CHAPTER 9

The role of vision in the development of finger-number interactions: Finger-counting and finger-montring in blind children[1]

Abstract

Previous research has suggested that the use of the fingers may play a functional role in the development of a mature counting system. However, the role of developmental vision in the development of a finger numeral representation remains unexplored. In the present study, fourteen congenitally blind children and fourteen matched sighted controls undertook three different test batteries respectively testing **(1)** general cognitive abilities, **(2)** the spontaneous use of finger-counting and finger-montring strategies, and **(3)** the canonicity level of the finger-counting and finger-montring habits. Compared to the sighted controls, blind children used their fingers less spontaneously to count and in a less canonical way to count and to show quantities. These results demonstrate that the absence of vision precludes the development of a typical finger numeral representation and suggest that the use of canonical finger-counting and finger-montring strategies relies on the visual recognition of particular hand shapes.

[1] This section is a modified version of an article with an identical title by Crollen, Mahe, Collignon and Seron, which has been accepted for publication to the Journal of Experimental Child Psychology.

1. Introduction

In the literature on numerical cognition, it is assumed that fingers play a functional role in the development of a mature counting system (Butterworth, 1999a; 1999b; 2005; Fuson, 1988; Fuson et al., 1982; Gelman & Gallistel, 1978). Developmental and cross-cultural studies have indeed shown that children use their fingers early in life while learning basic arithmetic operations and the conventional sequence of counting words (Butterworth, 1999b). More particularly, fingers have been found to contribute to: **(1)** giving an iconic representation of numbers (Fayol & Seron, 2005); **(2)** keeping track of the number words uttered while counting up or down at the numerable chain level (Fuson et al., 1982); **(3)** prompting the understanding that every symbolic number is a sum and/or a multiple of 10 (the base 10 numerical system) and that 10 is equal to two times five (the sub-base 5 system); **(4)** sustaining the induction of the one-to-one correspondence principle (Graham, 1999) by helping children to coordinate the act of tagging the object with saying the number word (Alibali & DiRusso, 1999; Fuson, 1988); **(5)** sustaining the assimilation of the stable-order principle by supporting the emergence of a routine to link fingers to objects in a sequential, culture specific stable order (Wiese, 2003a; 2003b).

To summarize, the use of fingers is assumed to play a critical role for both enumerating the number sequence (finger-counting) and representing and showing numbers to other people (finger-montring). Finger-montring is a term created by Di Luca and Pesenti (2008) to characterize the way people raise their fingers to show numerosities to other people. As pointed out by the authors, it is important to distinguish finger-montring from finger-counting as the finger configurations used for these two strategies often differ from each other (e.g., while children raise their index and middle finger to show the numerosity 2, they raise their thumb and their index finger to count to 2). These functional connections between fingers and numbers appear very robust since it has been observed that even a child born without forearms used her phantom fingers to count and to solve arithmetic problems (Poeck, 1965). In addition, performance on finger discrimination tasks at age 5 was shown to be a good predictor of arithmetic abilities at 6 and 8 years old (Fayol, et al., 1998; Marinthe et al., 2001). This finding was replicated by Noël (2005) and extended by Gracia-Baffalluy and Noël (2008) who observed that eight weeks of finger gnosis training could improve three numerical abilities (i.e., subitizing, finger-configuration naming and ordinality judgment) in a group of first graders (but see Fischer, 2010).

Interaction between numbers and fingers was also suggested by functional imaging studies. These studies found that similar parietal networks (i.e., the angular gyrus) were activated when subjects were submitted to tasks involving either finger movement control or number processing (Pesenti et al., 2000; Piazza et al., 2002; Pinel et al., 2004; Zago et al., 2001). Accordingly, the capacity to execute tasks requiring access to finger representations and numerical judgments was found to be disrupted after an acquired (Gerstmann, 1930; Mayer, Martory, Pegna, Landis, Delavelle & Annoni, 1999) or a transient lesion (via rTMS) of the left angular gyrus (Rusconi et al., 2005).

At the behavioral level, recent research has demonstrated that the repetitive use of a stable-order finger-counting habit may actually influence the way numerical magnitude is mentally represented and processed. First, traces of the base-5 finger-counting system (i.e., numbers larger than 5 always include a full hand representation) were witnessed by a disproportionate number of split five errors (i.e., errors deviating by the correct result by exactly ± 5) while children performed complex mental calculation (Domahs et al., 2008) and by larger reaction times when adults compare a pair of digits which contains a least one number larger than 5 (Domahs et al., 2010). Second, increased corticospinal activity of hand muscles was found when adults were required to put items in correspondence with elements of an ordered series (Andres et al., 2007; see Sato et al., 2007 for similar results in a parity judgment task). Third, it has even been argued that finger-counting habits could account for the origin and direction of the SNARC effect (Fias & Fischer, 2005; Fischer, 2006, 2008). Fourth, two recent studies demonstrated that children (Noël, 2005) and adults (Di Luca & Pesenti, 2008) named numerical finger configurations faster when these configurations conformed to their own finger-counting habit than when they did not. Canonical finger configurations were also reported to be reactivated when adults have to retrieve the result of simple arithmetic operations (Badets et al., 2010). Finally, Di Luca and colleagues (2006) showed that Italian participants identify Arabic digits from 1 to 10 faster and more accurately when the finger used to press the response button corresponds to the canonical Italian finger-digit mapping (i.e., from the right thumb to the right little finger for numbers 1 to 5 and from the left thumb to the left little finger for numbers 6 to 10).

Though many connections have been observed between finger movements and number processing, the reasons why such a relation exists remain unclear. On the one hand, according to a functionalist view, interactions between fingers and numbers arise in the course of *ontogenic* development because children discover (either spontaneously or by observing adults) that fingers may be helpful to perform counting and arithmetic procedures (Butterworth, 1999b, 2005). On the other hand, according to a redeployment hypothesis, the neural circuits initially dedicated to the representation of fingers was reused for numerical processing because the representation of fingers offered some functionally relevant resources to develop the concept of numbers in the course of *phylogenetic* development (Anderson, 2010; Penner-Wilger & Anderson, 2010).

Moreover, to be efficient, finger-counting and finger-montring probably require a precise knowledge of the position of the fingers on the hand and the recognition of particular hand shapes. Interestingly, these abilities are assumed to rest in the parietal cortex, a brain area which is often associated with the dorsal visual pathway. Furthermore, as finger-counting and finger-montring habits are culturally determined (e.g., European children start counting with a closed fist and unbend one finger after the other whereas Chinese children start counting with an open hand and bend one finger after the other; Butterworth, 1999b; Ifrah, 2000; Wiese, 2003a; 2003b), the question arises as to whether vision is critical or not for the elaboration of these interactions. The study of congenitally blind children represents a unique opportunity to investigate this issue.

In the present study, fourteen congenitally blind children and fourteen matched sighted children were submitted to three different test batteries. In the first battery, general cognitive abilities (IQ, working memory, finger discrimination, addition and knowledge of ordered sequences) were evaluated to determine whether both groups of children presented the basic skills that are required to undertake the tasks presented in the second test battery. In the second battery, six different numerical tasks were administered to examine whether children spontaneously used their fingers to count and to represent numbers. Finally, in the third battery, the canonicity level of the finger-counting and finger-montring strategies was assessed by explicitly asking children to count and to show quantity with their fingers.

The present paper therefore aims to address three different questions: **(1)** do blind children use their fingers to count and to show quantities? If vision is critical for the development of finger-number interactions, then blind children would not be expected to use their fingers spontaneously to resolve the numerical tasks of the second test battery. If, on the contrary, finger-number interactions may emerge from proprioceptive cues (i.e., the perception of finger movements), then blind children should use their fingers as often as sighted children do; **(2)** if blind children do not use or use their fingers less, do they even achieve the same level of performance as sighted children? If finger-counting is a necessary tool for the emergence of an efficient counting behavior, then blind children should be less accurate than sighted children in the second test battery. On the contrary, if the counting behavior emerges from other strategies, then blind children should achieve the same level of performance; **(3)** do blind children use their fingers in the same way as their sighted peers when they are explicitly required to count and to show quantities with their fingers (in the third test battery)? Given that canonical finger-digit configurations are culture-dependent (Butterworth, 1999b; Ifrah, 1981; Wiese, 2003a, 2003b), vision was expected to play a critical role in the acquisition (by imitation) of these canonical configurations. Therefore, blind children were expected to use their fingers (to count and to show numerosities) in a different way than sighted children.

2. Method and results

2.1 Participants

Sixteen blind children (7 girls and 9 boys) participated in the study. The results for two blind boys were discarded: one because his IQ was too low (< 72) and the other one because he had lost his vision after the second year of his life. The remaining 14 children (7 girls and 7 boys; 11 right-handed, 1 left-handed and 2 ambidextrous) were all born with visual impairment and did not have any other disability. Nine children came from Belgium and five from Canada. The children were between 7 and 13 years old (*M* = 9.9 ± 2.09) (see Table 9-1).

Table 9-1. Characteristics of the children

Blind Children							***Sighted Children***					
Name	*Gender*	*Country*	*Age*	*IQ*	*Handedness*	*Cause of blindness*	*Name*	*Gender*	*Country*	*Age*	*IQ*	*Handedness*
Cat	F	B	7.2	105.6	L	Unknown: adopted child	Emi	F	B	6.8	119.6	R
Sha	F	B	7.10	94.4	A	Retinopathy of prematurity	Lei	F	B	6.10	100.0	R
Sim	M	B	8.5	122.4	A	Unknown: adopted child	Mat	M	B	8.3	105.6	R
Eli	F	B	9.11	108.4	R	Retinopathy of prematurity	Mar	F	B	9.5	108.4	R
Ana	F	B	10.0	122.4	R	Retinopathy of prematurity	Nat	F	B	9.7	114.0	R
Sum	F	B	10.8	94.4	R	Eyeball atrophy	Bia	F	B	10.6	116.8	R
Ill	M	B	12.7	114	R	Glaucoma	Abd	M	B	12.3	102.8	R
Sal	M	B	12.11	80.4	R	Retinopathy of prematurity	Thé	M	B	12.10	94.4	R
Sel	M	B	13.5	94.4	R	Leber’s optic neuropathy	Den	M	B	13.10	100.0	A
Kor	F	C	8.9	102.8	R	Retinopathy of prematurity	Gre	M	C	8.5	122.4	R
Mat	M	C	9.5	97.2	R	Unknown malformation	Pie	M	C	10.11	122.4	R
Sil	F	C	7.7	105.6	R	Glaucoma	Pau	F	C	6.0	111.2	L
Ant	M	C	9.11	100	R	Retinopathy of prematurity	Bap	M	C	9.11	102.8	R
Lou	M	C	12.3	108.4	R	Retinopathy of prematurity	Con	F	C	12.8	122.4	R

Note. M = male; F = female; B = Belgium; C = Canada; L = left-handed; R = right-handed; A = ambidextrous

In order to take into account the cultural differences in the way children use their fingers to count and to show quantity (Butterworth, 1999b; Sato & Lalain, 2008), fourteen sighted children (12 right-handed, 1 left-handed and 1 ambidextrous) were selected to match the blind children on the nationality criterion. In addition, and as shown in Table 9-1, they were also matched on IQ, gender and age. IQ was estimated by two verbal subtests of the Wechsler Intelligence Scale for Children-III (Wechsler, 1996): the Similarity and Information subtests. As these subtests were quite representative of the verbal scale, the mean of their standard scores was calculated to estimate verbal IQ. Note that no performance subtest was administered because of the visual component of all these tasks. Mann-Whitney tests showed that the two groups did not differ in terms of age ($U = 93.5$, $p > .8$) or IQ estimation ($U = 66$, $p > .1$)

All test procedures were approved by the Research Ethics Boards of the Centre for Interdisciplinary Research in Rehabilitation of Greater Montreal (CRIR). Written informed parental consent was obtained for all the children. The sighted children were blindfolded during the tasks in order to place them in conditions similar to those of the blind participants.

2.2 Test Battery 1: General cognitive abilities

In this first battery, general cognitive abilities were evaluated to determine whether both groups of children had the level of performance required to undertake the counting tasks of the second test battery. In order to explore the presence of group differences, Mann-Whitney tests were performed with group as a grouping variable and the tasks' score as a dependent variable. We also ran t-tests for independent samples (with Bonferroni's correction) with the same variables. As these two analyses systematically led to the same conclusions, we only reported the exact statistics of the Mann-Whitney *U* test (because this test was more adapted to the not-normal distribution of our data). For the sake of comprehension, we nevertheless reported the mean scores of the two groups.

2.2.1 Working memory

Children's working memory capacities were evaluated because every task of the second test battery were very demanding for the working memory process.

Two different tests were used: a listening span task (Siegel & Ryan, 1989) and a pseudo-word repetition task. The listening span test was administered to assess the central executive component of the working memory. In the French adaptation of the test (Censabella & Noël, 2008), the experimenter read a set of sentences (from two to four) to the children who were instructed first to judge the truth of the sentences, and then to recall the last word of all the sentences in the set. The test comprised a total of 36 sentences (four sets of two sentences, four sets of three sentences and four sets of four sentences). Half the sentences were true (e.g., "*les abeilles fabriquent du miel*" – "bees make honey"), the other half were false (e.g., "*les girafes ont un long nez*" – "Giraffes have long noses"). The percentage of correct responses (i.e., the total number of items correctly recalled divided by the total number of items) was calculated for each child.

The pseudo-word repetition task was conducted in order to assess the phonological loop of the working memory. It is part of the standardized French BELEC battery (Mousty, Leybaert, Alegria, Content & Morais, 1994). The test included two pseudo-word lists differing in terms of syllabic complexity level (CV for the first list and CCV for the second list[2]). Each list comprised 4 one-syllable items, 4 two-syllable items, 4 three-syllable items, 4 four-syllable items and 4 five-syllable items. The span measure corresponded to the longest set for which all the target pseudo-words were correctly recalled.

Scores on the listening span test did not differ significantly between the two groups, $U = 92.5$, $p > .8$: blind children correctly recalled 77.62% of the words ($SD = 16.07$) and sighted children 77.46% ($SD = 11.83$). In contrast, when the children were asked to recall pseudo-words, the blind children had significantly better span scores ($M = 9.29 \pm 0.82$) than the sighted children ($M = 8.50 \pm 0.65$), $U = 47.5$, $p < .05$. The scores were nearly at the ceiling for CV syllables (only one of the sighted children made an error in this list), but were lower for CCV syllables.

2.2.2 Addition

In this task, children were asked to solve 8 additions with single-digit numbers. These additions were drawn from the Tedi-Math Battery (Van Nieuwenhoven, Grégoire & Noël, 2001) but were orally rather than visually presented. Each correct response was credited with 1 point, giving a maximum score of 8 points. These additions were chosen in order to examine whether children can deal with single-digit numbers, which are the target numbers of every task of the second test battery.

Scores on the addition test ranged from 3 to 8 ($M = 7.29 \pm 1.54$) in the blind group and from 6 to 8 in the sighted group ($M = 7.57 \pm 0.76$). The Mann-Whitney test did not show any significant group differences on this task, $U = 96$, $p > .9$.

[2] CV syllables consist of one consonant and one vowel, while CCV syllables consist of two consonants and one vowel.

2.2.3 Finger discrimination

The finger discrimination test was drawn from the NEPSY battery (Korkman, 2000). In this task, one or two fingers of each hand were touched by the experimenter and the children were asked to show the touched finger(s) with the index of the opposite hand. The procedure was first applied to the dominant hand, then to the non-dominant hand. The task comprised 14 items (10 "one-touched finger" items and 4 "two-touched fingers" items) on each hand. One point was given for each correctly recognized finger, giving a maximum score of 36. Children were submitted to this test in order to be sure that children had no difficulties in recognizing their fingers.

Again, blind children did not differ significantly from sighted children in this task ($M = 34.07 \pm 2.30$ and 32.14 ± 3.96 for blind and sighted children respectively), $U = 70.5$, $p > .1$.

2.2.4 Ordered-sequence knowledge

To assess the knowledge of the counting word sequence, children were asked: **(1)** to count orally as far as possible (they were stopped at 31 if they got that far); **(2)** to count up to 9 and up to 6; **(3)** to count on from 3 and from 7; **(4)** to count from 5 to 9 and from 4 to 8; and **(5)** to count down from 7 and from 15. All these items were drawn from the Tedi-Math Battery (Van Nieuwenhoven et al., 2001). The knowledge of three other ordered sequences were also evaluated: children were required to recite the days of the week, the months of the year, and the letters of the alphabet. One point was given for each correctly recited sequence. These different questions were asked to children because the knowledge of the ordered series is essential to perform one task of the second test battery (i.e., the ordered series manipulation task).

Statistical analyses showed that knowledge of the numerical chain was equivalent in both groups (*M* = 9.43 ± 1.16 and 9.86 ± 0.36 for blind and sighted children respectively), $U = 82$, $p > .3$. Concerning the knowledge of the three ordered sequences, one sighted child systematically failed to recite the days of the week, the months of the year and the letters of the alphabet. Otherwise, performance was equivalent in both groups.

2.2.5 Conclusion of the test battery 1

In summary, both groups of children had normal scores on all of the tasks so that blind and sighted children were assumed to be able to undertake the tasks of the second test battery. Besides, these results also suggest that the two groups were overall well balanced. Indeed, there was only one significant difference between the blind and the sighted children on the general cognitive abilities measures: blind children performed better than sighted ones in the pseudo-word repetition task, which is in line with the superior verbal memory skills already observed in congenitally blind adults (Amedi, Raz, Pianka, Malach, & Zohary, 2003).

2.3 Test Battery 2: Spontaneous finger use

The second test battery was devised to assess the spontaneous use of fingers in different numerical contexts. Children were thus not given any information about the efficiency of using either a finger-counting or a finger-montring strategy but were free to use any strategy they wanted to. All the tests were nevertheless designed in such a way that finger use could make their realization easier (by helping the children to keep track of intermediary results or by providing an external support for the working memory load). In order to examine the two first questions (i.e., **(1)** do blind children use their fingers to count and to show quantities; **(2)** do blind children achieve the same level of performance as sighted children), the experimenter assessed the children's performance by calculating the score and the number of times children used their fingers to solve the task. In this battery, the conventionality of the finger-counting behavior was not assessed. So, any cue indicating some finger movements was scored as a behavioral indicator of the use of fingers.

2.3.1 Counting words

In this task, children listened to five short stories of between 193 and 209 words ($M = 202.6 \pm 7.5$) and were required to count, for each story, the number of appearances of a specific target word. The target words were *mouche* (i.e., fly), *femme* (i.e., woman), *Georges* (i.e., Georges), *princesse* (i.e., princess) and *miséreux* (i.e., miserable). The correct answers were 7, 5, 6, 3 and 8 respectively. Participants were explicitly instructed not to count aloud. Each correct response was credited with 1 point. Moreover, to ensure that children were attentive to the story, two questions were asked about the content of each story, and a supplementary point was awarded if the two answers were correct. The maximum score was thus 10. As the counting words task required children to perform two tasks simultaneously (understanding the content of the story and counting the number of utterances of a target word), the use of fingers was expected to alleviate the working memory load by helping children to keep track of the target words already counted.

In this task, blind children used their fingers significantly less often than their sighted peers ($M = 2.86$ for blind and 6.57 for sighted), $U = 60$, $p = .05$, but nevertheless achieved the same level of performance, $U = 91$, $p > .7$ (see Fig. 9-1). The finger-counting strategy was only used by four blind children (Sha, Ana, Ill and Ant) as compared to ten sighted children.

2.3.2 <u>*Two-syllable counting*</u>

Children were exposed to 10 series of two phonetically dissimilar syllables (*/pa/* and */ji/*[3]) and were instructed to count the number of */pa/* and the number of */ji/* sounds in a sequence (e.g., "/pa/, /ji/, /ji/, /pa/, /pa/, /ji/" = 3 /pa/; 3 /ji/). The syllables were played every second. The total number of syllables ranged from 6 to 10; the number of */pa/*s ranged from 3 to 7 and the number of */ji/*s from 2 to 6. As the two-syllable counting task involves counting two series, finger-counting was expected to help the children not to lose track of what had already been counted.

In this task, blind children performed less well, $U = 51$, $p < .05$, and used their fingers substantially less often than the sighted controls ($M = 3.08$ for blind and 8.57 for sighted), $U = 41$, $p < .01$ (see Fig.9-1). Indeed, the finger-counting strategy was only used by four blind children (Ana, Ill, Sal and Ant), as compared to twelve sighted children. Note that one blind child (Sha) was discarded from the analysis because she misunderstood the instructions. Blind children often used a strategy that is very demanding on the working memory, namely a double counting strategy: they mentally keep track and update the count on two parallel counting sequences (e.g., 1 /ji/, 0 /pa/; 1 /ji/, 1 /pa/; 1 /ji/, 2/pa/, etc.). Interestingly, however, the blind children who used the finger-counting strategy were also those who achieved the highest level of performance ($M = 8.5$ for the children who used their fingers and 5 for the children who did not use them). In contrast, our data did not allow establishing the inverse relationship: the sighted children who did not use their fingers were not the children who achieved the lowest level of performance ($M = 8.5$ for the children who did not use their fingers and 8.42 for the children who used their fingers).

[3] The consonants */p/* and */j/* are articulated differently: */p/* is plosive, while */j/* is an approximant. They also differ in the place of articulation: */p/* is labial and */j/* dorsal. The vowels */a/* and */i/* differ in terms of the vowel height: */a/* is open and */i/* closed.

2.3.3 Counting with articulatory suppression

Children were required to count the number of times the experimenter touched their shoulder. In order to block the articulatory rehearsal process, children were required to utter nonsense words ("*bla bla bla*") while counting. The touching rhythm was random, and the number of touches ranged from 3 to 10. Finger-counting was therefore expected to be a helpful way of keeping track of the number of touches made by the experimenter.

In the counting with articulatory suppression task, blind children tended to perform less well, $U = 55$, $p = .07$, and used their fingers substantially less often than the sighted children, $U = 30.50$, $p < .001$ ($M = 2.15$ for blind and 8.57 for sighted) (see Fig. 9-1). Indeed, only three blind children (Ana, Sil and Ant) spontaneously used the finger-counting strategy whereas twelve sighted children did so. As in the previous task, the blind children who used the finger-counting strategy were the children who achieved the highest level of performance ($M = 9.67$ for the children who used their fingers and 6.9 for the children who did not use their fingers). In contrast and as in the previous task, our data did not allow establishing that the sighted children who did not use their fingers were also the children who achieved the lowest level of performance ($M = 9$ for the two sub-groups of sighted children).

Sha was once again discarded from the analysis because she misunderstood the instructions.

2.3.4 Enumeration questions

In this test, children were required to name a specific number of exemplars from 10 different target categories (5 boys' names, 4 jobs, 6 girls' names, 9 animals, 3 colours, 7 fruits, 4 toys, 8 household objects, 5 foods and 6 items of clothing). The enumeration question task thus required the children to: **(1)** retrieve information from the verbal long-term memory; **(2)** name this information; **(3)** keep track of the number of items already retrieved; **(4)** go on retrieving information from the long-term memory content; **(5)** stop the process as soon as the target number of exemplars had been reached. In this task, the use of fingers was expected to alleviate the load of the working memory by helping children to keep track of how far they had got.

In the enumeration questions task, the accuracy scores were the same for the two groups, $U = 89$, $p > .6$, but the finger-counting strategy was used significantly less often by blind ($M = 0.86$) than by sighted children ($M = 7.71$), $U = 11$, $p < .001$, (see Fig. 9-1). Only three blind children used the finger-counting strategy: two (Ana and Ant) used it to count beyond 6; one (Ill) used it after he had made an error. In the sighted group, on the other hand, all the children except one used this strategy.

2.3.5 Ordered series manipulation

Children were asked 10 questions requiring the manipulation of three ordered sequences (i.e., the letters of the alphabet, the months of the year, and the days of the week), for example, "what's the name of the seventh month of the year?", "how many letters are there between A and H?", "what's the name of the fourth day of the week?" Knowledge of these three sequences had previously been assessed by asking the child to recite them (see section 2.2.4). Here too, finger use was expected to facilitate the manipulation of the sequences.

Blind and sighted children's performances were equivalent, $U = 87$, $p > .8$, whereas their strategies for carrying out the task were not. As in the previous tasks, blind children relied on their fingers significantly less often than sighted children ($M = 1.71$ for blind and 7.54 for sighted), $U = 16.5$, $p < .001$ (see Fig. 9-1): five blind children used their fingers occasionally (Sha, Ana, Ill, Sal and Ant), but twelve sighted children used them regularly. Note that one sighted child was discarded from the analysis due to her inability to recite the days of the week, the months of the year and the letters of the alphabet (see section 2.2.4).

2.3.6 Numerosity communication

Five oral numerals (1, 2, 4, 7 and 8) and five sound sequences (3, 5, 6, 9 or 10 sounds) were presented through headphones and the children were instructed to help the experimenter guess the number/numerosity heard by using a non-verbal strategy. As writing and speaking were not allowed, the finger-montring strategy was expected to be used to give an iconic representation of the numbers/numerosities presented.

In the numerosity communication task, sighted children performed at ceiling whereas blind children made a few errors. However, this difference failed to reach significance, $U = 84$, $p > .1$. Moreover, both groups of participants used their fingers equally often, $U = 88$, $p > .4$ (see Fig. 9-1). In this task, all the blind children used their fingers to show the numerosity, but two changed their strategy in the course of the task: Eli replaced the finger-montring procedure by the production of sounds or gestures, and Sel used the index finger to draw the numbers. In the sighted group, two children never used the finger-montring strategy: one moved the head to draw the Arabic numbers, and the other used the hands to represent the shape of the Arabic numerals.

2.3.7 Conclusion of the test battery 2

The second test battery demonstrated that blind children used the finger-counting strategy significantly less frequently than sighted controls. In each task, there were only three or four blind children using their fingers. Interestingly, these children were almost always the same: Ana, Ill and Ant. In order to examine the potential influence of variables like IQ and age on frequency of finger-counting, we ran an additional stepwise regression analysis with group, IQ, age and pseudo-word recall performance as independent variables and the mean number of finger use (over the 5 enumeration tasks) as the dependent variable. The results of this analysis showed that the factor group was significant ($p < .001$) whereas the factors IQ ($p > .1$) age ($p > .2$), and pseudo-word recall ($p > .8$) were not.

Both groups of participants nevertheless achieved quite similar levels of performance in three of the five counting tasks (i.e., counting words, enumeration questions and ordered series manipulation). In the two other tasks (i.e., two-syllables counting and counting with articulatory suppression), however, the lack of finger use appeared to prevent blind children from achieving the same level of performance as sighted participants. Accordingly, blind children who used their fingers in these two tasks were the one who achieved a high level of performance.

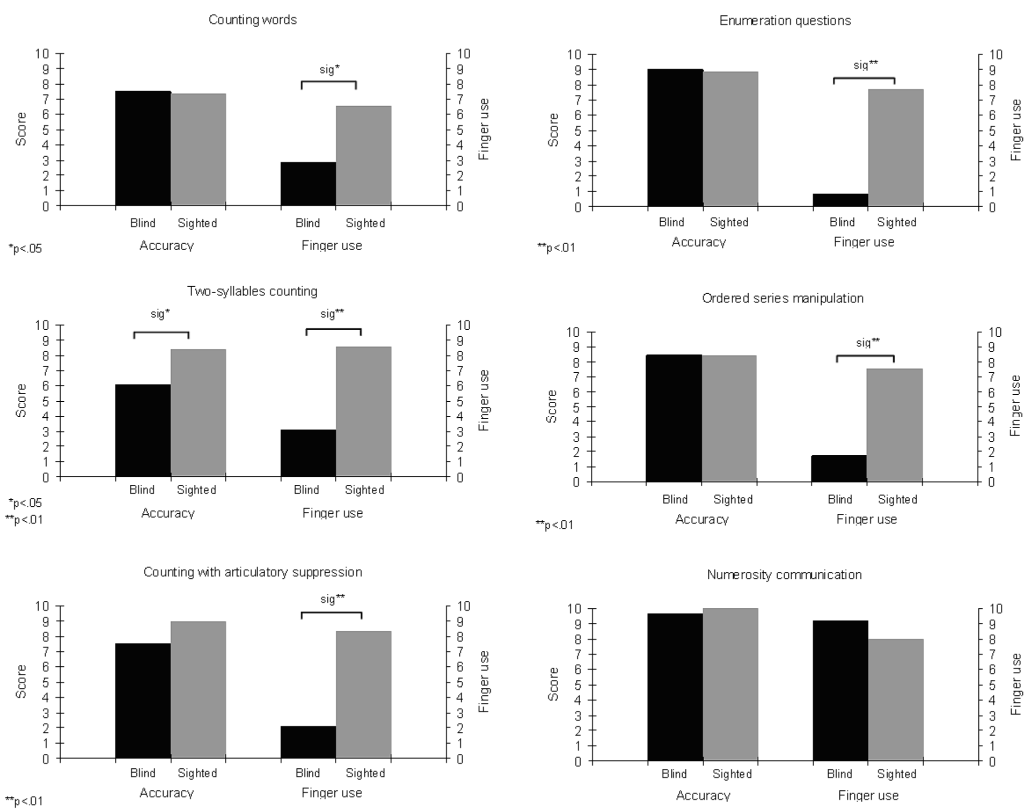


Fig. 9-1. Results of the test battery 2.

Moreover, as fingers were equally used by both groups in the numerosity communication task, blind children appeared to be aware that their fingers could be used to give an iconic representation of numbers. However, it is interesting to note that the lack of vision led blind participants to make a few errors while sighted ones did not make any.

2.4 Test Battery 3: Canonicity of the finger-based representations

This third battery was devised to assess the conventionality level of the children's finger-counting and finger-montring strategies. Children were therefore explicitly instructed to use their fingers either to count or to show a quantity.

2.4.1 Finger-counting

Children were presented with 10 sequences of tones and were explicitly asked to count the number of sounds they heard, using their fingers. The sequences comprised from 1 to 10 tones played at the rate of one per second. Each correct response was credited with 1 point and the conventionality of the finger-counting strategy of each child was assessed using three criteria. As Belgian and Canadian sighted children typically counted by raising their fingers in the order "thumb, index finger, middle finger, ring finger and little finger" of the dominant hand (for numbers 1 to 5) and then the same order of the non-dominant hand (for numbers 6 to 10), the following criteria were used: **(1)** the "raising" criterion (did the child raise his or her fingers to count?); **(2)** the "stable-order" criterion (did the child use the fingers of each hand in the conventional order?); and **(3)** the "laterality" criterion (did left-handed children start counting with their left hand and right-handed children with their right hand?) (Di Luca et al., 2006; Sato & Lalain, 2008). Compliance with each criterion (for each child and each counting sequence) was assessed by a dichotomized scale (0 = non-compliance and 1 = compliance).

The data demonstrated that blind children behaved in a less stereotypical way than sighted children. Indeed, whereas all the sighted children raised their fingers to count, only six blind children did so, $U = 25$, $p < .001$. The others used a kind of tactile stimulation: they drummed their fingers on the table, used one of their hands to touch and count the fingers of their other hand, or pinched the extremities of their fingers. The blind and sighted groups also differed significantly on the laterality criterion, $U = 47$, $p < .05$ (one sighted and two blind children were excluded from this analysis as they were ambidextrous). In the sighted group, only one child started counting with his non-dominant hand. Otherwise, right-handed children started counting with their right hand, and left-handed children started counting with their left hand. In the blind group, in contrast, only six children always started counting with their dominant hand. Finally and most importantly, blind children used their fingers in a less standard order than sighted children, $U = 56$, $p < .01$ (see Fig. 9-2). Eli counted by using a left-to-right oriented finger-digit mapping, namely from the little finger to the thumb of her left hand for the numbers 1 to 5, and from the thumb to the little finger of her right hand for the numbers 6 to 10. Kor and Sil started counting with their index finger and finished the counting sequence on their thumb. Mat used only one hand to count up to 6 and up to 7. Ill counted by using his two hands alternately, following a specific order (i.e., right forefinger, left forefinger, right middle finger, left middle finger, and so on). Sal also counted using his two hands alternately (from the little finger of the right hand to the thumb of the left hand). It is worth noting that the two blind children who used alternate counting (Ill and Sal) were not ambidextrous.

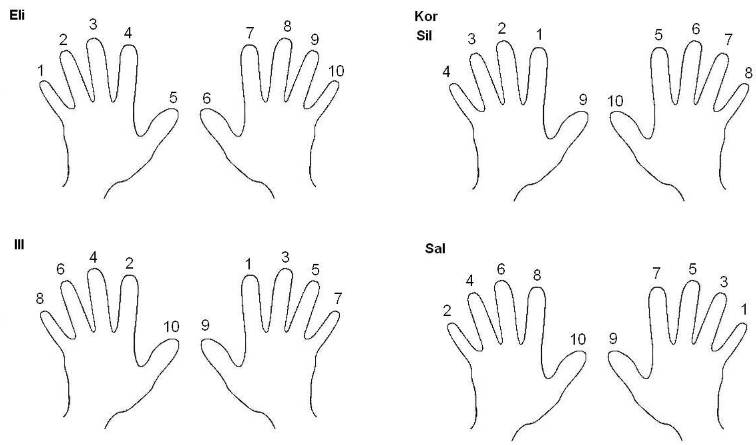


Fig. 9-2. The unusual finger-counting orders used by five blind children.

Interestingly, some blind children changed their strategy in the course of the task: Sil, for example, often started counting with the index finger but sometimes counted following the typical Canadian order. Conversely, every sighted child used the typical Belgian/Canadian finger-counting order (i.e., from the thumb to the little finger of one hand for numbers 1 to 5, and then from the thumb to the little finger of the other hand for numbers 6 to 10).

2.4.2 Finger-montring

The experimenter read 10 verbal numerals (from 1 to 10, randomly presented) and children were asked to use their fingers to show the numerosity corresponding to these verbal numerals. Each correct response was credited with 1 point and the canonicity of the finger configurations (for each child and for each numerosity) was assessed on a dichotomized scale (0 = “non-canonical configuration” and 1 = “canonical configuration”). The configurations considered canonical are shown in Figure 9-3.

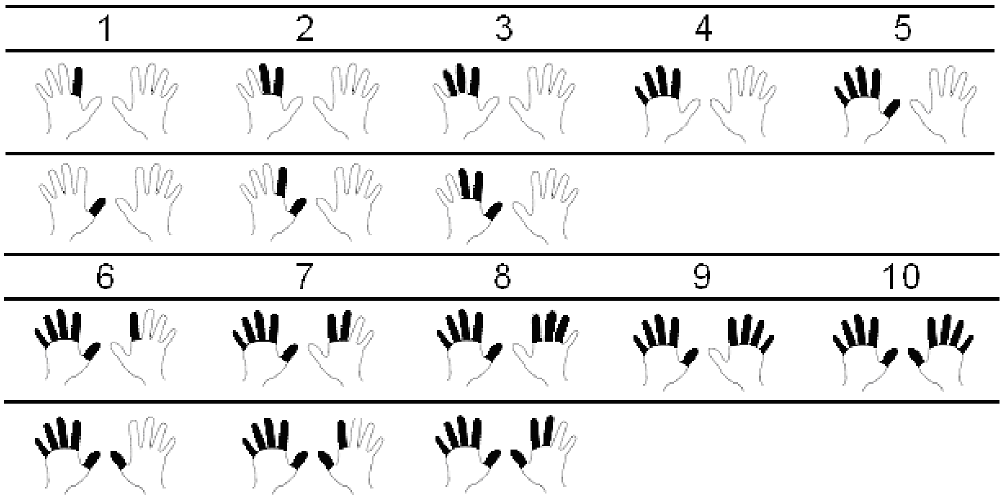


Fig. 9-3. Canonical finger-montring configurations for numbers 1 to 10. Darkened fingers correspond to raised fingers. For some numbers (1, 2, 3, 6, 7 and 8), two configurations were considered to be canonical, but only for the Canadian children. For the Belgian children, only the configurations represented on the first line were considered as canonical.

When required to show quantities by using their fingers, blind children again behaved differently to their sighted peers, $U = 58$, $p < .05$. Although eleven sighted children used canonical configurations to represent the numbers from 1 to 10, only five blind children did so. Mat represented the numbers 4 and 9 (4 + 5) with the fingers used for the counting behaviour (i.e., 4 was represented with the thumb, the index, the middle and the ring fingers). The other blind participants often represented even numbers by using both hands, in a symmetric way (see Fig. 9-4): Sel represented the number 2 by using both his thumbs; Sha represented the number 4 with the thumb and the forefinger of both her hands; Ill and Sil used their two forefingers, their two middle fingers and their two ring fingers to give an iconic representation of the number 6, etc. However, all the children used the canonical configurations of numbers 5 and 10 (one and two opened hands, respectively).

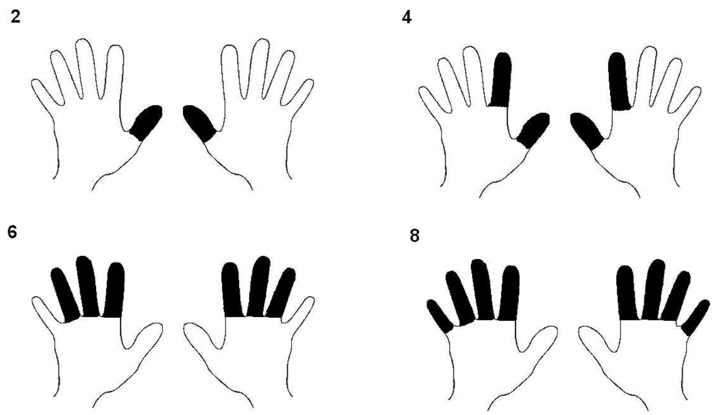


Fig. 9-4. Illustration of the symmetric finger-montring strategy used by blind children in the finger-montring task.

2.4.3 Conclusion of the test battery 3.

Taken together, the results of the third battery revealed that blind children used their fingers in a less canonical way than sighted children, both to count and to give an iconic representation of numbers. Interestingly, blind children did not systematically represent numbers larger than 5 by using a full hand representation. Instead, they used a kind of "symmetric" montring, indicating that blind children's finger-montring habits did not systematically exhibit the sub-base five property.

3. General discussion

Developmental, behavioral, neuropsychological and neuro-imaging studies have reported the existence of a close connection between number processing and finger representation. Since fingers provide a physical counterpart to number words (Andres et al., 2008), it has been suggested that they could facilitate the assimilation of the counting words sequence, help children to keep track of the number words while counting (i.e., finger-counting) and provide a tool for communicating numbers (i.e., finger-montring) (e.g., Fayol & Seron, 2005). Moreover, as digital and numerical processing still interact in adulthood, some authors have suggested that children's finger-counting and finger-montring habits may change the way numbers are mentally represented in adults (Di Luca et al., 2006; Pesenti et al., 2000; Sato et al., 2007; Zago et al., 2001), leading to a "finger-numeral representation".

In the present study, we investigated whether finger-counting and finger-montring behaviors may be shaped and influenced by visual experience. Our data provided responses to our three starting theoretical questions: **(1)** while vision is not necessary to the elaboration of numerical abilities within (Ferrand, Riggs, & Castronovo) and outside (Castronovo & Seron, 2007a) the subitizing range, vision appeared to play a critical role in the elaboration of the finger-number representation. Indeed, although blind children relied on the finger-montring strategy as often as sighted children, they appeared to use the finger-counting strategy less spontaneously; **(2)** fingers are a useful but not necessary tool for the development of the counting behavior. Indeed, although blind children performed less well than their sighted peers in the counting with articulatory suppression task and in the two-syllables counting task, they achieved the same level of performance in the three other counting tasks (i.e., counting words, enumeration questions, ordered series manipulation), thus indicating that counting behavior has emerged in these children; **(3)** vision plays a critical role in the acquisition of the culture-specific finger configurations. Blind children's finger-counting procedures and finger-montring configurations were indeed less canonical than those used by the sighted participants. Although blind children preserved the one-to-one correspondence between the to-be-counted set and the finger used to represent it, they often counted through touching or pressing their fingers in an atypical order which does not necessarily exhibit the sub-base-five property or the stable-order principle.

As the two groups performed at a similar level in the finger discrimination task, these conclusions cannot merely be attributed to a difference in finger discrimination capacity. Rather, blind and sighted children may develop an understanding of numbers through different strategies. Using the fingers to keep track of the counted elements or to make analogue representations is common among sighted children, but blind children probably have to develop strategies to compensate for their lack of vision. As suggested by previous research (Raz, Striem, Pundak, Orlov & Zohary, 2007; Röder, Rösler & Neville, 2001; Siegel & Ryan, 1989; Stankov & Splisbury, 1978), and by their better span scores at the pseudo-word repetition task (see section 2.2.1), it is possible that blind children rely much more on their auditory working memory than sighted children to manipulate numbers (see Cornoldi, Tinti, Mammarella, Re, & Varotto, 2009 for similar results with adults in a mental imagery task). In the same way as traces of the finger-counting behavior have been found in sighted adults' numerical cognition (Andres et al., 2007; Badets et al., 2010; Di Luca et al., 2006; Di Luca & Pesenti, 2008; Domahs et al., 2010), traces of the working memory use have been found in blind adults' numerical cognition. Indeed, although the behavioral data of a recent EEG study demonstrated that blind and sighted adults represented numbers through a similar spatial code, different neurophysiological correlates have been found to underlie number manipulation in the two groups (Sallilas et al., 2009). In this study, participants had to react as quickly as possible to an auditory target presented either in the left or in the right auditory space after a spoken number word had been presented as a prime. In both groups of participants, small spoken number words generated a spatial shift of attention towards the left auditory space and large spoken number words generated a spatial shift of attention towards the right auditory space (i.e., the SNARC effect; Fischer et al., 2003). In other words, small numerical primes facilitated the detection of left auditory target while large numerical primes facilitated the detection of right auditory target. However, while the amplitude of the sensory N100 component was modulated by congruency (i.e., small primes – left auditory target; large primes – right auditory target) only in the sighted group, the amplitude of the cognitive P300 was modulated by congruency only in the blind group. As the P300 reflected higher cognitive processes than the sensory N100, it was assumed that the lack of vision leads blind people to manipulate numbers in a higher cognitive way, relying much more on verbal working memory than on sensory-motor processes. Together with our observations, this finding suggests that congenitally blind individuals may compensate for their lack of vision by relying on the phonological loop of their verbal working memory rather than on the online use of fingers to keep track of numbers. Accordingly and interestingly, blind children performed less well than the sighted controls in the two tasks that involved interference with the working memory process. In the counting with articulatory suppression task, the articulatory rehearsal process was blocked while in the two-syllable counting task, the presentation rhythm of the two syllables was so fast that keeping track of the two counting sequences was really demanding. As learning basic arithmetic abilities is often very demanding for a child’s working memory, one may wonder whether training the finger-counting behavior of blind children could improve their numerical abilities (see Gracia-Baffalluy & Noël, 2008 for similar results with sighted children). Moreover, as finger discrimination appeared to be a good predictor of sighted children’s arithmetic abilities (Fayol et al., 1998; Marinthe et al., 2001; Noël, 2005), it could be interesting to test whether working memory capacity might be a good predictor of blind children's arithmetic abilities. In our experiment, the first battery was designed to determine whether both groups of children had the level of performance required to undertake the counting tasks of the second test battery. The second test battery, on the other hand, was designed to examine whether blind and sighted children used spontaneously their fingers to solve the enumeration tasks. Therefore, the tests created were not sensitive enough to examine this association between working memory and arithmetic abilities.

Our finding that blind children use their fingers less frequently than sighted children, combined with the observation that blind and sighted adults manifest the same behavioral SNARC effect (Castronovo & Seron, 2007b; Sallilas et al., 2009), suggests that the association between numerical and spatial representation is not uniquely attributable to finger-counting habits as postulated by some authors (Fias & Fischer, 2005; Fischer, 2006, 2008). Instead, as blind participants are Braille readers and as Braille is read from left-to-right, our finding supports the idea that the SNARC effect may be determined by the orientation of reading habits (Dehaene et al., 1993).

Moreover, as mentioned in our introduction, two different views have been proposed to account for the origin of the interactions between numbers and fingers: the functionalist (Butterworth, 1999, 2005) and the redeployment (Anderson, 2010; Penner-Wilger & Anderson, 2010) hypotheses. Because the present paper suggests that blind children do not use their fingers to develop the concept of numbers, it could be interesting to examine whether blind individuals show activation in the finger neural network during tasks requiring the representation of numbers. According to the functionalist view, it is the use of the fingers to represent numbers during numerical development that is the key element in the observation of the interactions between numbers and fingers. These interactions should therefore not manifest in blind people who did not use the finger-counting strategy during childhood. Conversely, according to the redeployment hypothesis, individuals without finger agnosia but who did not use the finger-counting and finger-montring strategy during infancy should nevertheless show traces of a numerical finger-based representation while performing numerical tasks in adulthood. So, blind adults, although they did not use their fingers to process numbers during infancy, should show: **(1)** greater reaction times while comparing a pair of digits which contains a least one number larger than 5 (Domahs et al., 2010); **(2)** increased corticospinal activity of hand muscles while performing a parity judgment task (e.g., Sato et al., 2007). We therefore argue that further investigation of numerical processing in blind adults may help to disentangle the functionalist and the redeployment hypotheses.

CHAPTER 10

Summary and Perspectives II

1. Blindness and interactions between numbers and space

In the first experiment of Chapter 8, early blind, late blind and sighted controls were asked to report whether auditory numerals were smaller or larger than 5 by pressing one of two response keys placed in each hand. The verbal numerals were centrally presented in order to not exacerbate differences in response selection by inducing a Simon effect (Daar & Pratt, 2008). The task was carried out either with hands parallel or with hands crossed (i.e., the left hand placed in the right external space). Results demonstrated that late blind and sighted controls showed a SNARC effect regardless of hand posture, while early blind displayed a SNARC effect only in the parallel posture and a reversed SNARC effect in the crossed posture. This study therefore provided a compelling demonstration that early visual experience drives the development of an external coordinate system for the visuo-spatial representation of numbers since early visual deprivation shapes the SNARC effect from an external- to a hand-centred coordinate system. Moreover, as congenitally blind adults also showed a reversed Simon effect in a crossed-hands paradigm (Röder et al., 2007) our results added to previous evidence that the similarity between the Simon and the SNARC effects was more than a mere analogy. In the second experiment of Chapter 8, participants were asked to judge the parity status of the auditory numerals ranging from 1 to 9 (except 5). In this task, EB, LB and sighted controls showed a classic SNARC effect in the crossed as well as in the uncrossed condition.

Because the lack of early vision prevents the development of an external coordinate system, it is normal that EB did not remap numbers onto an external frame of reference. The manifestation of this lack of external remapping (i.e., reversed SNARC effect in the crossed posture) was only observed in the comparison task but was not observed in the parity judgement task. In this sense, our data support the idea that different types of spatial information (visuo-spatial vs. verbal-spatial) are engaged differently in different tasks (comparison vs. parity judgment). Because the development of an external coordinate system is a visuo-spatial phenomenon (Röder et al., 2007), it is normal that blind people show, in crossed-hands posture: **(1)** a reversed SNARC effect in the task that primarily depends on visuo-spatial associations (i.e., magnitude comparison task); **(2)** a classic SNARC effect in the task that primarily requires verbal associations (i.e., parity judgment tasks).

Since our sighted participants showed a classic SNARC effect in the crossed-hands posture, our data also complemented those reported by Dehaene et al. (1993) and by Fischer and Hill (2004) but were not in accordance with those reported by Wood et al (2006). In Fischer and Hill's study (2004), numbers were presented auditorily. In Experiment 1, visual control over hands was allowed. For both uncrossed and crossed hand assignments, the SNARC effect was significant. However when visual control over hands was precluded, results were slightly different. When the hand assignment was crossed, the SNARC effect was significant, in accordance with Dehaene et al. (1993), but when the hand assignment was uncrossed, the SNARC effect disappeared. The authors attributed the non-significant SNARC effect to the stronger tactile and proprioceptive stimulation induced by hand-crossing, which may partially substitute for the lack of visual perception and help to build up a spatial reference frame for responses.

According to Wood et al. (2006), two relevant spatial frames of reference are available in SNARC tasks: the representational and the hand-based visuo-spatial frame of reference. The SNARC slopes are therefore a weighted sum of the activation of both coordinate systems. As pointed out by Cho and Proctor (2003), the mapping of stimulus-response compatibility depends on which frames of reference are activated in each experimental set: when hands are crossed, there is a conflict between representational and hand-based coordinates. If the saliency of both coordinates is approximately equal, a null SNARC effect is observed, since hand-based and representational associations are complementary. If the weights of both coordinates are unequal, a SNARC effect is observed in the direction of the coordinate system which is the most salient. In order to account for the fact that a classic SNARC effect was found in the studies of Dehaene et al. (1993) and Fischer and Hill (2004) but not in their study, Wood et al. (2006) proposed two interrelated processes. The first process is related to *the change from congruent to incongruent hand assignment.* While a fixed association of response keys could reduce the saliency of a hand-based frame of reference (Dehaene et al., 1993), the change of response assignments could increase it and therefore reduce the strength of the SNARC effect (Wood et al., 2006). While the change of response assignments could explain the divergences found between the studies of Wood et al. (2006) and Dehaene et al. (1993), the change of instructions could not account for our data and for the results of Fischer and Hill (2004). Indeed, both crossed and uncrossed hand assignments were tested in these two studies. So, Wood et al. (2006) postulated that another factor was able to reduce the saliency of the hand-based frame of reference. According to Wood et al. (2006), this could be the *saliency of the auditory information for the construction of the spatial context.* In our study as well as in the study by Fischer and Hill (2004), auditory number words were presented to blindfolded sighted participants. According to Wood et al. (2006), visual feedback of the response assignment is an important factor determining the direction of the SNARC effect in crossed-hands posture. Therefore, if the saliency of visual input regarding a hand-based coordinates is high, both hand-based and hand-independent frames of reference could influence the SNARC effect. In contrast, if the saliency of the visual input is low, the hand-independent frame of reference could influence the SNARC effect by more than the hand-base coordinate system (Fischer and Hill, 2004; Chapter 8 of the present thesis) (Wood et al., 2006). The lack of visual input could therefore account for the fact that a classic SNARC effect was observed in our experiment (with sighted participants in a crossed-hands posture) but not in the Wood study (Wood et al., 2006).

According to Wood et al. (2006), the probability of detecting a real SNARC effect in a crossed posture also increases with the size of the sample. While Wood et al. (2006) tested 32 participants, we only tested 13 sighted individuals. In our experiment, however, we analyzed our data with a linear mixed model, an analysis that presents two major advantages over the classic measures usually used to evaluate the SNARC effect (i.e., ANOVA or regression analyses): **(1)** the LMM is an extension of the general linear model but does not require observations to be independent with constant variance; **(2)** the LMM allows the specification of random and fixed effects and thus avoids averaging across all dimensions. By using this alternative statistical analysis, we probably overcome the apparent small size of our sample.

Moreover, in the literature on numerical cognition, numerous studies have identified the intraparietal sulcus (IPS) as an area critically involved in numerical processing (Piazza et al., 2004, 2007). Because interactions between visuo-motor functions and numbers rely on circuits linking the IPS to the premotor cortex, it could be interesting to record IPS activity and connectivity using fMRI while congenitally blind, late blind and sighted individuals perform the auditory comparison task described above in this section. While anterior parts of the parietal cortex are mainly concerned with sensori-motor processing, posterior parts of the parietal cortex are mainly connected to the visual system. Late blind and sighted people who map numbers onto a visuotopic frame of reference might therefore activate the posterior parts of the parietal cortex while the anterior parts of the parietal cortex might be activated in people who map numbers onto a somatotopic coordinate system (i.e., congenitally blind).

A reversal of the SNARC and Simon effects was also observed in sighted individuals through the concurrent use of practice incompatible mapping rules (Notebaert et al., 2006). Hence, the use of incompatible associations between explicit spatial information and spatial responses (i.e., press left when stimulus appears on the right and right when stimulus appears on the left) appears to reverse the SNARC effect while changing the associations between implicit spatial information and spatial responses (i.e., press left when stimulus is larger than 5 and right when stimulus is smaller than 5) appears to reverse the Simon effect. In our introduction, we already reported that the Simon and SNARC effect can both be explained in terms of dual route models (e.g., De Jong et al., 1994; Kornblum, Hasbroucq, & Osman, 1990). However, three different architectures for spatial response associations for space and numbers were proposed (see Figure 10-1). According to the first view (see Figure 10-1a), the input layer (explicit or implicit spatial information) is directly associated with the response layer (Gevers et al., 2006). According to the second view, the input layer activates a common spatial code before activating specific spatial responses (Hubbard et al., 2005; Walsh, 2003). Finally, according to the third view (see Fig. 10-1c), magnitude and locations activate distinct intermediate spatial representations which in turn activate the spatial responses. The data on sighted individuals as well as the reversal of the SNARC and Simon effects observed with congenitally blind individuals in the comparison task can, in our view, only be explained in terms of shared spatial representation (see Fig. 10-1b). While this shared representation is, by default, eye-centred in sighted and late blind individuals, it is, by default, hand-centred in people who have lacked vision since birth. In contrast, the data of our parity judgment task is better explained in terms of a direct association between the input and response layers.

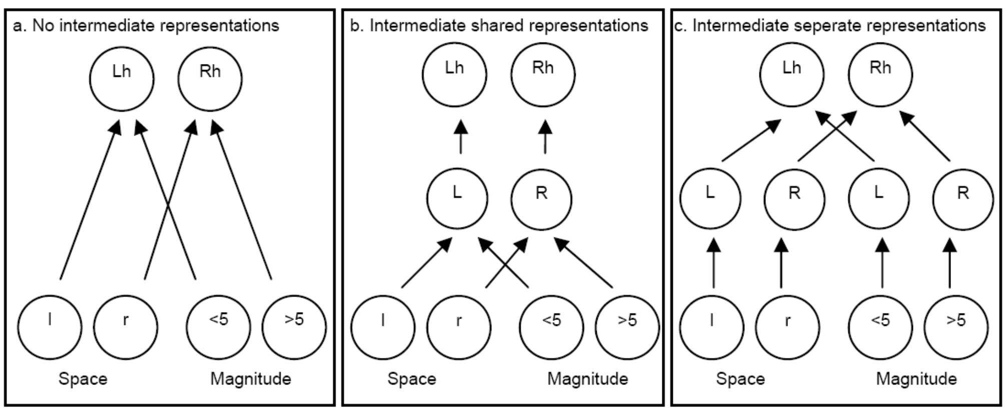


Fig. 10-1. Architectures for spatial response associations. The bottom layer represents the input: either a spatial stimulus (presented on the left (l) or on the right (r) side of space) or a numerical stimulus (smaller (<5) or larger (>5) than five). **(A)** Direct association between the input and the response layers. **(B)** Common spatial code for spatial and numerical inputs. **(C)** Distinct spatial representations for spatial and numerical inputs. *Reproduced from Notebaert et al. (2006).*

Two major pieces of experimental data may however contradict the hypothesis of a common mechanism underlying the representation of numerical and physical space. First, there is the evidence that the SNARC and Simon effects present different temporal characteristics: while the SNARC effect is not affected by the speed of response, the Simon effect only occurs when the speed of response is fast (Mapelli et al., 2003). However, in our view, and as suggested by Notebaert et al. (2006), these different time courses do not necessarily imply different spatial representations (Mapelli et al., 2003), but rather may be explained in terms of how fast the shared spatial code is activated: while it is quickly activated with explicit physical locations, it takes longer to extract spatial information from numbers. In this sense, the different time courses of the Simon and SNARC effects are not in contradiction with the idea of a shared representation of numbers and space.

The second evidence contradicting the hypothesis of a common mechanism for numerical and physical space is the observation of dissociations between numerical and spatial processing in recent patients' reports. Priftis, Zorzi, Meneghello, Marenzi and Undlta (2006), for example, described neglect patients showing a number interval bisection bias but a classic SNARC effect in a parity judgment task. Similarly, Doricchi and colleagues reported a double dissociation between number and physical line bisection in right hemisphere brain damage patients (Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005; Doricchi, Merola, Aiello, Guariglia, Bruschini, Gevers et al., 2009). Hence, some patients who presented a strong bias in number bisection only exhibited a weak or no bias in line bisection; inversely, some patients who presented a strong bias in line bisection only exhibited a weak or no bias in number bisection. Interestingly, deviation in numerical interval bisection was associated with prefrontal damage and spatial working memory deficit (Doricchi et al., 2005, 2009). Following these patient studies, a double dissociation was found between the type of working memory and the type of task: while the SNARC effect disappeared under verbal load in parity judgment tasks (van Dijck et al., 2009), it only disappeared under spatial load in magnitude comparison tasks (Herrera et al., 2008; van Dijck et al., 2009). These results therefore indicated that numbers might be associated with multiple spatial codes which, depending on the task, have a visuo-spatial or a verbal component. As already mentioned, the data presented in Chapter 8 are in accordance with this idea.

2. Blindness and interactions between numbers and fingers

In the last study (Chapter 9) of the present thesis, we investigated whether finger-counting and finger-montring behaviours might be shaped and influenced by visual experience. Congenitally blind and sighted children were thus required to perform three test batteries, respectively testing: **(1)** general cognitive abilities, **(2)** the spontaneous use of finger-counting and finger-montring strategies; **(3)** the canonicity level of the finger-counting and finger-montring habits. The results demonstrated that blind children used their fingers significantly less often and in a less canonical way than sighted children. So, while it was assumed that finger-counting strategies draw on visual, proprioceptive and motor representations (Andres et al., 2008), our study showed that the visual representation of fingers was determinant in the development of a finger-based representation.

Blind and sighted children nevertheless achieved quite similar levels of performance in three enumeration tasks (i.e., counting words, enumeration question, ordered series manipulation) of the second test battery. In two other tasks (i.e., counting with articulatory suppression, two-syllable counting), however, the lack of finger use appeared to prevent blind children from achieving the same level of performance as sighted participants. As these two tasks were very demanding on working memory resources, it was hypothesized, in line with some recent data on blind adults (Sallilas et al., 2009), that blind people learn to manipulate numbers through an auditory working memory process. When this process was disrupted due to the demands of the tasks, blind children performed less well than their sighted peers. In line with this, we could hypothesize that sighted children's performance would decrease in tasks involving interference with the finger-counting behaviour (e.g., in tasks involving moving the fingers in a rhythm non-congruent with the enumeration timing; Michaux, Pesenti, & Andres, 2010). Similarly, as finger discrimination appeared to be a good predictor of sighted children's arithmetic abilities (Fayol et al., 1998; Marinthe et al., 2001; Noël, 2005), it could be interesting to test whether working memory capacity might be a good predictor of blind children's arithmetic abilities. In our experiment, the first battery was designed to determine whether both groups of children had the level of performance required to undertake the counting tasks of the second test battery. The second test battery, on the other hand, was designed to examine whether blind and sighted children spontaneously used their fingers to solve the enumeration tasks. Therefore, the tests created were not sensitive enough to examine this association between working memory and arithmetic abilities. Our study also presents two additional major limits. First, the tests used in our study didn't allow us to determine the mathematical achievement of the children. Indeed, the addition subtest of the first test battery only comprised single-digit numbers. The children therefore performed at ceiling. In order to better determine the impact of the lack of finger use on mathematical achievement, other measures should therefore be collected. It is indeed possible that blind children perform at a quite similar level as sighted children but only in tasks that did not require a deep understanding of the mathematical procedures. Second, our study did not allow us to explain why 3 of the 14 blind children spontaneously used their fingers. How did these children learn the finger-counting strategy? Did their parents teach them? With these informations, we could propably propose some hypotheses about the development of the finger-number interactions.

As we have already mentioned in Chapter 9, two different views have been proposed in the literature to account for the origin of these connections between numbers and fingers. According to a functionalist view, interactions between fingers and numbers arise in the course of *ontogenic* development (Andres et al., 2008; Butterworth, 1999b, 2005; Michaux, Pesenti, Badets, Di Luca, & Andres, 2010). In contrast, according to a redeployment hypothesis, the interactions between numbers and fingers arise in the course of *phylogenetic* development (Anderson, 2010; Penner-Wilger & Anderson, 2008). Interesting predictions can be made from these two different views. While the functional hypothesis predicts that the lack of finger counting during child development will prevent the interactions between numbers and fingers from arising in adulthood, the redeployment hypothesis predicts that individuals who did not use the finger-counting strategy during infancy (in the absence of any related deficit such as finger agnosia) will nevertheless show traces of a numerical finger-based representation when performing numerical tasks in adulthood. As our last study demonstrated that blind children do not use their fingers to count but rather use their verbal working memory, future research should examine whether traces of the finger-counting behaviour could nevertheless be found in blind people's numerical processing. In this sense, despite its limits, our study constitutes a first step towards the understanding of the origin of finger-number interactions. By showing that blind children did not use their fingers to count, we opened the field of investigation and offered a plan to disentangle the functionalist and the redeployment hypotheses.

References

Aiken, L.R., & Williams, F.N. (1968). Three variables related to reaction time to compare single-digit numbers. *Perceptual & Motor Skills*, *27*, 197−206.

Alibali, M.W., & DiRusso, A.A. (1999). The function of gesture in learning to count: more than keeping track. *Cognitive Development, 14 (1)*, 37−56.

Allik, J. & Tuulmets, T. (1991). Occupancy model of perceived numerosity. *Perception & Psychophysics, 49 (4)*, 303−314.

Amedi, A., Raz, N., Pianka, P., Malach, R. & Zohary, E. (2003). Early visual cortex activation correlates with superior verbal-memory performance in the blind. *Nature Neuroscience, 6*, 758−766.

Anderson, M.L. (2010). Neural reuse: a fundamental organizational principle of the brain. *Behavioral and Brain Sciences*, *33*, 245−313.

Andres, M., Davare, M., Pesenti, M., Olivier, E., & Seron, X. (2004). Number magnitude and grip aperture interaction. *Neuroreport, 15 (18)*, 2773−2777.

Andres, M., Di Luca, S., & Pesenti, M. (2008). Finger-counting: the missing tool? *Behavioral and Brain Sciences, 31*, 642−643.

Andres, M., Ostry, D.J., Nicol, F., & Paus, T. (2008). Time course of number magnitude interference during grasping. *Cortex, 44 (4)*, 414−419.

Andres, M., Seron, X., & Olivier, E. (2005). Hemispheric lateralization of number comparison. *Cognitive Brain Research*, *25*, 283−290.

Andres, M., Seron, X., & Olivier, E. (2007). Contribution of hand motor circuits to counting. *Journal of Cognitive Neuroscience, 19*, 563−576.

Ansari, D. (2007). Does the parietal cortex distinguish between “10”, “Ten” and ten dots? *Neuron*, *53*, 165−167.

Ansari, D., Donlan, C., Thomas, M.S.C., Ewing, S.A., Peen, T., Karmiloff-Smith, A. (2003). What makes counting count? Verbal and visuo-spatial contributions to typical and atypical number development. *Journal of Experimental Child Psychology, 85,* 50−62.

Ansari, D., Garcia, N., Lucas, E., Hamon, K., & Dhital, B. (2005). Neural correlates of symbolic number processing in children and adults. *Neuroreport, 16,* 1769−1773.

Antell, S.E., & Keating, D.P. (1983). Perception of numerical invariance in neonates. *Child development, 54,* 695−701.

Aschcraft, M.H., & Battaglia, J. (1978). Cognitive arithmetics: Evidence for retrieval and decision processes in mental addition. *Journal of Experimental Psychology: Human Learning and Memory, 4*, 527−538.

Ashida, H. (2004). Action-specific extrapolation of target motion in human visual system. *Neuropsychologia, 42*, 1515−1524.

Azañón, E., & Soto-Faraco, S. (2008). Changing reference frames during the encoding of tactile events. *Current Biology, 18*, 1044−1049.

Badets, A., Andres, M., Di Luca, S., & Pesenti, M. (2007). Number magnitude potentiates action judgements. *Experimental Brain Research, 180 (3),* 525−534.

Badets, A., & Pesenti, M. (2010). Creating number semantics through finger movement perception. *Cognition, 115 (1),* 46−53.

Badets, A., Pesenti, M., & Olivier, E. (2010). Response-effect compatibility of finger-numeral configurations in arithmetical context. *The Quarterly Journal of Experimental Psychology, 63 (1)*, 16−22.

Bachtold, D., Baumuller, M., & Brugger, P. (1998). Stimulus-response compatibility in representational space. *Neuropsychologia, 36 (8),* 731−735.

Baroody, A.J. (1987). *Children's mathematical thinking: A developmental framework for preschool, primary, and special education teachers.* New York: Teacher's College.

Barth, H., Kanwisher, N., & Spelke, E. (2003). The construction of large number representations in adults. *Cognition, 86,* 201−221.

Berteletti, I., Lucangeli, D., Piazza, M., Dehaene, S., & Zorzi, M. (2010). Numerical estimation in preschoolers. *Developmental Psychology, 46 (2),* 545−551.

Bevan, W. & Turner, E. (1964). Assimilation and contrast in the estimation of number. *Journal of Experimental Psychology, 67 (5),* 458–462.

Bijeljac-Babic, R., Bertoncini, J., & Mehler, J. (1991). How do four-day-old infants categorize multisyllabic utterances. *Developmental Psychology, 29,* 711−721.

Booth, J.L. & Siegler, R.S. (2006). Developmental and individual differences in pure numerical estimation. *Developmental Psychology, 41 (6),* 189−201.

Booth, J.L., & Siegler, R.S. (2008). Numerical magnitude representations influence arithmetic learning. *Child Development, 79 (4),* 1016−1031.

Brannon, E.M., Abbott, S., & Lutz, D.J. (2004). Number bias for the discrimination of large visual sets in infancy. *Cognition, 93,* B59−B68.

Bremner, A.J., Holmes, N.P., & Spence, C. (2008). Infants lost in (peripersonal) space? *Trends in Cognitive Science, 12,* 298–305.

Brysbaert, M. (1995). Arabic number reading: On the nature of the numerical scale and the origin of phonological recoding. *Journal of Experimental Psychology: General, 124,* 434−452.

Buckley, P.B. & Gillman, C.B. (1974). Comparison of digit and dot patterns. *Journal of Experimental Psychology, 103,* 1131–1136.

Burbaud, P. Degreze, P., Lafon, P., Franconi, J.M., Bouligand, B., Bioulac, B., Caille, J.M., & Allard, M. (1995). Lateralization of prefrontal activation during internal mental calculation: a functional magnetic resonance imaging study. *Journal of Neurophysiology*, *74*, 2194−2200.

Burr, D., & Ross, J. (2008). A visual sense of number. *Current Biology, 18 (6),* 425–428.

Butterworth, B. (1999a). *The Mathematical Brain*. London: Macmillan.

Butterworth, B. (1999b). A head for figures. *Science, 284,* 928−929.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46,* 3–18.

Calabria, M., & Rossetti, Y. (2005). Interference between number processing and line bisection: a methodology. *Neuropsychologia, 43 (5),* 779−783.

Carey, S. (2001). Cognitive foundations of arithmetic: evolution and ontogenesis. *Mind & Language*, *16*, 37−55.

Castronovo, J. & Seron, X. (2007a). Numerical estimation in blind subjects: evidence of the impact of blindness and its following experience. *Journal of Experimental Psychology: Human Perception and Performance, 33 (5),* 1089–1106.

Castronovo, J., & Seron, X. (2007b). Semantic numerical representation in blind subjects: the role of vision in the spatial format of the mental number line. *The Quarterly Journal of Experimental Psychology, 60 (1),* 101−119.

Cattaneo, Z., Fantino, M., Tinti, C., Silvanto, J., & Vecchi, T. (2010). Crossmodal interaction between the mental number line and peripersonal haptic space representation in sighted and blind individuals. *Attention, Percpetion, & Psychophysics, 72 (4),* 885−890.

Censabella, S. & Noël, M.P. (2008). The inhibition capacities of children with mathematical disabilities. *Child Neuropsychology*, *14*, 1−20.

Cheatham, P.G., & White, C.T. (1954). Temporal numerosity: III. Auditory perception of number. *Journal of Experimental Psychology*, *47*, 425−428.

Cho, Y.S., & Proctor, R.W. (2003). Stimulus and response representations underlying orthogonal stimulus-response compatibility effects. *Psychonomic Bulletin and Review, 10*, 45−73.

Chochon, F., Cohen, L., van de Moortele, P.F., & Dehaene, S. (1999). Differential contributions of the left and right inferior parietal lobules to number processing. *Journal of Cognitive Neuroscience, 11,* 617−630.

Church, R.M., & Meck, W.H. (1984). The numerical attribute of stimuli. In H.L. Roitblat, T.G. Bever, & H.S. Terrace (Eds.), *Animal Cognition* (pp. 445−464). Hillsdale, NJ: Erlbaum.

Cohen, L., & Dehaene, S. (1996). Cerebral networks for number processing: Evidence from a case of posterior callosal lesion. *Neurocase, 2*, 155−174.

Cohen Kadosh, R., Cohen Kadosh, K., Kaas, A., Henik, A., & Goebel, R. (2007). Notation-dependent and –independent representations of numbers in the parietal lobes. *Neuron, 53,* 307−314.

Collignon, O., Charbonneau, G., Lassonde, M., Lepore, F. (2009). Early visual deprivation alters multisensory processing in peripersonal space. *Neuropsychologia, 47,* 3236−3243.

Collignon, O., Voss, P., Lassonde, M., & Lepore, F. (2009). Cross-modal plasticity for the spatial processing of sounds in visually deprived subjects. *Experimental Brain Research, 192 (3),* 343−358.

Cooper, R.G. (1984). Early number development: discovering number space with addition and subtraction. In C. Sophian (Ed.), *Origins of cognitive skills* (pp. 157−192). Hillsdale , NJ: Erlbaum.

Cordes, S., Gelman, R., Gallistel, C.R., & Whalen, J. (2001). Variability signatures distinguish verbal from non-verbal counting for both large and small numbers. *Psychonomic Bulletin and Review, 8 (4),* 698–707.

Cornoldi, C., Tinti, C., Mammarella, I.C., Re, A.M., & Varotto, D. (2009). Memory for an imagined pathway and strategy effects in sighted and in totally congenitally blind individuals. *Acta Psychologica, 130,* 11−16.

Coull, J.T., & Nobre, A.C. (1998). Where and when to pay attention: the neural systems for directing attention to spatial locations and to time intervals as revealed by both PET and fMRI. *Journal of Neuroscience, 18 (18),* 7426−7435.

Cousineau, D. (2005). Confidence intervals in within-subjects designs: A simpler solution to Loftus and Masson's method. *Tutorials in Quantitative Methods for Psychology, 1 (1),* 42−45.

Crollen, V., Castronovo, J., & Seron, X. (2011). Under- and over-estimation: A bi-directional mapping process between symbolic and non-symbolic representations of number? *Experimental Psychology, 58 (1),* 39−49.

Daar, M., & Pratt, J. (2008). Digits affect actions: The SNARC effect and response selection. *Cortex, 44,* 400−405.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44,* 1–42.

Dehaene, S. (1996). The organization of brain activations in number comparison: event-related potentials and the additive-factors method. *Journal of Cognitive Neuroscience, 8,* 47−68.

Dehaene, S. (1997). *The number sense.* New York: Oxford University Press.

Dehaene, S. (2001). Precis of the number sense. *Mind and Language, 16 (1)*, 16–36.

Dehaene, S. (2003). The neural basis of the Weber-Fechner law: a logarithmic mental number line. *Trends in Cognitive Sciences, 7 (4)*, 145–147.

Dehaene, S. (2009). Origins of mathematical intuitions. The case of arithmetic. *The Year in Cognitive Neuroscience, 1156*, 232−259.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122 (3)*, 371–396.

Dehaene, S., & Changeux, J.P. (1993). Development of elementary numerical abilities: a neuronal model. *Journal of Cognitive Neuroscience, 5*, 390−407.

Dehaene, S., & Cohen, L. (1991). Two mental calculation systems: a case study of severe acalculia with preserved approximation. *Neuropsychologia, 29*, 1045−1074.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83–120.

Dehaene, S. & Cohen, L. (1997). Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex, 33*, 219– 250.

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neuroscience, 21*, 355−361.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 626−641.

Dehaene, S., Izard, V., & Piazza, M. (2005). Control over non-numerical parameters in numerosity experiments. *Unpublished manuscript (available on www.unicog.org).*

Dehaene, S., Izard, V., Spelke, E., & Pica, P. (2008). Log or linear? Distinct intuitions of the number scale in Western and Amazonian indigene cultures. *Science, 30,* 1217–1220.

Dehaene, S., & Marques, J.F. (2002). Cognitive euroscience: scalar varibility in price estimation and the cognitive consequences of switching to the euro. *Quarterly Journal of Experimental Psychology, 55,* 705−731.

Dehaene, S., Piazza, M., Pinel, P., Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20,* 487−506.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science, 284 (5416),* 970−974.

De Hevia, M.D., Girelli, L., & Vallar, G. (2006). Numbers and space: a cognitive illusion? *Experimental Brain Research, 168,* 254−264.

De Jong, R., Liang, C.C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 731–750.

Delazer, M., Domahs, F., Bartha, L., Brenneis, C., Lochy, A., Trieb, T., & Benke, T. (2003). Learning complex arithmetic-an fMRI study. *Brain Research Cognitive Brain Research, 18 (1),* 76−88.

De Smedt, B., Verschaffel, L., & Ghesquière, P. (2009). The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. *Journal of Experimental Child Psychology*, *103,* 469−479.

Diester, I., & Nieder, A. (2007). Semantic associations between signs and numerical categories in the prefrontal cortex. *Plos Biology, 5,* e294.

DiLollo, V. (1964). Contrast effects in the judgement of lifted weights. *Journal of Experimental Psychology, 68*, 383−387.

Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger-digit compatibility in Arabic numerical processing. *The Quarterly Journal of Experimental Psychology, 59 (9),* 1648−1663.

Di Luca, S., Lefèvre, N., & Pesenti, M. (2010). Place and summation coding for canonical and non-canonical finger numeral representations. *Cognition, 117,* 95−100.

Di Luca, S., & Pesenti, M. (2008). Masked priming effect with canonical finger numeral configurations. *Experimental Brain Research*, *185 (1),* 27−39.

Di Luca, S., & Pesenti, M. (2010). Absence of low-level visual difference between canonical and noncanonical finger-numeral configurations. *Experimental Psychology, 57 (3),* 202−207.

Domahs, F., Krinzinger, H., & Willmes, K. (2008). Mind the gap between both hands: Evidence for internal finger-based number representations in children's mental calculation, *Cortex*, *44,* 359−367.

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H.C. (2010). Embodied numerosity: implicit hand-based representation influence symbolic number processing across cultures. *Cognition, 116,* 251−266.

Doricchi, F., Guariglia, P., Gasparini, M., Tomaiuolo, F. (2005). Dissociation between physical and mental number line bisection in right hemisphere brain damage. *Nature Neuroscience, 8 (12),* 1663−1665.

Doricchi, F., Merola, S., Aiello, M., Guariglia, P., Bruschini, M., Gevers, W. et al. (2009). Spatial orienting biases in the decimal numeral system. *Current Biology*, *19*, 682−687.

Durgin, F.H. (1995). Texture density adaptation and the perceived numerosity and distribution of texture. *Journal of Experimental Psychology: Human Perception and Performance, 21 (1),* 149−169.

Fayol, M., Barrouillet, P., & Marinthe, C. (1998). Predicting mathematical achievement from neuropsychological performance: a longitudinal study. *Cognition*, *68,* 63−70.

Fayol, M., & Seron, X. (2005). About numerical representations: insights from neuropsychological, experimental and developmental studies. In J.I.D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 3−22). New York: Psychology Press.

Feigenson, L., Dehaene, S., & Spelke, E. (2004). Core systems of number. *Trends in Cognitive Sciences*, *8*, 307−314.

Féron, J., Gentaz, E., & Streri, A. (2006). Evidence of amodal representation of small numbers across visuo-tactile modalities in 5-month-old infants. *Cognitive Development*, *21*, 81−92.

Ferrand, L., Riggs, K.J., & Castronovo, J. (2010). Subitizing in congenitally blind adults. *Psychonomic Bulletin & Review, 17(6),* 840−845.

Fias, W., Brysbaert, M., Geypens, F., & d’Ydewalle, G. (1996). The importance of magnitude information in numerical processing: evidence from the SNARC effect. *Mathematical Cognition, 2 (1),* 95–110.

Fias, W., & Fischer M.H. (2005). Spatial representation of numbers. In J.I.D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 43−54). New York: Psychology Press.

Fias, W., Lauwereyns, J., & Lammertyn, J. (2001). Irrelevant digits affect feature-based attention depending on the overlap of neural circuits. *Cognitive Brain Research, 12,* 415−423.

Finke, R.A., & Freyd, J.J. (1985). Transformations of visual memory induced by implied motions of pattern elements. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 11*, 780−794.

Finke, R.A., Freyd, J.J., & Shyi, G.C.W. (1986). Implied velocity and acceleration induce transformations of visual memory. *Journal of Experimental Psychology: General, 115,* 175−188.

Fischer, J.P. (2010). Numerical performance increased by finger training: a fallacy due to regression toward the mean? *Cortex*, *46 (2),* 272–273.

Fischer, M.H. (2001). Number processing induces spatial performance biases. *Neurology, 57 (5)*, 822−826.

Fischer, M.H. (2003). Spatial representations in number processing - evidence from a pointing task. *Visual Cognition, 10,* 493−508.

Fischer, M.H. (2006). The future for SNARC could be stark. *Cortex, 42,* 1066–1068.

Fischer, M.H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex, 44*, 386–392.

Fischer, M.H., Castel, A.D., Dodd, M.D., & Pratt, J. (2003). Perceiving numbers causes spatial shifts of attention. *Nature Neuroscience*, *6,* 555−556.

Fischer, M.H., & Hill, R.A. (2004). *SNARC in the Dark: Input Modality Affects Number Representation.* 22nd European Workshop of Cognitive Neuropsychology, Bressanone, Italy.

Fischer, M.H., Warlop, N., Hill, R.L., & Fias, W. (2004). Oculomotor bias induced by number perception. *Experimental Psychology, 51 (2)*, 91−97.

Freyd, J.J., & Finke, R.A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *10*, 126−132.

Freyd, J.J., & Finke, R.A. (1985). A velocity effect for representational momentum. *Bulletin of the Psychonomic Society, 23,* 443−446.

Frith, C.D. & Frith, U. (1972). The solitaire illusion: an illusion of numerosity. *Perception & Psychophysics, 11 (6),* 409−410.

Fuson, K.C. (1988). *Children's Counting and Concepts of Number*. New York: Springer-Verlag.

Fuson, K.C., & Kwon, Y. (1992). Learning addition and subtraction: Effects of number word and other cultural tools. In J. Bideau, C. Meljac, & J.P. Fisher (Eds.), *Pathways to number* (pp. 351−374). Hillsdale, NJ: Erlbaum.

Fuson, K.C., Richards, J., & Briars, D.J. (1982). The acquisition and elaboration of the number word sequence. In C.J. Brainerd (Ed.), *Children's logical and mathematical cognition*. New York: Springer-Verlag.

Gallistel, C.R. & Gelman, R. (1992). Pre-verbal and verbal counting and computation. *Cognition*, *44*, 43–74.

Gallistel, C.R. & Gelman, R. (2000). Non-verbal numerical cognition: from reals to integers. *Trends in Cognitive Sciences*, *4 (2)*, 59–65.

Gandini, D., Lemaire, P., & Dufau, S. (2008). Older and young adults’ strategies in approximate quantification. *Acta Psychologica*, *129(1)*, 175−189;

Geary, D.C. (1994). *Children's mathematical development: Research and practical applications*. Washington, DC: American Psychological Association.

Gelman, R. (1978). Cognitive development. *Annual Review of Psychology*, *29*, 297–332.

Gelman, R., & Gallistel, C.R. (1978). *The Child's Understanding of Number*. Cambridge, MA: Harvard University Press.

Gerstmann, J. (1930). Zur symptomatologie der hirnläsionen im übergangsgebiet der unteren parietal-und mittleren occipitalwindung. *Nervenarzt, 3*, 691−695.

Gevers, W., Reynvoet, B. & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87, B87–B95*.

Gevers, W., Reynvoet, B. & Fias, W. (2004). The mental representation of ordinal sequences is spatially organised: evidence from days of the week. *Cortex*, *40*, 171–172.

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van de Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number-space interactions. *Journal of Experimental Psychology : General, 139(1),* 180─190.

Gevers, W., Verguts, T., Reynvoet, B., Caessens, B., & Fias, W. (2006). Numbers and space: a computational model of the SNARC effect. *Journal of Experimental Psychology: Human Perception and Performance, 32 (1),* 32−44.

Gilmore, C.K., McCarthy, S.E., & Spelke, E.S. (2010). Non-symbolic arithmetic abilities and mathematics achievement in the first year of formal schooling. *Cognition, 115,* 394−406.

Ginsburg, N. (1978). Perceived numerosity, item arrangement, and expectancy. *The American Journal of Psychology, 91 (2),* 267−273.

Ginsburg, N. (1980). The regular-random numerosity illusion: rectangular patterns. *The Journal of General Psychology, 103,* 211−216.

Ginsburg, N. (1982). Solitaire illusion: replication and extension. *Perceptual and Motor Skills, 54*, 209−210.

Ginsburg, N. & Nicholls, A. (1988). Perceived numerosity as a function of item size. *Perceptual and Motor Skills, 67,* 656−658.

Ginsburg, N., & Pringle, N. (1988). Haptic numerosity perception: effect of item arrangement. *American Journal of Psychology, 101 (1),* 131−133.

Gold, J.I., & Shadlen, M.N. (2002). Banburismus and the brain: decoding the relationship between sensory stimuli, decisions, and reward. *Neuron, 36,* 299−308.

Gordon, P. (2004). Numerical cognition without words: evidence from Amazonia. *Science, 306 (5695),* 496–499.

Grabner, R.H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *Neuroimage, 38,* 346−356.

Grabner, R.H., Ischebeck, A., Reishofer, G., Koschutnig, K., Delazer, M., Ebner, F., & Neuper, C. (2009). Fact learning in complex arithmetic and figural-spatial tasks: the role of the angular gyrus and its relation to mathematical competence. *Human Brain Mapping, 30 (9),* 2936−2952.

Gracia-Baffaluy, M. & Noël, M.P. (2008). Does finger training increase young children’s numerical performance? *Cortex, 1*, 1−8.

Graham, T.A. (1999). The role of gesture in children's learning to count. *Journal of Experimental Child Psychology, 74 (4)*, 333−355.

Halberda, J., & Feigenson, L. (2008). Developmental change in the acuity of the ‘‘Number Sense’’: The approximate number system in 3-, 4-, 5-, 6-year-olds and adults. *Developmental Psychology, 44 (5),* 1457−1465.

Halberda, J., Mazzocco, M.M.M., & Feigenson, L. (2008). Individual differences in non-verbal number acuity correlate with maths achievement. *Nature, 455,* 665−668.

Harrington, D.L., Rao, S.M., Haaland, K.Y., Bobholz, J.A., Mayer, A.R., Binderx, J.R., & Cox, R.W. (2000). Specialized neural systems underlying representations of sequential movements. *Journal of Cognitive Neuroscience, 12* (1), 56−77.

Hauser, M.D., & Carey, S. (2003). Spontaneous representations of small numbers of objects by rhesus macaques: examinations of content and format. *Cognitive Psychology, 47*, 367–401.

Hauser, M.D., McNeilage, P., & Ware, M. (1996). Numerical representations in primates. Proc. Natl. Acad. Sci. USA, 93, 1514−1517.

Hauser, M.D., Carey, S., & Hauser, L.B. (2000) Spontaneous number representation in semi-free-ranging rhesus monkeys. *Proc. R. Soc. Lond. B. Biol. Sci., 267,* 829–833.

Hauser, M.D., Tsao, F., Garcia, P., & Spelke, E.S. (2003). Evolutionary foundations of number: spontaneous representation of numerical magnitudes by cotton-top tamarins. *Proc. R. Soc. Lond., 270,* 1441–1446.

Herrera, A., & Macizo, P. (2008). Cross-notational semantic priming between symbolic and nonsymbolic numerosity. *The Quarterly Journal of Experimental Psychology, 61(10),* 1538−1552.

Herrera, A., Macizo, P., & Semenza, C. (2008). The role of working memory in the association between number magnitude and space. *Acta Psychologica, 128,* 225−237.

Hoeckner, S.H., Moeller, K., Zauner, H., Wood, G., Haider, C., Gabner, A., & Nuerk, H.C. (2008). Impairments of the mental number line for two-digit numbers in neglect. *Cortex, 44 (4),* 429−438.

Holloway, I.D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology, 103,* 17−29.

Holloway, I.D., Price, G.R., & Ansari, D. (2010). Common and segregated neural pathways for the processing of symbolic and nonsymbolic numerical magnitude: An fMRI study. *Neuroimage, 49,* 1006−1017.

Hubbard, E.M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews, 6,* 435−448.

Hubbard, T.L., & Bharucha, J.J. (1988). Judged displacement in apparent vertical and horizontal motion. *Perception & Psychophysics, 44,* 211–221.

Ifrah, G. (2000). *The universal history of numbers*. London: Harvill.

Indow, T., & Ida, M. (1977). Scaling of dot numerosity. *Perception and Psychophysics, 22 (3),* 265−276.

Iversen, W., Nuerk, H.C., Jager, L., & Willmes, K. (2006). The influence of an external symbol system on number parity representation, or what's odd about 6? *Psychonomic Bulletin & Review, 13,* 730–736.

Izard, V. & Dehaene, S. (2008). Calibrating the mental number line. *Cognition, 106 (3),* 1221−1247.

Izard, V., Dehaene-Lambertz, G., & Dehaene, S. (2008). Distinct cerebral pathways for object identity and number in human infants. *Plos Biology, 6 (2),* e11.

Izard, V., Sann, C., Spelke, E.S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences, 106 (25),* 10382−10385.

Jordan, K.E, & Brannon, E.M. (2006). The multisensory representation of number in infancy. *Proceedings of the National Academy of Sciences*, *103,* 3486−3489.

Kaufman, L., Lord, M.W., Reese, T.W. & Volkmann, J. (1949). The discrimination of visual number. *American Journal of Psychology, 62,* 498–525.

Kaufman, L., Vogel, S.E., Wood, G., Kremser, C., Schocke, M., Zimmerhackl, L.B., & Koten, J.W. (2008). A developmental fMRI study of nonsymbolic numerical and spatial processing. *Cortex, 44,* 376−385.

Kazandjian, S., Cavézian, C., Zivotofsky, A.Z., & Chokron, S. (2010). Bisections in two languages: when number processing, spatial representation, and habitual reading direction interact. *Neuropsychologia, 48 (14),* 4031−4037.

Keus, I.M., Jenks, K.M., & Schwarz, W. (2005). Psychophysiological evidence that the SNARC effect has its functional locus in a response selection stage. *Cognitive Brain Research*, *24,* 48−56.

Keus, I.M., & Schwarz, W. (2005). Searching for the functional locus of the SNARC effect: evidence for a response-related origin. *Memory and cognition, 33,* 681−695.

Kiefer, M., & Dehaene, S. (1997). The time course of parietal activation in single-digit multiplication: Evidence from event related potentials. *Mathematical Cognition, 3,* 1−30.

Knops, A., Thirion, B., Hubbard, E.M., Michel, V., & Dehaene, S. (2009). Recruitment of an area involved in eye movements during mental arithmetic, *Science, 324,* 1583−1585.

Knops, A., Viarouge, A., & Dehaene, S. (2009). Dynamic representations underlying symbolic and non-symbolic calculation: evidence from the operational momentum effect. *Attention, Perception and Psychophysics, 71 (4),* 803–821.

Kobayashi, T., Hiraki, K., & Hasegawa, T. (2005). Auditory-visual intermodal matching of small numerosities in 6-month-old infants. *Developmental Science, 8*, 409−419.

Korkman, M. (2000). *Nepsy Handbok.* Stockholm: Psykologiförlaget AB.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-response compatibility: A model and taxonomy. *Psychological Review, 97*, 253−270.

Krueger, L.E. (1972). Perceived numerosity. *Perception and Psychophysics, 11 (1),* 5–9.

Krueger, L.E. (1982). Single judgments of numerosity. *Perception and Psychophysics, 31 (2),* 175–182.

Krueger, L.E. (1984). Perceived numerosity: a comparison of magnitude production, magnitude estimation, and discrimination judgments. *Perception and Psychophysics, 35 (6),* 536−542.

Krueger, L.E. (1989). Reconciling Fechner and Stevens: toward a unified psychophysical law. *Behavioral and Brain Sciences, 12,* 251−320.

Lammertyn, J., Fias, W., & Lauwereyns, J. (2002). Semantic influences on feature-based attention due to overlap of neural circuits. *Cortex, 38,* 878−882.

Le Clec'H, G., Dehaene, S., Cohen, L., Mehler, J., Dupoux, E., Poline, J.B., Lehéricy, S., van de Moortele, P.F., & Le Bihan, D. (2000). Distinct cortical areas for names of numbers and body parts independent of language and input modality. *Neuroimage, 12 (4),* 381−391.

Le Corre, M., & Carey, S. (2007). One, two, three, four, nothing more: an investigation of the conceptual sources of the verbal counting principles. *Cognition, 105,* 395−438.

Lindemann, O., Abolafia, J.M., Girardi, G., & Bekkering, H. (2007). Getting a grip on numbers: numerical magnitude priming in object grasping. *Journal of Experimental Psychology: Human Perception and Performance, 33 (6),* 1400−1409.

Lipton, J.S., & Spelke, E. (2003). Origins of number sense: large number discrimination in human infants. *Psychological Science, 14,* 396−401.

Lipton, J. S., & Spelke, E. S. (2004). Discrimination of large and small numerosities by human infants. *Infancy, 5,* 271−290.

Lipton, J.S. & Spelke, E. (2005). Preschool children's mapping of number words to non-symbolic numerosities. *Child Development, 76 (5),* 978–988.

Lorch, R. F., & Myers, J. L. (1990). Regression-analyses of repeated measures data in cognitive research. *Journal of Experimental Psychology-Learning Memory and Cognition, 16(1),* 149–157.

Lu, C.H., & Proctor, R.W. (1994). Processing of an irrelevant location dimension as a function of the relevant stimulus dimension. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 286−298.

Mandler, G. & Shebo, B. (1982). Subitizing: an analysis of its component processes. *Journal of Experimental Psychology: General, 111,* 1–22.

Manis, M. & Armstrong, G.W. (1971). Contrast effects in verbal output. *Journal of Experimental Social Psychology, 7*, 381−388.

Mapelli, D., Rusconi, E., & Umiltà, C. (2003). The SNARC effect: An instance of the Simon effect? *Cognition, 88,* B1−B10.

Marinthe, C., Fayol, M., & Barrouillet, P. (2001). Gnosies digitales et développement des performances arithmétiques. In A. Van Hout, C. Meljac, & J.P. Fischer (Eds), *Troubles du Calcul et Dyscalculies chez l'Enfant* (pp. 239−254). Paris: Masson.

Marton, F., & Neuman, D. (1990). The Perceptibility of Numbers and the Origin of Arithmetic Skills. Göteborg: Department of Education and Educational Research, University of Göteborg.

Mayer, E., Martory, M. D., Pegna, A. J., Landis, T., Delavelle, J., & Annoni, J. M. (1999). A pure case of Gerstmann syndrome with a subangular lesion. *Brain, 122 (6),* 1107−1120.

McCrink, K., Dehaene, S., & Dehaene-Lambertz, G. (2007). Moving along the mental number line: operational momentum in nonsymbolic arithmetic. *Perception and Psychophysics, 69 (8),* 1324−1333.

McCrink, K., & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science, 15(11),* 776−781.

McCrink, K., & Wynn, K. (2009). Operational momentum in large-number addition and subtraction by 9-month-olds. *Journal of Experimental Child Psychology, 103,* 400–408.

Mechner, F. (1958). Probability relations within response sequences under ratio reinforcement. *Journal of Experimental Analysis of Behavior, 1,* 109−121.

Meck, W.H., & Church, R.M. (1983). A mode control model of counting and timing processes. *Journal of Experimental Psychology: Animal Behavior Processes, 9,* 320−334.

Michaux, N., Pesenti, M., & Andres, M. (2010). Selective interference of finger movements with basic arithmetic problem solving. Poster presented at the BAPS annual Meeting, Brussels, Belgium.

Michaux, N., Pesenti, M., Badets, A., Di Luca, S., & Andres, M. (2010). Let us redeploy attention to sensorimotor experience. *Behavioral and Brain Sciences, 33(4),* 283−284.

Miller, A.L. & Baker, R.A. (1968). The effects of shape, size, heterogeneity, and instructional set on the judgment of visual number. *American Journal of Psychology, 81 (1),* 83−91.

Minturn, A.L., & Reese, T.W. (1951). The effect of differential reinforcement on the discrimination of visual number. *Journal of Psychology, 31,* 201–231.

Mousty, P., Leybaert, J., Alegria, J., Content, A., Morais, J. (1994). *BELEC: Batterie d'évaluation du langage écrit*. Bruxelles: LAPSE (Université Libre de Bruxelles).

Moyer, R.S., & Landauer, T.K. (1967). Time required for judgments of numerical inequality. *Nature, 215,* 1519−1520.

Mundy, E., & Gilmore, C.K. (2009). Children's mapping between symbolic and nonsymbolic representations of number. *Journal of Experimental Child Psychology, 103 (4),* 490−502.

Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience, 32,* 185−208.

Nieder, A., Freedman, D.J., & Miller, E.K. (2002). Representation of the quantity of visual items in the primate prefrontal cortex. *Science*, *297*, 1708−1711.

Nieder, A., & Miller, E.K. (2003). Coding of cognitive magnitude: compressed scaling of numerical information in the primate prefrontal cortex. *Neuron, 37,* 149−157.

Nieder, A., & Miller, E.K. (2004). A parieto-frontal network for visual numerical information in the monkey. *Proceedings of the National Academy of Sciences, 101,* 7457−7462.

Noël, M. P. (2005). Finger gnosia: a predictor of numerical abilities in children? *Child Neuropsychology, 11 (5),* 413−430.

Notebaert, W., Gevers, W., Verguts, T., & Fias, W. (2006). Shared spatial representations for numbers and space: The reversal of the SNARC and the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance, 32 (5),* 1197−1207.

Notebaert, K., & Reynvoet, B. (2009). Different magnitude representations in left and right hemisphere: evidence from the visual half field technique. *Laterality, 14 (3),* 228−245.

Pagel, B., Heed, T., & Röder, B. (2009). Change of reference frame for tactile localization during child development. *Developmental Science, 12 (6),* 929−937.

Peirce, C.S. (1931-1935). *Collected papers.* Cambridge: Harvard University Press.

Penner-Wilger, M., & Anderson, M.L. (2008). An alternative view of the relation between finger gnosis and math ability: redeployment of finger representations for the representation of numbers. *Proceedings of the 30th Annual Meeting of* *the Cognitive Science Society, Austin, TX, July 23−26, 2008,* ed. B.C. Love, K. McRae, & V.M. Sloutsky, pp. 1647−1652. Cognitive Science Society.

Pesenti, M., Thioux, M., Seron, X., & De Volder, A. (2000). Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: a PET study. *Journal of Cognitive Neurosciences, 12 (3),* 461−479.

Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences, 14 (12),* 542−551

Piazza, M., Facoetti, A., Trussardi, A.N., Berteletti, I., Conte, S., Lucangeli, D., Dehaene, S., & Zorzi, M. (2010). Developmental trajectory of number acuity reveals a severe impairment in developmental dyscalculia. *Cognition, 116,* 33−41.

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. *Neuron*, *44,* 547−555.

Piazza, M., Mechelli, A., Butterworth, B., & Price, C.J. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *Neuroimage, 15 (2),* 435−446.

Piazza, M., Mechelli, A., Price, C.J., Butterworth, B. (2006). Exact and approximate judgments of visual and auditory numerosity: an fMRI study. *Brain Research, 1106,* 177−188.

Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. (2007). A magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron, 53*, 293–305.

Pica, P., Lemer, C., Izard, V. & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science, 306*, 499–503.

Pika, S., Nicoladis, E., & Marentette, P. (2009). “How to order a beer”: Cultural differences in the use of conventional gestures for numbers. *Journal of Cross-Cultural Psychology, 40,* 70−80.

Pinel, P., & Dehaene, S. (2010). Beyond hemispheric dominance: Brain regions underlying the joint lateralization of language and arithmetic to the left hemisphere. *Journal of Cognitive Neuroscience, 22 (1),* 48−66.

Pinel, P., Dehaene, S., Rivière, D., & Le Bihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *Neuroimage, 14 (5), 1013−1026.*

Pinel, P., Piazza, M., Le Bihan, D., & Dehaene, S. (2004). Distributed and overlapping cerebral representations of number, size, and luminance during comparative judgments. *Neuron, 41 (6),* 983−993.

Pinhas, M., & Fischer, M. (2008). Mental movements without magnitude? A study of spatial biases in symbolic arithmetic. *Cognition, 109,* 408–415.

Poeck, K. (1965). Phantoms following amputation in early childhood and in congenital absence of limbs. *Cortex, 1,* 269−275.

Polk, T.A., Reed, C.L., Keenan, J.M., Hogarth, P., & Anderson, C.A. (2001). A dissociation between symbolic number knowledge and analogue magnitude information. *Brain and Cognition, 47,* 545−563.

Priftis, K., Zorzi, M., Meneghello, F., Marenzi, R., & Undlta, C. (2006). Explicit versus implicit processing of representational space in negelct: Dissocitations in accessing the mental number line. *Journal of Cognitive Neuroscience, 18 (4),* 680−688.

Proctor, R.W., & Cho, Y.S. (2006). Polarity correspondence: a general principle for performance of speeded binary classification tasks. *Psychological Bulletin, 132 (3)*, 416−442.

Ratinckx, E., & Brysbaert, M. (2002). Interhemispheric Stroop-like interference in number comparison: Evidence for strong interhemispheric integration of semantic number information. *Neuropsychology, 16 (2),* 217−229.

Ratinckx, E., Brysbaert, M., & Reynvoet, B. (2001). Bilateral field interactions and hemispheric asymmetry in number comparison. *Neuropsychologia, 39,* 335−345.

Raz, N., Striem, E., Pundak, G., Orlov, T., & Zohary, E. (2007). Superior serial memory in the blind: a case of cognitive compensatory adjustment. *Current Biology, 17,* 1129−1133.

Restle, F. (1970). Speed of adding and comparing numbers. *Journal of Experimental Psychology, 83 (2),* 274–278.

Revkin, S.K., Piazza, M., Izard, V., Zamarian, L., Karner, E., & Delazer, M. (2008). Verbal numerosity estimation deficit in the context of spared semantic representation of numbers: A neuropsychological study of a patient with frontal lesions. *Neuropsychologia, 46,* 2463−2475.

Reynvoet, B., & Brysbaert, M. (1999). Single-digit and two-digit Arabic numerals address the same semantic number line. *Cognition, 72 (2),* 191–201.

Reynvoet, B., & Brysbaert, M. (2004). Cross-notation number priming investigated at different stimulus onset asynchronies in parity and naming tasks. *Experimental Psychology, 51 (2),* 81–90.

Reynvoet, B., Brysbaert, M., & Fias, W. (2002). Semantic priming in number naming. *Quarterly Journal of Experimental Psychology-A, 55 (4),* 1127–1139.

Reynvoet, B., & Ratinckx, E. (2004). Hemispheric differences between left and right number representations: effects of conscious and unconscious priming. *Neuropsychologia, 42,* 713−726.

Rilling, M., & McDiarinid, C. (1965). Signal detection in fixed-ratio schedules. *Science, 148,* 526−527.

Rivera, S.M., Reiss, A.L., Eckert, M.A., & Menon, V. (2005). Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. *Cerebral Cortex, 15 (11),* 1779−1790.

Röder, B., Föcker, J., Hötting, K., & Spence, C. (2008). Spatial coordinate systems for tactile spatial attention depend on developmental vision: Evidence from event-related potentials in sighted and congenitally blind adult humans. *European Journal of Neuroscience, 28,* 475–483.

Röder, B., Kusmierek, A., Spence, C., & Schicke (2007). Developmental vision determines the reference frame for the multisensory control of action. *Proceedings of the National Academy of Sciences, 104 (11),* 4753−4758.

Röder, B., Rösler, F., & Neville, H.J. (2001). Auditory memory in congenitally blind adults: a behavioral-electrophysiological investigation. *Cognitive Brain Research, 11,* 289−303.

Röder, B., Rösler, F., & Spence, C. (2004). Early vision impairs tactile perception in the blind. *Current Biology, 14,* 121−124.

Roggeman, C., Verguts, T., & Fias, W. (2007). Priming reveals differential coding of symbolic and non-symbolic quantities. *Cognition, 105,* 380−394.

Roitman, J.D., Brannon, E.M., & Platt, M.L. (2007). Monotonic coding of numerosity in macaque lateral intraparietal area. *Plos Biology, 5 (8),* e208.

Rossetti, Y., Jacquin-Courtois, S., Rode, G., Ota, H., Michel, C., & Boisson, D. (2004). Does action make the link between number and space representation? Visuo-manual adaptation improves number bisection in unilateral neglect. *Psychological Science, 15* (6), 426−430.

Rossetti, Y., Rode, G., Pisella, L., Farne, A., Li, L., Boisson, D., & Perenin, M.T. (1998). Prism adaptation to a rightward optical deviation rehabilitates left hemispatial neglect. *Nature, 395* (6698), 166−169.

Rousselle, L., & Noël, M.P. (2007). Basic numerical skills in children with mathematics learning disabilities: A comparison of symbolic vs. non-symbolic number magnitude processing. *Cognition, 102*, 361–395.

Roux, F.E., Boetto, S., Sacko, O., Chollet, F., & Tremoulet, M. (2003). Writing, calculating, and finger recognition in the region of the angular gyrus: a cortical stimulation study of Gerstmann syndrome. *Journal of Neurosurgery, 99 (4)*, 716−727.

Rueckert, L., Lange, N., Partiot, A., Appolonio, I., Litvan, I., Le Bihan, D., & Grafman, J. (1996). Visualizing cortical activation during mental calculation with functional MRI. *NeuroImage, 3,* 97−103.

Rusconi, E., Turatto, M., Umiltà, C. (2007). Two orienting mechanisms in posterior parietal lobule: An rTMS study of the Simon and SNARC effects. *Cognitive Neuropsychology, 24 (4)*, 373−392.

Rusconi, E., Walsh, V., & Butterworth, B. (2005). Dexterity with numbers: rTMS over left angular gyrus disrupts finger gnosis and number processing. *Neuropsychologia, 43 (11)*, 1609−1624.

Salillas, E., El-Yagoubi, R., & Semenza, C. (2008). Sensory and cognitive processes of shifts of spatial attention induced by numbers: An ERP study. *Cortex, 44,* 406−413.

Salillas, E., Granà, A., El-Yagoubi, R., & Semenza, C. (2009). Numbers in the blind's « eye ». *Plos ONE, 4 (7),* 1−6.

Santens, S., & Gevers, W. (2008). The SNARC effect does not imply a mental number line. *Cognition, 108,* 263−270.

Santens, S., Roggeman, C., Fias, W., & Verguts, T. (2010). Number processing pathways in human parietal cortex. *Cerebral Cortex, 20 (1),* 77−88.

Sato, M., Cattaneo, L., Rizzolatti, G., & Gallese, V. (2007). Numbers within our hands: modulation of corticospinal excitability of hand muscles during numerical judgment. *Journal of Cognitive Neurosciences, 19,* 684−693.

Sato, M., & Lalain, M. (2008). On the relationship between handedness and hand-digit mapping in finger counting. *Cortex, 44,* 393−399.

Scholl, B.J. (2001). Objects and attention: the state of the art. *Cognition*, *80,* 1–46.

Schwarz, W., & Keus, I.M. (2004). Moving the eyes along the mental number line: comparing SNARC effects with saccadic and manual responses. *Perception & Psychophysics, 66 (4),* 651−664.

Shallice, T., & Evans, M.E. (1978). The involvement of the frontal lobes in cognitive estimation. *Cortex*, *14*, 294–303.

Shore, D. I., Spry, E., & Spence, C. (2002). Confusing the mind by crossing the hands. *Cognitive Brain Research, 14,* 153–163.

Siegel, L.S. & Ryan, E.B. (1989). The development of working memory in normally achieving and subtypes of learning disabled children. *Child Development, 60,* 973−980.

Siegler, R.S., & Booth, J.L. (2004). Development of numerical estimation in young children. *Child Development, 75,* 428−444.

Siegler, R.S., & Opfer, J.E. (2003). The development of numerical estimation: evidence for multiple representations of numerical quantity. *Psychological Science, 14 (3)*, 237–243.

Simon, J.R. (1969). Reaction toward the source of stimulation. *Journal of Experimental Psychology, 81*, 1974−1976.

Simon, J.R. & Rudell, A. (1967). Auditory S–R compatibility: The effect of an irrelevant cue on information processing. *Journal of Applied Psychology*, *51*, 300–304.

Simon, J.R. & Wolf, J.D. (1963). Choice reaction times as a function of angular stimulus-response correspondence and age. *Ergonomics, 6,* 99−105.

Simon, T.J. (1997). Reconceptualizing the origins of number knowledge: a “non numerical” account. *Cognitive development, 12*, 349−372.

Sophian, C., & Chu, Y. (2008). How do people apprehend large numerosites? *Cognition, 107,* 460−478.

Stanescu-Cosson, R., Pinel, P., van de Moortele, P.F., Le Bihan, D., Cohen, L., & Dehaene, S. (2000). Understanding dissociations in dyscalculia: a brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. *Brain, 123,* 2240−2255.

Stankov, L., Spilsbury, G. (1978). The measurement of auditory abilities of blind, partially sighted, and sighted children. *Applied Psychological Measurement, 2,* 491−503.

Starkey, P., & Cooper R.G. Jr. (1980). Perception of numbers by human infants. *Science, 210 (4473),* 1033−1035.

Starkey, P., Spelke, E.S., & Gelman, R. (1983). Detection of intermodal numerical correspondences by human infants. *Science, 222*, 179−181.

Starkey, P., Spelke, E.S., & Gelman, R. (1990). Numerical abstraction by human infants. *Cognition, 36,* 97−127.

Stevens, S.S. (1953). On the brightness of lights and the loudness of sounds. *Science, 118*, 576.

Stevens, S.S. (1955). The measurement of loudness. *Journal of the Acoustical Society of America, 27,* 815–829.

Stevens, S.S (1957). On the psychophysical law. *Psychological Review, 64 (3),* 153–181.

Stevens, S.S. (1966). Matching functions between loudness and ten other continua. *Perception and Psychophysics, 1*, 5–8.

Stevens, S.S. & Greenbaum, H. (1966). Regression effect in psychophysical judgment. *Perception and Psychophysics, 1*, 439–446.

Stoianov, I., Umiltà, C., & Zorzi, M. (2005). Computational investigations of the Simon and the SNARC effects. Annual Meeting of the Cognitive Science Society.

Strack, F. & Mussweiler, T. (1997). Explaining the enigmatic anchoring effect: mechanisms of selective accessibility. *Journal of Personality and Social Psychology, 73 (3)*, 437−466.

Strauss, M.S., & Curtis, L.E. (1981). Infant perception of numerosity. *Child development, 52,* 1146−1152.

Svenson, O., & Sjöberg, K. (1983). Evolution of cognitive processes for solving simple additions during the three first school years. *Scandinavian Journal of Psychology, 24,* 117−124.

Szücs, D., & Csépe, V. (2005). The parietal distance effect appears in both the congenitally blind and matched sighted controls in an acoustic number comparison task. *Neuroscience letters, 384,* 11−16.

Teghtsoonian, R. (1973). Range effects in psychophysical scaling and a revision of Steven's law. *The American Journal of Psychology, 86 (1)*, 3–27.

Teghtsoonian, R. & Teghtsoonian, M. (1978). Range and regression effects in magnitude scaling. *Perception and Psychophysics, 24 (4),* 305–314.

Temple, E. & Posner, M. I. (1998). Brain mechanisms of quantity are similar in 5-year-olds and adults. *Proceedings of the National Academy of Sciences, 95 (13),* 7836−7841.

Thompson, J.C., Abbott, D.F., Wheaton, K.J., Syngeniotis, A., & Puce, A. (2004). Digit representation is more than just hand waving. *Cognitive Brain Research, 21 (3),* 412−417.

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: heuristics and biases. *Science, 185,* 1124−1131.

Townsend, J.T., & Ashby, F.G. (1978). Methods of modeling capacity in simple processing systems. In N. J. Castellan, & F. Restle (Eds.), *Cognitive theory* (pp. 199–239). Hillsdale, NJ: Erlbaum.

Townsend, J.T., & Ashby, F.G. (1983). *Stochastic modelling of elementary psychological processes.* NY: Cambridge University Press.

Trick, L., & Pylyshyn, Z.W. (1993). What enumeration studies can show us about spatial attention: Evidence for limited capacity preattentive processing. *Journal of Experimental Psychology: Human Perception and Performance, 19,* 331─351.

Trick, L., & Pylyshyn, Z.W. (1994). Why are small and large numbers enumerated differently? A limited capacity preattentive stage in vision. *Psychological Review, 101*, 80–102.

Uller, C., Huntley-Fenner, G., Carey, S., & Klatt, L. (1999). What representations might underlie infant numerical knowledge? *Cognitive Development*, *14*, 1−36.

Umiltà, C., & Nicoletti, R. (1990). Spatial stimulus-response compatibility. In R.W. Proctor & T.G. Reeve (Eds.), *Stimulus-response compatibility: An integrated perspective* (pp. 89−116). Amsterdam: Elsevier.

Valle-Inclàn, F. (1996). The locus of interference in the Simon effect: An ERP study. *Biological Psychology, 43*, 147–162.

van der Lubbe, R.H.J., Jaskowski, P., Wauschkuhn, B., & Verleger, R. (2001). Influence of time pressure in a simple response task, a choice-by-location task and the Simon task. *Journal of Psychophysiology*, *15*, 241–255.

van Dijck, J.P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. *Cognition, 113*, 248−253.

Van Loosbroek, E., & Smitsman, A.W. (1990). Visual perception of numerosity in infancy. *Developmental Psychology, 26*, 916−922.

Van Nieuwenhoven, C., Grégoire, J. & Noël, M.-P. (2001). *Le TEDIMATH. Test diagnostique des compétences de base en mathématiques*. Paris: ECPA.

van Oeffelen, M.P., & Vos, P.G. (1982). A probabilistic model for the discrimination of visual number. *Perception &Psychophysics, 32*, 163−170.

Venkatraman, V., Siong, S.C., & Chee, M.W.V. (2006). Effect of language switching on arithmetic: a bilingual FMRI study. *Journal of Cognitive Neurscience*, *18*, 64−74.

Verguts, T. & Fias, W. (2004). Representation of number in animals and humans: a neural model. *Journal of Cognitive Neuroscience, 16 (9)*, 1493−1504.

Verguts, T., Fias, W. & Stevens, M. (2005). A model of exact small-number representation. *Psychonomic Bulletin & Review, 12 (1),* 66–80.

Walsh, V. (2003). A theory of magnitude: common cortical metrics of time, space and quantity. *Trends in Cognitive Science, 7 (11),* 483−488.

Washburn, D.A., & Rumbaugh, D.M. (1991). Ordinal judgments of numerical symbols by macaques (Macaca Mulata). *Psychological Science, 2,* 190−193.

Wechsler, D. (1996). *WISC-III Manual: Canadian Supplement*. Orlando, FL: Psychological Corporation.

Whalen, J., Gallistel, C.R. & Gelman, R. (1999). Non-verbal counting in humans: the psychophysics of number representation. *Psychological Science, 10 (2),* 130–137.

Wiese, H. (2003a). Iconic and non-iconic stages in number development: the role of language. *Trends in Cognitive Sciences*, *7* (9), 385−390.

Wiese, H. (2003b). *Numbers, Language, and the Human Mind*. Cambridge, MA: Cambridge University Press.

Wilson, D., & Pratt, J. (2007). Evidence from a response choice tasks reveals selection bias in the attentional cueing paradigm. *Acta Psychologica, 126,* 216−225.

Wood, G., Nuerk, H.C., & Willmes, K. (2006). Crossed hands and the SNARC effect: a failure to replicate Dehaene, Bossini and Giraux (1993). *Cortex, 42,* 1069−1079.

Wood, J.N., & Spelke, E.S. (2005). Infant's enumeration of actions: numerical discrimination and its signature limits. *Developmental Science*, *8*, 173−181.

Wynn, K. (1990). Children’s understanding of counting. *Cognition*, *36*, 155−193.

Wynn, K. (1992a). Addition and subtraction by human infants. *Nature, 358,* 749−750.

Wynn, K. (1992b). Children's acquisition of the number words and the counting system. *Cognitive Psychology*, *24,* 220−251.

Wynn K. (1995). Infants possess a system of numerical knowledge. *Current Directions in Psychological Science, 4,* 172–176.

Wynn, K. (1996). Infants’ individuation and enumeration of actions. *Psychological Science, 7 (3),* 164−169.

Wynn, K., Bloom, P., & Chiang, W.C. (2002). Enumeration of collective entities by 5-month-old infants. *Cognition, 83,* B55–B62.

Xu, F. (2003). Numerosity discrimination in infants: evidence for two systems of representations, *Cognition*, *89*, B15−B25.

Xu, F., & Arriaga, R.I. (2007). Number discrimination in 10-month-old infants. *British Journal of Developmental Psychology*, *25,* 103−108.

Xu, F., & Spelke, E.S. (2000). Large number discrimination in 6-month-old infants. *Cognition, 74,* B1−B11.

Xu, F., Spelke, E.S., & Goddard, S. (2005). Number sense in human infants. *Developmental Science*, *8,* 88−101.

Yamamoto, S., & Kitazawa, S. (2001). Reversal of subjective temporal order due to arm crossing. *Nature Neuroscience, 4,* 759–765.

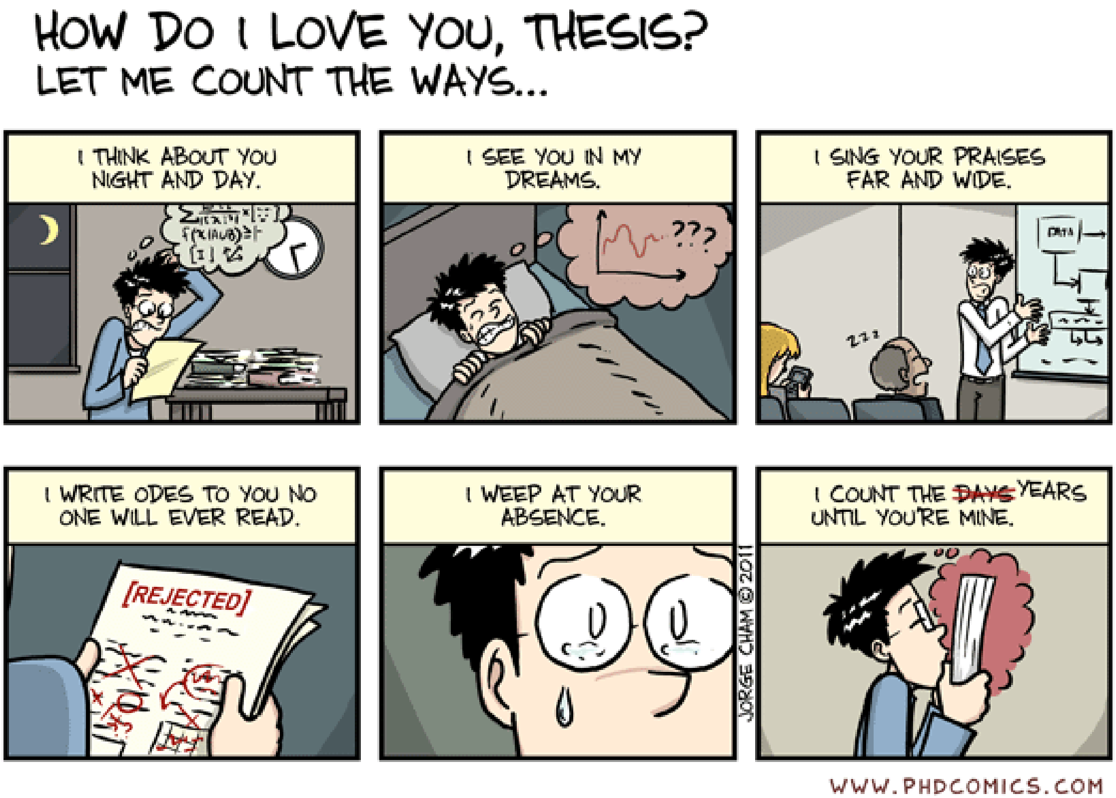
Zago, L., Pesenti, M., Mellet, E., Crivello, F., Mazoyer, B., & Tzourio-Mazoyer, N. (2001). Neural correlates of simple and complex mental calculation. *Neuroimage, 13 (2),* 314−327.

Zebian, S. (2005). Linkages between number concepts, spatial thinking, and directionality of writing: The SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*, 165−190.

Zorzi, M., Priftis, K., Meneghello, F., Marenzi, R., & Umilta, C. (2006). The spatial representation of numerical and non-numerical sequences: Evidence from neglect. *Neuropsychologia, 44 (7),* 1061−1067.

Zorzi, M., Priftis, K., & Umiltà, C. (2002). Brain damage: Neglect disrupts the mental number line. *Nature, 417*, 138−139.

Zorzi, M., & Umiltà, C. (1995).A computational model of the Simon effect. *Psychological Research, 58*, 193−205.


HOW DO I LOVE YOU, THESIS?
LET ME COUNT THE WAYS...
I THINK ABOUT YOU NIGHT AND DAY.
I SEE YOU IN MY DREAMS.
???
I SING YOUR PRAISES FAR AND WIDE.
DATA
I WRITE ODES TO YOU NO ONE WILL EVER READ.
[REJECTED]
I WEEP AT YOUR ABSENCE.
JORGE CHAM © 2011
I COUNT THE ~~DAYS~~ YEARS UNTIL YOU'RE MINE.
WWW.PHDCOMICS.COM