed out by

Notebaert et al. (2006), this model also encounters difficulty to account for the behavioural data on number bisection tasks with hemineglect patients (Zorzi et al., 2002, 2006) and healthy adults (Longo & Lourenco, 2007), as well as the neuro-imaging data showing activation for both numerical and visuospatial tasks (Dehaene et al., 2003). Moreover, how could Gevers et al.'s (2006) model account for the phenomenon of number-form synaesthesia indicating that a portion of the population consciously mentally represents numerical magnitude on a spatial support? Couldn't we consider this phenomenon as amplification in some people of the classic spatial-numerical mental representation (i.e., oriented mental continuum) existing implicitly usually in the population? However that may be, we have to acknowledge that our results do not allow us to conclude in favour of one model instead of the other. Nevertheless, whatever model is defended, the claim that numerical processing presents spatial characteristics, suggesting the existence of a dominant spatial-numerical association (i.e., small-left/large-right) reflected by the SNARC effect, is strong and has gathered a large set of data to support it. Therefore, in view of our results with blind people, one straightforward conclusion can be drawn: the absence of vision does not preclude the elaboration of the small-left/large-right spatial-numerical association, whether this association is mentally represented on a shared representation or not.

4.2. Future research perspectives

4.2.1. On early visual deprivation

Our studies, combined with Szücs & Csépe's (2005) study, constitute a first step in the investigation of the impact of early visual deprivation on numerical cognition. Therefore, there is still a lot of work to do, many questions to answer and results to further investigate.

It would be relevant to further explore whether congenitally or early blind people present better numerical estimation abilities in general or essentially in particular contexts. For example, it would be interesting to submit a group of congenitally or early blind and matched sighted participants to a numerical estimation task involving proprioception, like in our key-press estimation task, but with another response-effector, such as the feet, instead of the hand. With such a task, we would be able to disentangle between the possibilities that blind people present better numerical abilities thanks to their experience with numbers either in touch through the use of the hand (e.g., discrimination of patterns of dots in Braille reading), or rather through proprioception in general (e.g., locomotion). It would be also interesting to see whether blind participants would still demonstrate the ability to compensate for Weber's law compared to sighted participants, when submitted to a numerical estimation task, which involves symbolic to non-symbolic translation (e.g., production of a syllable repeatedly until participants feel they have reached approximately a target number), but no more proprioception.

In our compensatory mechanisms hypothesis, we made the assumption that blind people might present a greater use of mental calculation (e.g., when they go shopping) than sighted people. So it would be relevant to examine whether this postulated particular experience with numbers has repercussions in blind people's arithmetical abilities.

A closer look should be taken in the study of blind and sighted children numerical representations and abilities. For example, in view of Mix's (1999) results showing that children numerical abilities are limited by the features of the target sets, it might be interesting to investigate whether blind children develop their numerical representations and abilities at the same speed than sighted children, or whether vision could play a facilitative role at this stage of development.

An ecological approach of early visual deprivation in numerical cognition would be useful as well. Indeed, it would be helpful to conduct methodological observation on how blind children learn numbers and numerosities at school. Our hypothesis on blind people's numerical compensatory mechanisms would also benefit from observation and inquiries with blind adults on their daily life activities and use of numbers and numerosities.

All these perspectives of research do not obviously constitute an exhaustive review of all the questions that could be investigated in blind people's numerical cognition, since this field of research has only begun to be explored.

4.2.2. On the role of numerical experience

Further research need also to be conducted in order to bring more evidence to the theoretical postulate that experience with numbers and numerosities has an impact on numerical competences. For example, the study of a particular population well-known for its extended expertise with numbers, like mathematicians, might be interesting. Indeed, it would be relevant to investigate whether mathematicians' numerical estimation abilities are better than normal adult participants (i.e., without any particular extensive numerical experience) in general or not, on non-symbolic (e.g., patterns of dots) and/or symbolic (e.g., Arabic numerals) material. In addition, it might be possible, in such population, to observe neural evidence of the impact of expertise with numbers and numerosities on numerical processing with the use of the adaptation paradigm in neuro-imaging (fMRI). Indeed, with the introduction of this experimental neuro-imaging procedure, Piazza et al. (2004) found that the intraparietal coding for numbers in humans is compatible with that in macaque monkeys (Nieder & Miller, 2003), but also that species present difference in numerical neural coding precision: humans demonstrated a Weber fraction of about 0.17, whereas macaque monkeys showed a Weber fraction of 0.35. These results then indicate that the prolonged brain maturation, the greater experience with numerical quantity and the training with symbolic codes in humans may account for their enhanced precision in numerical neural coding. In consequence, with the same paradigm, mathematicians, who have greater numerical experience than "normal" adults, might present functional evidence of an increased precision in their numerical neural coding.

Finally, it would be relevant to study whether the influence of a numerical training is limited to the developmental period of childhood when the brain presents neural plasticity (e.g., Siegler & Opfer, 2003; Lipton & Spelke, 2005), or whether at adulthood, individuals still have the possibility to enhance their numerical processing abilities through experience. One way to explore this question would be to submit a group of adults to different tests to measure their numerical and arithmetical competences before and after a training period with numbers and numerosities. The training sessions would be conducted in order to improve participants' numerical skills on symbolic and non-symbolic material, by the repetition of several numerical tasks with systematic feed-back (e.g., numerical estimation task of visual arrays with increasing magnitude, measurement estimation task, estimation of arithmetical problems' results). The examination of the participants' post-training results would allow seeing whether their numerical processing abilities can be enhanced; and if it is the case, whether it is globally or not (i.e., on symbolic and non-symbolic material, in different numerical tasks or only in the trained tasks).

5. Summary of the main findings

In conclusion, the set of experiences reported in this thesis have significantly contributed to a better understanding of the role of vision in the elaboration of numerical representations and skills. In addition, it constitutes a first step in the study of numerical cognition in a particular population: congenitally or early blind people. Here is the summary of our main findings:

1. Vision is not crucial and necessary in the elaboration of a semantic numerical representation with the same properties to those generally attributed to sighted people's semantic numerical representation: numbers are represented along a mental continuum oriented from left to right, obeying Weber's law.

2. The particular experience following early visual deprivation seems to have a positive impact on numerical processing abilities, specifically in a context involving a symbolic to non-symbolic numerical translation and proprioception.

3. Support has been given to the new theoretical proposal made in the literature on the role of experience with numbers, allowing the development of better mapping abilities between the symbolic representations of numbers and their corresponding numerical magnitudes.

4. The postulate that the semantic numerical representation is modality-independent has been reinforced, as classical behavioural effects have been observed in the auditory modality.

5. According to the numerical context and the numerical input, different patterns of performance can be observed in numerical estimation tasks.