Journal of Experimental Child Psychology xxx (2011) xxx–xxx

Contents lists available at ScienceDirect

Journal of Experimental Child Psychology

journal homepage: www.elsevier.com/locate/jecp

# The role of vision in the development of finger–number interactions: Finger-counting and finger-montring in blind children

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ARTICLE INFO

*Article history:*
Received 17 January 2011
Revised 3 March 2011
Available online xxxx

*Keywords:*
Finger counting
Blindness
Finger–number interactions
Finger montring
Enumeration
Numerical processing

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 elaboration of a finger numeral representation remains unexplored. In the current study, 14 congenitally blind children and 14 matched sighted controls undertook three different test batteries that examined (a) general cognitive abilities, (b) the spontaneous use of finger-counting and finger-montring strategies (where "finger-montring" is a term used to characterize the way people raise their fingers to show numerosities to other people), and (c) the canonicity level of the finger-counting and finger-montring habits. Compared with sighted controls, blind children used their fingers less spontaneously to count and in a less canonical way to count and 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.



## Introduction

The question of how children develop a conceptual understanding of numbers and counting remains unresolved. Although it has been argued that implicit principles guide the development of

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doi:10.1016/j.jecp.2011.03.011

counting skills (i.e., the principles-first model [e.g., Gelman & Gallistel, 1978]), some researchers have suggested that children first learn to count by reciting a verbal string of undifferentiated counting words and then gradually discover the regularities of the counting procedure (i.e., the procedures-first model [e.g., Briars & Siegler, 1984; Fuson, 1988]). Whatever the respective contribution of the principles-first and procedures-first models, it was assumed that fingers may play a functional role in the development of a mature counting system (Butterworth, 1999a, 1999b, 2005; Fuson, 1988; Fuson, Richards, & Briars, 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 particular, fingers have been found to contribute to (a) giving an iconic representation of numbers (Fayol & Seron, 2005), (b) keeping track of the number words uttered while counting up or down at the numerable chain level (Fuson et al., 1982), (c) 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 $2 \times 5$ (the sub-base 5 system), (d) 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), and (e) 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 because the finger configurations used for these two strategies often differ from each other; for example, whereas children raise their index and middle fingers to show the numerosity 2, they raise their thumb and index finger to count to 2. These functional connections between fingers and numbers appear to be very robust given that 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 5 years of age was shown to be a good predictor of arithmetic abilities at 6 and 8 years of age (Fayol, Barrouillet, & Marinthe, 1998; Marinthe, Fayol, & Barrouillet, 2001). This finding was replicated by Noël (2005) and extended by Gracia-Bafalluy and Noël (2008), who observed that 8 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 participants were submitted to tasks involving either finger movement control or number processing (Pesenti, Thioux, Seron, & De Volder, 2000; Piazza, Mechelli, Butterworth, & Price, 2002; Pinel, Piazza, Le Bihan, & Dehaene, 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 lesion (Gerstmann, 1930; Mayer et al., 1999) or a transient lesion (via repetitive transcranial magnetic stimulation [rTMS]) of the left angular gyrus (Rusconi, Walsh, & Butterworth, 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, Krinzinger, & Willmes, 2008) and by larger reaction times when adults compare a pair of digits containing at least one number larger than 5 (Domahs, Moeller, Huber, Willmes, & Nuerk, 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, Seron, & Olivier, 2007; see Sato, Cattaneo, Rizzolatti, & Gallese, 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 (spatial numerical association of response code) effect (Fias & Fischer, 2005; Fischer,

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2006, 2008). This effect indicates that small numbers are preferentially represented to the left, whereas larger numbers are preferentially represented to the right, and thus is considered to reflect the left-to-right orientation of the mental representation of numbers (Dehaene, Bossini, & Giraux, 1993). 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 need to retrieve the result of simple arithmetic operations (Badets, Pesenti, & Olivier, 2010). Finally, Di Luca, Granà, Semenza, Seron, and Pesenti (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 1–5 and from the left thumb to the left little finger for numbers 6–10).

Although 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 *ontogenetic* development because children discover (either spontaneously or by observing adults) that fingers may be helpful to perform counting and arithmetic procedures (Butterworth, 1999a, 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, 2008).

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 that is often associated with the dorsal visual pathway. Furthermore, because 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, 1981; Wiese, 2003a; Wiese, 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 current study, 14 congenitally blind children and 14 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 test 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 current article aimed to address three questions. First, do blind children use their fingers to count and to show quantities? If vision is critical for the development of finger–number interactions, blind children would not be expected to spontaneously use their fingers 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), blind children should use their fingers as often as sighted children do. Second, if blind children do not use their fingers or use them less, do they achieve the same level of performance as sighted children? If finger-counting is a necessary tool for the emergence of an efficient counting behavior, 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, blind children should achieve the same level of performance. Third, 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.

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Therefore, blind children were expected to use their fingers (to count and to show numerosities) in a different way than sighted children.

## Method and results

### *Participants*

A total of 16 blind children (7 girls and 9 boys) participated in the study. The results for 2 blind boys were discarded (1 because his IQ was too low [<72] and 1 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) all were born with visual impairment and did not have any other disability. Of the 14 children, 9 came from Belgium and 5 came from Canada. The children were between 7 and 13 years old (mean age = 9.9 ± 2.09 years) (see Table 1).

To take into account the cultural differences in the way children use their fingers to count and to show quantity (Butterworth, 1999a, 1999b; Sato & Lalain, 2008), 14 sighted children (12 right-handed, 1 left-handed, and 1 ambidextrous) were selected to match the blind children on the nationality criterion. As we will see later, the finger-counting and finger-montring behaviors of Canadian and Belgian children were not different from each other. In addition, and as shown in Table 1, sighted children were also matched to blind children on IQ ($M = 110.2$), gender (7 girls and 7 boys), and age ($M = 9.3 \pm 2.4$ years, range = 6–13). IQ was estimated by two verbal subtests of the Wechsler Intelligence Scale for Children-III (Wechsler, 1996): Similarity and Information. Because 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, $U = 93.5$, $p > .80$, or IQ estimation, $U = 66.0$, $p > .10$.

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

### *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. To explore the presence of group differences, Mann–Whitney *U* 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. Because these two analyses systematically led to the same conclusions, we reported only the exact statistics of the Mann–Whitney *U* test (because this test was more adapted to the non-normal distribution of our data). For ease of comprehension, we nevertheless reported the mean scores of the two groups (although the Mann–Whitney *U* test did not compare mean scores).

#### *Working memory*

Children's working memory capacities were examined using two different tests: 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 of the sentences were true (e.g., "*Les abeilles fabriquent du miel*" [Bees make honey]), and 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

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**Table 1**
Characteristics of the children.

| Blind children | | | | | | | Sighted children | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Gender | Country | Age (years; months) | IQ | Handedness | Cause of blindness | Name | Gender | Country | Age (years; months) | 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.

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number of items correctly recalled divided by the total number of items) was calculated for each child.

The pseudo-word repetition task was conducted 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 (consonant–vowel [CV] for the first list and consonant–consonant–vowel [CCV] for the second list). Each list comprised four one-syllable items, four two-syllable items, four three-syllable items, four four-syllable items, and four five-syllable items. The span measure corresponded to the longest set for which all of the target pseudo-words were correctly recalled.

Scores on the listening span test did not differ significantly between the two groups, $U = 92.5$, $p > .80$; blind children correctly recalled 77.62% ($SD = 16.07$) of the words, and sighted children correctly recalled 77.46% ($SD = 11.83$) of the words. In contrast, when the children were asked to recall pseudo-words, blind children had significantly better span scores ($M = 9.29 \pm 0.82$) than sighted children ($M = 8.50 \pm 0.65$), $U = 47.5$, $p < .05$. The scores were nearly at the ceiling for CV syllables (only 1 sighted child made an error in this list) but were lower for CCV syllables.

*Addition*

In this task, children were asked to solve eight addition problems with single-digit numbers. These addition problems were drawn from the Tedi-Math battery (Van Nieuwenhoven, Grégoire, & Noël, 2001) but were orally presented rather than visually presented. Each correct response was credited with 1 point, giving a maximum score of 8 points.

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 ($M = 7.57 \pm 0.76$) in the sighted group. The Mann–Whitney test did not show any significant group differences on this task, $U = 96.0$, $p > .90$.

*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 finger of the opposite hand. The procedure was first applied to the dominant hand and then to the nondominant hand. The task comprised 14 items (10 "one-touched finger" items and 4 "two-touched fingers" items) on each hand. A score of 1 point was given for each correctly recognized finger, giving a maximum score of 36.

Again, blind children did not differ significantly from sighted children in this task ($M$s = $34.07 \pm 2.30$ and $32.14 \pm 3.96$ for blind and sighted children, respectively), $U = 70.5$, $p > .10$.

*Ordered sequence knowledge*

To assess the knowledge of the counting word sequence, children were asked (a) to count orally as far as possible (they were stopped at 31 if they got that far), (b) to count up to 9 and up to 6, (c) to count on from 3 and from 7, (d) to count from 5 to 9 and from 4 to 8, and (e) to count down from 7 and from 15. All of these items were drawn from the Tedi-Math battery (Van Nieuwenhoven et al., 2001). The knowledge of three other ordered sequences was also evaluated; children were required to recite the days of the week, the months of the year, and the letters of the alphabet. A score of 1 point was given for each correctly recited sequence.

Statistical analyses showed that knowledge of the numerical chain was equivalent in both groups ($M = 9.43 \pm 1.16$ and $9.86 \pm 0.36$ for blind and sighted children, respectively), $U = 82.0$, $p > .30$. Concerning knowledge of the three ordered sequences, 1 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.

*Summary of test battery 1*

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 well balanced overall. Indeed, there was only one significant difference between blind and sighted children on the general cognitive abilities measures, namely that blind children performed better than sighted children in the pseudo-words repetition task, in line with the superior verbal memory skills already observed in congenitally blind adults (Amedi, Raz, Pianka, Malach, & Zohary, 2003).

### *Test battery 2: spontaneous finger use*

The second test battery was devised to assess the spontaneous use of fingers in different numerical contexts. Thus, children were not informed about the possibility to use their fingers but were free to use any strategy they wanted. All of the tests nevertheless were 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). To examine our first two questions, (a) Do blind children use their fingers to count and to show quantities? and (b) 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 assessed as a behavioral indicator of the use of fingers.

#### *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* (fly), *femme* (woman), *Georges* (Georges), *princesse* (princess), and *miséreux* (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. Thus, the maximum score was 10. Because 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*s = 2.86 and 6.57 for blind and sighted children, respectively), $U = 60.0$, $p = .05$, but nevertheless achieved the same level of performance, $U = 91.0$, $p > .70$ (see Fig. 1). The finger-counting strategy was used by only 4 blind children (Sha, Ana, Ill, and Ant) as compared with 10 sighted children.

#### *Two-syllable counting*

Children were exposed to 10 series of two phonetically dissimilar syllables (/pa/ and /ji/)[1] and were instructed to count the numbers of /pa/ and /ji/ sounds in a sequence (e.g., "/pa/, /ji/, /ji/, /pa/, /pa/, /ji/ " = 3 /pa/, 3 /ji/). The syllables were emitted at a rate of one per second. The total number of syllables ranged from 6 to 10; the number of /pa/ sounds ranged from 3 to 7, and the number of /ji/ sounds ranged from 2 to 6. Because 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, $U = 51.0$, $p < .05$, and used their fingers substantially less often than sighted controls (*M*s = 3.08 and 8.57 for blind and sighted children, respectively), $U = 41.0$, $p < .01$ (see Fig. 1). Indeed, the finger-counting strategy was used by only 4 blind children (Ana, Ill, Sal, and Ant) as compared with 12 sighted children. Note that 1 blind child (Sha) was excluded 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/). Interestingly, however, blind children who used the finger-counting strategy were

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

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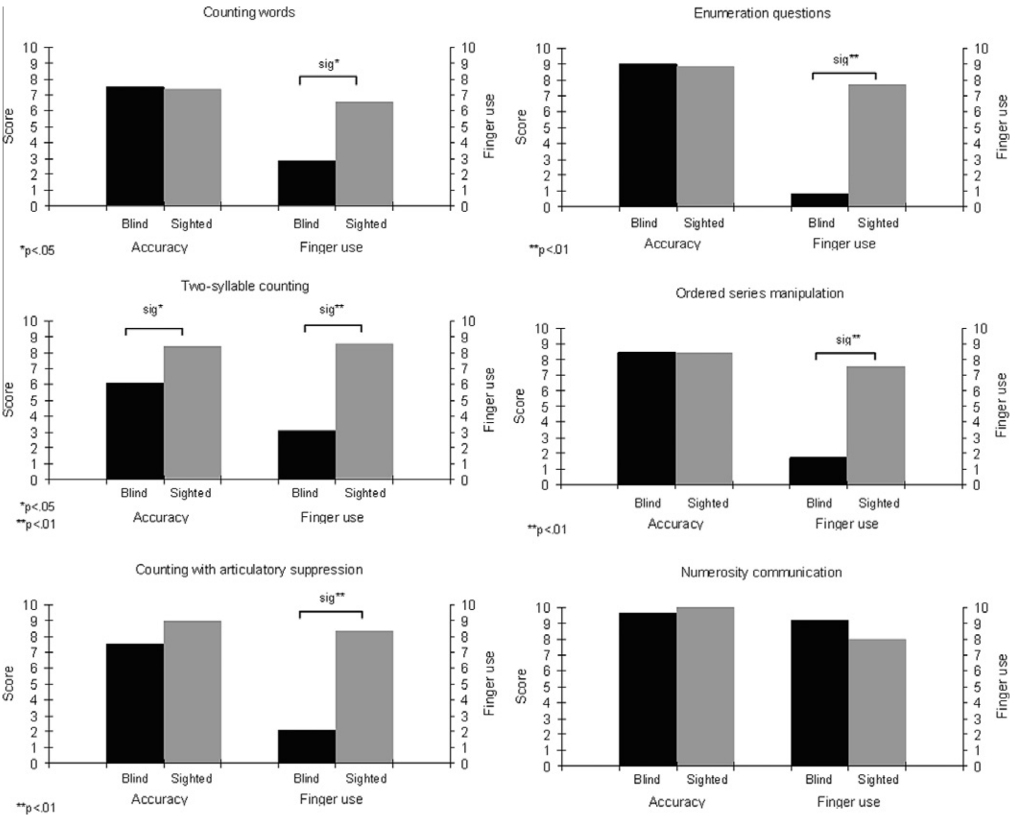


**Fig. 1.** Results of test battery 2.

also the ones who achieved the highest level of performance ($M = 8.5$ for children who used their fingers, $M = 5$ for children who did not use them). In contrast, our data did not allow establishing the inverse relationship; sighted children who did not use their fingers were not the ones who achieved the lowest level of performance ($M = 8.5$ for children who did not use their fingers, $M = 8.42$ for children who used their fingers).

*Counting with articulatory suppression*

Children were required to count the number of times the experimenter touched their shoulder. 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. Therefore, finger-counting was 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, $U = 55.0$, $p = .07$, and used their fingers substantially less often than sighted children, $U = 30.5$, $p < .001$ ($M$s = 2.15 and 8.57 for blind and sighted children, respectively) (see Fig. 1). Indeed, only 3 blind children spontaneously used the finger-counting strategy (Ana, Sil, and Ant), whereas 12 sighted children did so. As in the previous task, blind children who used the finger-counting strategy were the ones who achieved the highest level of performance ($M = 9.67$ for children who used their fingers, $M = 6.9$ for children who did not use their fingers). In contrast, and as in the previous task, our data did not allow establishing the inverse relationship; sighted children who did not use their fingers were

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not the children who achieved the lowest level of performance ($M = 9.0$ for the two subgroups of children).

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

*Enumeration questions*

In this test, children were required to name a specific number of exemplars from 10 different target categories (five boys' names, four jobs, six girls' names, nine animals, three colors, seven fruits, four toys, eight household objects, five foods, and six items of clothing). Thus, the enumeration question task required the children to (a) retrieve information from the verbal long-term memory, (b) name this information, (c) keep track of the number of items already retrieved, (d) go on retrieving information from the long-term memory content, and (e) 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 gotten.

In the enumeration questions task, the accuracy scores were the same for the two groups, $U = 89.0$, $p > .60$, but the finger-counting strategy was used significantly less often by blind children ($M = 0.86$) than by sighted children ($M = 7.71$), $U = 11.0$, $p < .001$ (see Fig. 1). Only 3 blind children used the finger-counting strategy; of these, 2 used it to count beyond 6 (Ana and Ant) and 1 used it after he had made an error (Ill). In the sighted group, on the other hand, all of the children except 1 used this strategy.

*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?", and "What's the name of the fourth day of the week?" Knowledge of these three sequences had previously been assessed by asking the children to recite them (see "Ordered-sequence knowledge" section above). Here too, finger use was expected to facilitate the manipulation of the sequences.

Blind and sighted children's performances were equivalent, $U = 87.0$, $p > .80$, but 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 ($M$s = 1.71 and 7.54 for blind and sighted children, respectively), $U = 16.5$, $p < .001$ (see Fig. 1). Only 5 blind children used their fingers occasionally (Sha, Ana, Ill, Sal, and Ant), whereas 12 sighted children used them regularly. Note that 1 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 "Ordered sequence knowledge" section above).

*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 nonverbal strategy. Because 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, $U = 84.0$, $p > .10$. Moreover, both groups of participants used their fingers equally often, $U = 88.0$, $p > .40$ (see Fig. 1). In this task, all of the blind children used their fingers to show the numerosity, but 2 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, 2 children never used the finger-montring strategy (1 moved the head to draw the Arabic numbers, and 1 used the hands to represent the shape of the Arabic numerals).

*Summary of 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 3 or 4 blind children using their fingers. Interestingly, these children were nearly always the same: Ana, Ill, and Ant. To examine the potential influence of variables such as 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 five enumeration tasks) as the dependent variable. The results of this analysis showed that the factor group was significant ($p < .001$), whereas the factors IQ ($p > .10$), age ($p > .20$), and pseudo-word recall ($p > .80$) 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). However, in the other two tasks (i.e., two-syllable counting and counting with articulatory suppression), 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 ones who achieved a high level of performance.

Moreover, because fingers were used equally 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, whereas sighted participants did not make any.

### *Test battery 3: canonicity of the finger-based representations*

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

#### *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 emitted 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. Because Belgian and Canadian sighted children typically counted by raising their fingers in the order of thumb, index finger, middle finger, ring finger, and little finger of the dominant hand (for numbers 1–5) and then the same order of the nondominant hand (for numbers 6–10), the following criteria were used: (a) the "raising" criterion (did children raise their fingers to count?), (b) the "conventional order" criterion (did children use the fingers of each hand in the conventional order?), and (c) the "laterality" criterion (did left-handed children start counting with their left hand, and did right-handed children start counting with their right hand?) (Sato & Lalain, 2008). Compliance with each criterion (for each child and each counting sequence) was assessed by a dichotomized scale (0 = noncompliance and 1 = compliance). The criteria were evaluated independently from each other.

The data demonstrated that blind children behaved in a less stereotypical way than sighted children on every criterion. Indeed, whereas all of the sighted children raised their fingers to count, only 6 blind children did so (Ana, Sum, Sal, Mat, Sil, and Ant), $U = 25.0$, $p < .001$. 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, $U = 47.0$, $p < .05$ (1 sighted child and 2 blind children were excluded from this analysis because they were ambidextrous). In the sighted group, most of the children started counting with their dominant hand; indeed, 11 of the 12 right-handed children started counting with their right hand, whereas the only left-handed child started counting with her left hand. In the blind group, 6 of the 11 right-handed children started counting with their right hand, whereas the remaining 6 blind children (5 right-handed and 1 left-handed) started counting with their left hand. Interestingly, the 6 children who raised their fingers to count (Ana, Sum, Sal, Mat, Sil, and Ant) were not necessarily the ones who started counting with their dominant hand (Cat, Ana, Ill, Sal, Sel, Mat, and Ant). Moreover, and most important, blind children also used their fingers in a less standard order than sighted children, $U = 56.0$, $p < .01$. 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 1–5 and from the thumb to the little finger of her right hand for the numbers 6–10. 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 7. Ill counted by using his two hands alternately, follow-

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ing a specific order (right forefinger, left forefinger, right middle finger, left middle finger, etc.). 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 2 blind children who used alternate counting (Ill and Sal) were not ambidextrous. Interestingly, some blind children changed their strategy in the course of the task; for example, Sil often started counting with the index finger but sometimes counted following the typical Canadian order. In addition to not being conventional, the finger-counting behavior of blind children did not respect the stable-order principle either. 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 1–5 and then from the thumb to the little finger of the other hand for numbers 6–10) and never changed their finger-counting procedure in the course of the task. Finally, and interestingly, 2 of the 3 blind children who systematically and spontaneously used their fingers in the second test battery (Ana and Ant) were also the children who showed typical finger-counting behavior (i.e., both respect the three criteria). Because these children performed quite well in the enumeration tasks, it could be interesting to examine whether finger-counting training could improve the mathematical achievement of blind children.

*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 = noncanonical configuration and 1 = canonical configuration). The configurations considered to be canonical are shown in Fig. 2.

When required to show quantities by using their fingers, blind children again behaved differently from their sighted peers, $U = 58.0$, $p < .05$. Whereas 11 sighted children used canonical configurations to represent the numbers from 1 to 10, only 5 blind children did so. Mat represented the numbers 4 and 9 (4 + 5) with the fingers used for the counting behavior (i.e., 4 was represented with the thumb and the index, middle, and ring fingers). The other blind participants often represented even numbers by using both hands in a symmetric way; Sel represented the number 2 by using both of 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, and so on. However, all of the children used the canonical configurations of numbers 5 and 10 (one and two opened hands, respectively).

*Summary of 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

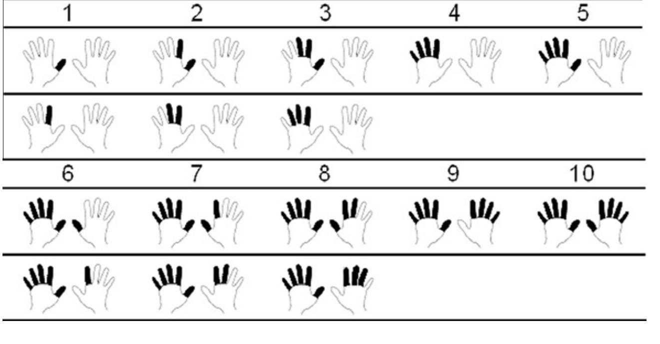


**Fig. 2.** Canonical finger-montring configurations for numbers 1–10. Darkened fingers correspond to raised fingers. For some numbers (1, 2, 3, 6, 7, and 8), two configurations were considered to be canonical.

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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 5 property.

## General discussion

Developmental, behavioral, neuropsychological, and neuroimaging studies have reported the existence of a close connection between number processing and finger representation. Because fingers provide a physical counterpart to number words (Andres, Di Luca, & Pesenti, 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, because digital and numerical processing still interact during 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 current 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. First, although vision is not necessary to the elaboration of numerical abilities within (Ferrand, Riggs, & Castronovo, 2010) 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. Second, fingers are a useful but unnecessary 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-syllable counting task, they achieved the same level of performance in the three other counting tasks (i.e., counting words, enumeration questions, and ordered series manipulation), thereby indicating that the counting behavior has emerged in these children. Third, 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 5 property or the stable-order principle.

Because the two groups performed at a similar level in the finger discrimination task, these conclusions cannot be attributed merely 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 need 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 & Spilsbury, 1978) and by their better span scores at the pseudo-word repetition task (see "Working memory" section above), 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 & Pesenti, 2008; Di Luca et al., 2006; 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 electroencephalogram (EEG) study demonstrated that blind and sighted adults represent numbers through a similar spatial code, different neurophysiological correlates have been found to underlie number manipulation in the two groups (Sallilas, Granà, El-Yagoubi, & Semenza, 2009). In this study, participants needed to react as quickly as possible to an auditory target presented either in either the left or 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 toward the left auditory space and large spoken number words generated a spatial shift of attention toward the right auditory space (i.e., the SNARC effect [Fischer, Castel, Dodd, & Pratt, 2003]). In other words, small numerical primes facilitated the detection of left auditory target, whereas large numerical primes facilitated the detection of right auditory target. However, whereas the amplitude of the sensory N100 component was modulated by congruency (i.e., small primes-left auditory target and 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. Because 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 more cognitive way, relying much more on working memory than on sensorimotor processes. Together with our observations, this finding suggests that congenitally blind individuals may compensate for their lack of vision by relying on working memory skills 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, whereas 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 very demanding. Because learning basic arithmetic abilities is often very demanding for children's working memory, one may wonder whether training the finger-counting behavior of blind children could improve their numerical abilities (see Gracia-Bafalluy & Noël, 2008, for similar results with sighted children). Moreover, because 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 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 representations is not uniquely attributable to finger-counting habits as postulated by some authors (Fias & Fischer, 2005; Fischer, 2006, 2008). Instead, because blind participants are Braille readers and 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 the Introduction, two different views have been proposed to account for the origin of the interactions between numbers and fingers: the functionalist hypothesis (Butterworth, 1999a, 1999b, 2005) and the redeployment hypothesis (Anderson, 2010; Penner-Wilger & Anderson, 2008). Because the current article 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. Therefore, these interactions should not manifest in blind people who did not use the finger-counting strategy during childhood. Conversely, according to the redeployment hypothesis, individuals who do not have finger agnosia but who did not use the finger-counting and finger-montring strategies during infancy should nevertheless show traces of a numerical finger-based representation while performing numerical tasks during adulthood. So, although blind adults did not use their fingers to process numbers during infancy, they should show (a) activation of the left angular gyrus while performing arithmetic tasks (e.g., Pesenti et al., 2000), (b) greater reaction times while comparing a pair of digits that contains at least one number larger than 5 (Domahs et al., 2010), and (c) increased corticospinal activity of hand muscles while performing a parity judgment task (e.g., Sato et al., 2007). Therefore, we argue that further investigation of numerical processing in blind adults may help to disentangle the functionalist and redeployment hypotheses, which might not be two mutually exclusive theories.

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