The role of fingers in the development of counting and arithmetic skills

Virginie Crollen and Marie-Pascale Noël

Institut de Recherche en Sciences Psychologiques (IPSY)

Centre de Neuroscience Système et Cognition (NeuroCS)

Université Catholique de Louvain,

Place Cardinal Mercier 10, B-1348 Louvain-la-Neuve, Belgium

Correspondence concerning this article should be addressed to:

Virginie Crollen

Institut de Recherche en Sciences Psychologiques (IPSY)

Centre de Neuroscience Système et Cognition (NeuroCS)

Université Catholique de Louvain

Place Cardinal Mercier 10

B-1348 Louvain-la-Neuve

Belgium

Email: virginie.crollen@uclouvain.be.

Tel: (0032) 10 47 40 89

Word count (main text): 5795

Abstract

Interactions between fingers and numbers have been reported in the existing literature on numerical cognition. The aim of the present research was to test whether hand interference movements might have an impact on children performance in counting and basic arithmetic problem solving. In Experiment 1, 5-year-old children had to perform both a one-target and a two-target counting task in three different conditions: with no constraints, while making interfering hand movements or while making interfering foot movements. In Experiment 2, first and fourth graders were required to perform addition problems under the same control and sensori-motor interfering conditions. In both tasks, the hand movements caused more disruption than the foot movements, suggesting that finger-counting plays a functional role in the development of counting and arithmetic.

Keywords: counting; finger-counting; numerical development; arithmetic.

Word count (abstract): 124

1. Introduction

Following the observation that children use their fingers at an early age (Butterworth, 1999a, 1999b) while learning counting (Gelman & Gallistel, 1978; Fuson, 1988) and basic arithmetic operations (Geary, 2004, 2007; Geary & Hoard, 2005), a large amount of research started to study the role fingers play in the acquisition of the number concept. While fingers have traditionally been seen as the “missing tool” (Andres, Di Luca & Pesenti, 2008) that sustains the assimilation of basic numerical abilities or the “missing link” (Fayol and Seron, 2005) that permits the connection between non-symbolic numerosities and symbolic numbers, new and compelling evidence which constrains this hypothesis has now been highlighted in the literature (see Crollen, Seron & Noël, 2011a for a review).

Lafay, Thevenot, Castel and Fayol (2013) for example developed a task in which preschoolers (between 4 and 5 years) were presented with sets of pictures. Participants were first asked to name the pictures one by one and just after to give the cardinal number of pictures in the collection. A very high correlation was observed between the frequency of finger use and the percentages of correct responses, thus supporting the idea that fingers are a useful tool in the development of the counting system. However, despite this correlation, the authors (Lafay et al., 2013) also reported that some children who never used their fingers were nevertheless able to perform optimally in the enumeration task. These observations, suggesting that finger-counting is not a necessary step for the acquisition of good counting abilities, are quite in line with the data reported by Crollen, Mahe, Collignon and Seron (2011b). These authors indeed demonstrated that blind children who did not use finger-counting could nevertheless develop their counting skills quite normally.

It has also been repeatedly observed that children use their fingers while learning to solve simple addition and subtraction problems (Jordan, Huttenlocher & Levine, 1992; Jordan, Levine & Huttenlocher, 1994). Accordingly, performance on finger gnosia tasks (i.e. the ability to distinguish which fingers have been lightly touched without visual feedback) was shown to be a good predictor of arithmetic performances: children with a weaker ability to identify and discriminate their fingers appeared to be less efficient in mathematical tasks than children with a high finger gnosia (Costa, Silva, Chagas, Krinzinger, Lonneman, Willmes, Wood, & Haase, 2011; Fayol, Barrouillet & Marinthe, 1998; Noël, 2005). The specific sub-base-five structure of the finger-counting system (i.e. numbers larger than 5 always include a full hand representation) also appears to induce a disproportionate number of split five errors (i.e. errors deviating by the correct result by exactly ±5) when children (Domahs, Krinzinger, & Willmes, 2008) perform mental calculation. Finally, the act of making passive (Imbo, Vandierendonck & Fias, 2011) and active (Michaux, Masson, Pesenti & Andres, 2013) hand movements appears to disrupt basic arithmetic problem solving in adults.

In this paper, we wanted to directly evaluate the impact of hand interference movements on the child's performance in counting and basic addition problem solving. To do so, 2 experiments were created. In Experiment 1, 5-year-old children were asked to perform a one-target and a two-target counting task in three different conditions: 1) a control 'resting' condition allowing an investigation of the spontaneous use of the fingers in the task; 2) a condition requiring concurrent hand movements which prevented the use of a finger-counting strategy; and 3) a condition requiring concurrent foot movements in order to assert the specificity of the putatively disruptive impact of hand movements on counting. If fingers are functionally related to the counting process in young children, then: 1) hand movements should be more disrupting than the interfering foot movements; 2) fingers should be used more frequently during the high-demanding task (i.e. more in the two-target than in the one-target counting task); and 3) the hand interference movements should be more disrupting in the two-target task.

Experiment 2 was designed to measure the impact of hand interference movements on basic arithmetic. To do so, first-grade and fourth-grade children were asked to solve addition problems under the same three experimental conditions as described in Experiment 1 (control, hand interference and foot interference). While first graders were tested twice (at the beginning and at the end of the school year), fourth graders were only tested once. In this sense, we were able to perform a longitudinal as well as a transversal evaluation of children's performance. First graders were selected as they are at the beginning of the single-digit additions learning process. At the beginning of this school year, children mostly use counting strategies to solve additions (Carpenter & Moser, 1984; Geary 1990) but they also learn to use more and more mature strategies along the year (e.g., from the counting all to the counting on procedure; Fuson, 1982). Accordingly, we wanted to examine the possible changes that occur in finger use while doing additions during grade 1. Fourth graders were tested as, at that age, children are supposed to retrieve simple addition solutions from long-term memory (Bailey, Littlefield, & Geary, 2012). As counting procedures are progressively replaced by memory retrieval through arithmetical fact learning (Siegler, 1987), we expect that the hand condition would be less interfering 1) for easy additions than for large additions and 2) at the end of the learning process (i.e. less disrupting for fourth graders than for first graders) rather than at the beginning of this process. Yet, as significant hand interference is still visible in adults (Imbo et al., 2011; Michaux et al., 2013), we expected a decrease but not a disappearance of that hand interference effect over development. In this experiment, we also tested children's finger gnosis as well as their memory skills in the phonological loop, visuo-spatial sketchpad and central executive. These measures were taken to examine their relations with arithmetic facts learning and the use of finger-counting.

2. Experiment 1

2.1 Method

2.1.1 Participants

We recruited 30 kindergarteners from 2 Belgian schools. However, 7 participants were discarded because they were unable to follow the instructions of the tasks. The remaining participants therefore included 10 girls and 13 boys between the ages of 5 years and 1 month and 6 years and 2 months ($M \pm SD = 5.6 \pm .4$), six of whom were left-handed. Written informed parental consent was obtained for all of the children.

2.1.2 Procedure

Children were required to perform two different counting tasks. In the *one-target counting* task, they had to count the number of times a particular sound was presented within a sequence. In the *two-target counting* task, they were exposed to series of 2 different but intermixed sounds and were asked to keep track and separately count the number of items of each of the 2 category lists.

As stimuli, we used two animal sounds (a dog and a horse) and two object sounds (a telephone and a fire alarm). The total number of sounds in both tasks was beyond the subitizing range: we used 2 different sequences of 6, 7 and 8 sounds and thus played a total of 6 sequences. In the one-target task, the sequence comprised either an animal sound or an object sound. Participants had to count and, at the end, report the number of sounds presented within the sequence. In the two-target task, each sequence was made of one animal sound and one object sound. The number of appearances of each target item ranged from 2 to 5 within a sequence. This was chosen in order to allow children to represent all the target quantities with their fingers. As shown in Table 1, three lists of stimuli pairs were used. Each item began with the presentation on the computer screen of a green light and ended with the presentation of a red light, both for 2,000 msec, indicating respectively the beginning and the end of the sequence. Every sound lasted one second. In the one-target counting task, the inter-stimulus interval varied within each sequence between 600 and 1,900 msec so that all sequences (of 6, 7 and 8 sounds) lasted 13,100 msec. In the two-target counting task, the inter-stimulus interval varied between 600 and 2,400 msec so that all sequences lasted 16,600 msec. This was done to prevent children from using the duration of the sequence as a cue to approximate their count.

Insert Table 1 about here

Each sequence in both tasks was also repeated in three different conditions: a control condition and two interference conditions. In the control condition, children were required to perform the counting tasks without any additional constraints. In the hand interference condition, children had to perform the counting task while repeatedly squeezing a ball in each hand. In the foot interference condition, children had to perform the task while repeatedly squeezing a ball with their feet. Contrary to the sound sequence, the rhythm of the interference movements was imposed as regular (one squeeze every second). To assist the children in maintaining this rhythm, a video representing the interference movements (i.e. a hand or a foot squeezing a ball every second) was shown in the center of the computer screen and children were asked to follow the rhythm of the video. The video was presented alone 8 s. before the experimental trials began so that the children could practice the movements, and kept showing up until the end of the trial. During the experimental trials, the video lasted 25,000 msec in the one-target counting task and 28,000 msec in the two-target counting task. The experimenter looked whether the children were correctly following the imposed rhythm of the interference movements. Children who could not manage to do it were discarded (n = 7). The three different lists of items were counterbalanced across conditions. The order of tasks and conditions was counterbalanced across participants. The experimenter noted the children’s responses and then calculated their accuracy scores. One point was given for each correct response. The experimenter also noted the number of times a child used his fingers to perform the task (this number was divided by the total number of items in the task and multiplied by 100 to give a percent measure). Procedures were approved by the Research Ethics Boards of the University of Louvain, Belgium.

2.2 Results

An ANOVA with tasks (one-target vs. two-target counting tasks) and conditions (control, hand interference and foot interference) as repeated measures was first performed on children's accuracy scores (i.e. percentage of correct responses). The task effect approached significance, $F(1, 22) = 3.06$, $p = .09$, $\eta^2 = .12$, indicating that performance tended to be slightly better in the one-target counting task ($M \pm SEM = 71.5\% \pm 4.83$) than in the two-target counting task ($M \pm SEM = 65.17\% \pm 3.67$). A significant effect of condition was highlighted, $F(2, 44) = 5.79$, $p = .01$, $\eta^2 = .21$. Bonferroni post-hoc comparison tests indicated that children performed less well in the hand interference condition ($M \pm SEM = 60.33\% \pm 5.67$) compared to in the control ($M \pm SEM = 74.5\% \pm 4.17$, $p = .01$) and foot interference conditions ($M \pm SEM = 70.17\% \pm 3.83$, $p < .05$), which, in turn, did not differ from each other, $p > .6$. The task x condition interaction failed to reach significance, $F(2, 44) = 1.81$, $p > .1$, $\eta^2 = .08$.

Secondly, we examined the use of fingers in both the control and the foot interference conditions (the hand condition was not involved in this analysis as children were prevented from using the finger-counting strategy). A 2 (tasks: one-target counting vs. two-target counting) x 2 (condition: control vs. foot) repeated measures ANOVA was therefore performed and showed a main effect of task, $F(1, 22) = 39.44$, $p < .001$, $\eta^2 = .64$, and a main effect of condition, $F(1, 22) = 11.46$, $p < .001$, $\eta^2 = .34$ (see Figure 1B). Children used their fingers more often in the two-target counting task ($M \pm SEM = 65.17\% \pm 8.33$) than in the one-target counting task ($M \pm SEM = 13.33\% \pm 5.17$) and also more often in the control condition ($M \pm SEM = 47.5\% \pm 6.33$) than in the foot interference condition ($M \pm SEM =$

31.17% ± 5.67). The task x condition interaction was not significant, $F(1, 22) = .001$, $p > .9$, $\eta^2 = .001$.

Insert Figure 1 about here

Correlation analyses were then performed on each task separately in order to see whether the finger use measure of the control condition could predict performance of every condition. As shown in Table 2, none of the correlations were significant in the one-target counting task. In the two-target counting task, the finger use measure of the control condition marginally predicted performance in the control condition, $r(22) = .37$, $p = .08$, showing that children who often used their fingers in the control condition actually tended to achieve better counting scores. It also predicted performance in the hand interference condition but in a negative way showing that children who used their fingers a lot in the control counting condition were those who performed more weakly when the dual task prevented them from using their fingers to count. Finally, this measure did not predict performance in the foot interference condition.

Insert Table 2 about here

2.3 Conclusions

Experiment 1 showed that kindergarteners tended to use their fingers while counting, especially when the task was more demanding and required to separately keep track of the number of items coming from 2 category lists. When the use of the fingers was prevented by the hand interference condition, counting performance dropped significantly. Such a drop of performance was however not observed in the foot condition. By showing that finger movements selectively disrupt children's counting procedure, experiment 1 adds evidence to previous data suggesting that finger-counting plays a selective role in number-related processes (Imbo et al., 2011; Michaux et al., 2013).

Experiment 2

Experiment 2 aimed at measuring the role of finger-counting, working memory and finger gnosis in an addition task.

3.1 Method

3.1.1 Participants

Two groups of children participated in this study and were recruited from different Belgian schools: 1) 29 first-grade children (17 girls, 12 boys) between the ages of 5.7 and 6.7 ($M \pm SD$ = 6.2 ± 0.3), three of whom were left-handed; and 2) 20 fourth-grade children (8 girls, 12 boys) between the ages of 8.7 and 10.7 (M = 9.6 ± 0.5), four of whom were left-handed. Written informed parental consent was obtained for all of the children. The first age group was tested twice (in October and in May) in order to evaluate performances in a longitudinal way and at the beginning of the mathematical learning. The second age group was tested once (in January) to allow a later and transversal evaluation of performances.

3.1.2 Procedure

In this study, children were asked to solve 18 addition problems under the same three conditions as in Experiment 1. These additions always involved two single-digit numbers but were of three different levels of difficulty. The first level included additions whose outcome was less than or equal to 5. The second level included additions whose outcome was between 7 and 9. The third level included additions whose outcome ranged between 11 and 13. The operations were visually presented in the Arabic format (courier new font, size 64, bold) in the center of a computer screen. The children had to solve them in the same control and interference conditions as described in the previous task. In the control condition, children were required to perform the task without any additional constraints. In the hand interference condition, children had to solve the additions while squeezing a ball in each hand. In the foot interference condition, children had to calculate while squeezing a ball with their feet. As previously, the imposed rhythm of the interference movements was regular (one squeeze every second). A video representing the interference movements appeared above the addition problem presented. Children were trained to follow the rhythm of the video before being required to solve the operations while squeezing the ball. During the experimental trials, the interfering movements were always presented alone during 4,000 msec. Children were asked to follow the rhythm as soon as the video begins. After 4,000 msec, the addition appeared in the center of the screen and stayed visible until children give a response. The experimenter pressed the space bar as soon as the child gave a verbal response. The press of the space bar ended the trial, the videos and the data (i.e. reaction times) collection. The experimenter had to press the space bar again to launch the next trial which was presented 1000 ms after the press. Participants were required to perform the task as fast and as accurately as possible. Procedures were approved by the Research Ethics Boards of the University of Louvain, Belgium.

In this experiment, children were also asked to perform a finger gnosis test and four working memory tasks. To test *finger gnosia*, the same procedure as the one used by Noël (2005) was applied. The child faced the experimenter, one arm extended with fingers spread out, the palm down and the hand placed in a box in order to hide it from the child's view. The experimenter touched one or two fingers of each child's hand. The hand was then removed from the box and participants were asked to show the touched finger(s) with the index finger of the opposite hand. In the first part of the test, unique and simultaneous touches were mixed. Fifteen trials were done with each hand; each finger received an isolated stimulation twice (10 trials) and was part of a simultaneous stimulation on two occasions (5 trials). In the second part of the test, successive stimulations of two fingers were provided and the child had to show, in the correct order, the two fingers touched. Each finger was touched twice (5 trials). The procedure was first applied to the dominant hand and then to the non-dominant hand. One point was given for each finger correctly identified, given a maximum score of 30 for each hand. Measures for both hands were merged in the results section as statistical analyses revealed that they were highly correlated, $r(48) = .67$, $p < .001$, and not different from each other, $t(48) = 0.39$, $p > .6$.

Working memory measures included the word span, the catego span, the listening span and the Corsi block tapping tests. The *words span* test was used to examine the phonological loop of the working memory. In this test, children were presented with a series of words (from 2 to 7) and had to immediately repeat them back in the correct order. Three sequences were arranged for each sequence length. Advancing to the next level requires reproducing 2 correct sequences out of 3. The corrected span (span of the child + 0.5 if the child succeeds 1 trial of the higher level) was calculated for each child. The *catego span test* (Noël, 2009) was used to examine children's central executive. This test differs from the traditional word span task by adding a processing demand to the requirement. Children had indeed to recall the words read by the examiner but by classifying them into their semantic category (food vs. animals). The test included sequences of 3 to 7 words. Advancing to the next level requires 2 correct sequences out of 3. The corrected span was measured for each child. Children also performed the listening span test. In this test, children listen to sets of 2 to 7 sentences and complete a factual verification question for the content of each sentence. After the last sentence of each set, children have to recall the final word of each sentence in the order in which they were presented. The span represents the maximum number of sentence performed correctly on at least 2 out of 3 trials. The corrected span was calculated for each child. Children were finally submitted to the *Corsi Block Tapping test* (Corsi, 1972; Milner, 1971). This test assesses the visuo-spatial sketchpad and consists of a series of 9 blocks arranged irregularly on a 23 x 28 cm board. The blocks are tapped, one per second, by the examiner in randomized sequences of increasing length and children have to reproduce the sequences, progressing until no longer accurate. Advancing to the next level requires reproducing 2 correct sequences out of 3. The corrected span was calculated for each child.

3.2 Results

To examine first-grade children's performances in the addition subtest, a 2 (session: beginning vs. end of the school year) x 3 (condition: control, hand interference, foot interference) x 3 (difficulty: level 1, level 2, level 3) repeated measures ANOVA was carried out on the percentage of correct responses. Two children were discarded from this analysis (one who presented outlier data which were two standard deviations greater than the overall mean; and one who did not perform the second testing session). Results highlighted a main effect of session, F (1, 26) = 29.84, $p < .001$, $\eta^2 = .53$, showing that first graders performed better at the end of the school year ($M \pm SEM$ = 79.67% ± 2.5) than at the beginning of the year ($M \pm SEM$ = 60.67% ± 3.5). A main effect of difficulty was also found, F(2, 52) = 96.52, $p < .001$, $\eta^2 = .79$: children's accuracy decreased with the increasing difficulty of the additions. All pairwise comparisons were significant ($M \pm SEM$ = 90.33% ± 2.00 for level 1; $M \pm SEM$ = 76.17% ± 3.17 for level 2; $M \pm SEM$ = 44.00% ± 4.00 for level 3, all $p_s < .001$). More importantly, we found a main effect of condition, F (2, 52) = 9.54, $p < .001$, $\eta^2 = .27$: accuracy scores were lower in the hand interference condition ($M \pm SEM$ = 64.00% ± 3.17) by comparison to the foot interference ($M \pm SEM$ = 74.83% ± 2.83) and control conditions ($M \pm SEM$ = 71.67% ± 2.73), both $p_s < .01$. These two last conditions were not different from each other, $p > .1$. Two interactions were also significant: a session x difficulty interaction F(2, 52) = 3.83, $p < .05$, $\eta^2 = .13$; and a difficulty x condition interaction, F(4, 104) = 3.19, $p < .05$, $\eta^2 = .11$. To further analyze the session x difficulty interaction, the difference between the first and the second sessions (dSessions) was computed for each difficulty level. The measure thus obtained was then submitted to a repeated-measures ANOVA. The main effect of difficulty was significant, F(2, 52) = 3.83, $p < .05$, $\eta^2 = .13$: dSessions was larger for difficulty levels 2 and 3 than for difficulty level 1 (both $p_s < .05$). It was in contrast similar in the difficulty levels 2 and 3, $p > .3$. In order to further analyze the difficulty x condition interaction, we performed separate ANOVAs for the 3 difficulty levels with the condition factor as the repeated measure. In the first and second difficulty levels, there was no difference between the conditions, $F(2, 52) = 2.78$, $p > .05$, $\eta^2 = .10$ for the first level; $F(2, 52) = 2.14$, $p > .1$, $\eta^2 = .08$ for the second level of difficulty. The condition factor was by contrast significant for the additions from the third level, $F(2, 52) = 10.41$, $p < .001$, $\eta^2 = .29$: the children's performance was smaller in the hand interference condition than in the foot interference and control conditions, both $p_s < .01$. The control and foot interference conditions were by contrast not different to one another, $p > .9$ (see Figure 2A and 2B). Our results thus suggest a specific role of fingers in the calculation process of young children.

The fourth graders' accuracy scores (i.e. percentage of correct responses) was also examined with a 3 (condition: control, hand interference, foot interference) x 3 (difficulty: level 1, level 2, level 3) repeated measures ANOVA. Results revealed a main effect of difficulty, $F(2, 38) = 14.9$, $p < .001$, $\eta^2 = .44$, indicating that additions from the first ($M \pm SEM$ = 98% ± 1.00) and second levels ($M \pm SEM$ = 97.17% ± 9.5) were overall better performed than the additions from the third level ($M \pm SEM$ = 85.5% ± 3.17), both $p_s < .01$. Additions from the first and second levels were not different to one another, $p > .9$. A significant main effect of condition was also found, $F(2, 38) = 3.85$, $p < .05$, $\eta^2 = .17$, as well as a significant difficulty x condition interaction, $F(4, 76) = 3.31$, $p <. 05$, $\eta^2 = .15$. Indeed, the hand interference condition ($M \pm SEM$ = 91.17% ± 2.00) induced lower accuracy scores than the foot condition ($M \pm SEM$ = 96.33% ± 1.33), $p < .05$, but was not different from the control condition (93.33% ± 1.67), $p > .1$. The foot interference and control conditions were not different either, $p > .1$. The difference between the hand and foot interference conditions appeared in the additions from the third level of difficulty only, $F(2, 38) = 0.24$, $p > .7$, $\eta^2 =$

.01 for level 1 ; $F(2, 38) = 1.65$, $p > .2$, $\eta^2 = .08$ for level 2 ; $F(2, 38) = 4.35$, $p < .05$, $\eta^2 = .19$ for level 3 (see Figure 2C).

Insert Figure 2 about here

To test whether the interference conditions were more disrupting at the beginning of the arithmetic learning process, a disruption score was calculated as follows : $DS = \frac{\text{AS control} - \text{AS Interference}}{\text{AS Control}}$, where "DS" corresponds to the disruption score, "AS Control" to the mean accuracy score in the control condition and "AS Interference" to the mean accuracy score in the interference condition (hand or foot interference condition). Two additional first graders were discarded from this analysis because they presented outlier data which were two standard deviations greater than the overall mean response. The measures obtained in the first graders' first and second testing session were first compared using a paired samples t-test. Results did not highlight any significant effect, $t(24) = 1.24$, $p > .2$ for the hand interference DS; $t(24) = 1.41$, $p > .1$ for the foot interference DS. The measures obtained for the first graders (first testing session) and fourth graders were then compared with an independent samples t-test. While the DS of the foot interference condition was similar in both groups, $t(43) = 1.25$, $p > .2$, the DS of the hand interference condition was larger in first graders ($M \pm SEM = 0.12 \pm 0.03$) than in fourth graders ($M \pm SEM = 0.02 \pm 0.02$), $t(43) = 2.62$, $p < .05$.

A factor analysis was run on the three verbal working memory measures using a principal component extraction analysis. Table 3 reports the communality and the loading of each variable. In grade 1, the working memory factor accounted for 51% of the variance and, in grade 4, it accounted for 61% of the variance. Correlation analyses were then computed to measure how much this verbal working memory measure as well as the finger gnosis and block tapping tests were related to early numerical development. As shown in Table 4, only one correlation was found in 1st graders: the verbal working memory measure significantly predict accuracy scores of the hand interference condition. In 4^{th} graders, none of the correlations were significant.

Insert Tables 3 & 4 about here

4. General discussion

Mathematical development is a great challenge for children and is a long-lasting process that lags well behind the development of the counting list or its use in an enumeration task (e.g. Wynn, 1992). In the literature, it has been hypothesized that finger-counting could sustain this development. In particular, it has been shown that children often use their fingers to: 1) show how old they are; 2) count; or 3) solve simple arithmetic problems such as additions. Some authors have therefore argued that fingers provide a physical counterpart to number words (Andres et al., 2008) and, accordingly, that they could be necessary to the assimilation and understanding of number meaning. Others (Alibali & DiRusso, 1999; Costa et al., 2011) considered that fingers may allow children to alleviate their working memory load and thus perform better in complex numerical tasks. Our paper was interested in testing the impact of hand interference movements on children's counting and basic arithmetic problem solving.

In Experiment 1, 5- to 6-year-olds were asked to perform a one-target and a two-target counting task under a control and two sensori-motor interfering conditions (hand interference vs. foot interference). We demonstrated that children used their fingers more frequently when the task was demanding (i.e. in the two-target counting task). Moreover, by preventing the use of the finger-counting strategy in the hand interference condition, we also disrupted children's performance in the two-target counting task. Finally, as the foot interference condition did not lead to the same interference effect as the hand interference movements, our results also support the idea that fingers play a selective role in counting-related processes (Imbo et al., 2011; Michaux et al., 2013). Another aspect of the results pattern that needs to be addressed regards the correlations that were found between the frequency of finger use and the performance observed in the two-target counting task: while finger use positively correlates with accuracy in the control condition (as also observed in Lafay et al., 2013), it negatively predicts performance in the hand interference condition. These correlations suggest that finger-counting actually support numerical development (Costa et al., 2011; Fayol et al., 1998): more often children use their fingers, better they will be in these counting tasks while more disrupted they will be while realizing finger movements that are unrelated to finger-counting.

In Experiment 2, 29 first-grade children and 20 fourth-grade children had to solve addition problems under the same experimental conditions as described in the previous task (control, hand interference, and foot interference). First graders were tested twice. Fourth graders were tested once. This procedure allowed us to compare children's performances in a longitudinal as well as in a transversal way. Our results demonstrated that in first grade, the hand interference condition was more disrupting than the foot interference condition. Furthermore, this hand interference effect was mostly disrupting in the most difficult additions. In fourth grade, the hand interference led to lower performance than the foot interference in the larger additions. However, this disrupting effect was lower than the one observed in grade 1. The weak disrupting effect observed in fourth graders stands in contrast with the adult literature showing significant disruption of hand movements in basic arithmetic problem solving (Imbo et al., 2011, Michaux et al., 2013). However, our experiment only analyzed children's accuracy scores while the studies of Imbo et al. (2001) and Michaux et al. (2013) took reaction times into account. Differences similar to previous findings (Imbo et al., 2001; Michaux et al., 2013) might have emerged at later developmental stage if RT were considered.

In both grades, hand interference movements caused significant disruption during the difficult additions (outcome between 11 and 13). This observation may indicate that fingers serve as a passing back-up strategy while answers cannot be derived automatically or through mental manipulations (Siegler & Jenkins, 1989). The persistence of their use is generally an indication of a fact retrieval deficit or of a math learning disability (Jordan, Hanich, & Kaplan, 2003; Ostad, 1997, 1999, Geary, Hoard, Byrd-Craven, & DeSoto, 2004). Altogether, these data may therefore suggest that finger-counting is a starting point that is generally overcome in favor of more elaborate and abstract numerical representations (see the mathematics didactics view discussed in Moeller, Martignon, Wessolowski, Engel, & Nuerk, 2011).

In the literature, some authors recently underlined the fact that finger-counting may serve as an incremental counter that helps children to keep track of the counting (Crollen et al., 2011b) and calculation process (Geary et al., 2004). Geary et al. (2004) for example reported that low working memory capacity in first graders was often associated with more finger-counting strategy and more finger-counting errors. Moreover, as reported by Noël (2009) in preschoolers, or by Noël, Seron, and Trovarelly (2004) in first graders, arithmetic skills correlated significantly with the phonological loop and the central executive, but not with the visuo-spatial sketchpad (see also Caviola, Mammarella, Cornoldi, & Lucangeli, 2012; Friso-van den Bos, van der Ven, Kroesbergen, & van Luit, 2013 for a review). Here, we found that our verbal working memory measure significantly correlates with 1st graders' accuracy scores in the hand interference condition. No correlation was observed with the block tapping test, nor with the performance in the finger gnosis test. Our failure to replicate the association between finger gnosis and arithmetic abilities (Costa et al., 2011; Fayol et al., 1998; Noël, 2005) might be due to the small sample used. Yet, despite this low statistical power, a significant correlation was reported between the verbal working memory measure and the 1st graders' accuracy scores in the hand condition. In this condition, finger-counting could no longer be used and low working memory capacity was then associated to higher error rates. As we did not collect information about the use of finger-counting in the control condition of our second experiment, we are unfortunately not able to correlate this measure with the children's accuracy scores (as we did in experiment 1). Further studies should probably do this in order to better understand the exact role fingers play in arithmetic development. All together, these data may however suggest that finger-counting actually serves as an incremental counter that helps children to keep track of their computations and discharge their working memory load while learning basic arithmetic problem solving.

To conclude, data in the existing literature suggest that fingers may play a functional role at different levels of numerical development. Fingers may indeed be used to: 1) point to items while counting (e.g., Alibali & DiRusso, 1999); 2) keep track of the number words uttered while reciting the counting sequence in counting tasks (Lafay et al., 2013); 3) keep track of the counting process while solving arithmetic operations (Geary, 1994). In all cases, fingers are used as an external tool that helps children to keep track of their count. By using this tool repeatedly, children probably build a digital representation of numbers. In this paper, we propose that fingers are (also) a procedural tool that helps the development of mathematical cognition. Within this view, referring to one's fingers is therefore particularly instructive in numerical tasks that require updating and manipulation of numbers such as counting (Imbo et al., 2011), addition (Michaux et al., 2013) and arithmetic word problems (Costa et al., 2011). Finger-counting is, in contrast, less relevant in numerical tasks that require fact retrieval such as multiplication (Michaux et al., 2013). While our paper did not directly demonstrate this, our findings may be interpreted in that sense and therefore opens the finger-number debate to new directions.

Acknowledgements

VC is a post-doctoral researcher and MPN is a research associate at the National Fund for Scientific Research (Belgium). The authors are grateful to Blandine Capriotti and Elodie Colin for their help in the data collection.

References

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.

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

Bailey, D.H., Littlefield, A., & Geary, D.C. (2012). The codevelopment of skill at and preference for use of retrieval-based processes for solving addition problems: Individual and sex differences from first to sixth grades. *Journal of Experimental Child Psychology, 113(1),* 78-92.

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

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

Carpenter, T.P., & Moser, J.M. (1984). The acquisition of addition and subtraction concepts in grades one through three. *Journal for Research in Mathematics Education, 15(3),* 179−202.

Caviola, S., Mammarella, I.C., Cornoldi, C., & Lucangeli, D. (2012). The involvement of working memory in children's exact and approximate mental addition. *Journal of Experimental Child Psychology, 112(2),* 141–160.

Corsi, P.M. (1972). Human memory and the medial temporal region of the brain. *Dissertation Abstracts International, 34 (02),* 891B.

Costa, A.J., Silva, J.B.L., Chagas, P.P., Krinzinger, H., Lonneman, J., Willmes, K., Wood, G., & Haase, V.G. (2011). *Front. Psychology*, 2:368. doi: 10.3389/fpsyg.2011.00368.

Crollen, V., Mahe, R., Collignon, O., & Seron, X. (2011b). The role of vision in the development of finger-number interactions: finger-counting and finger-montring in blind children. *Journal of Experimental Child Psychology, 109,* 525–539.

Crollen, V., Seron, X., & Noël, M.P. (2011a). Is finger-counting necessary for the development of arithmetic abilities? *Front. Psychology 2:242.* doi: 10.3389/fpsyg.2011.00242.

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.

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.

Friso-van den Bos, I., van der Ven, S.H.G., Kroesbergen, E.H., & van Luit, J.E.H. (2013). Working memory and mathematics in primary school children: A meta-analysis. *Educational Research Review, 10,* 29−44.

Fuson, K. (1982). An Analysis of the Counting-On Procedure. In T. Carpenter, J. Moser, and T. Romberg (eds.) *Addition and-Subtraction: A Cognitive Perspective*. Lawrence Erlbaum Associates: New Jersey.

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

Geary, D.C. (1990). A componential analysis of an early learning deficit in mathematics. *Journal of Experimental Child Psychology, 49,* 363−383.

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

Geary, D.C. (2004). Mathematics and learning disabilities. *J. Learn Disabil., 37,* 4−15.

Geary, D.C. (2007). An evolutionary perspective on learning disability in mathematics. *Dev. Neuropsychol., 32,* 471−519.

Geary, D. C., & Hoard, M. K. (2005). Learning disabilities in arithmetic and mathematics: Theoretical and empirical perspectives. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 253-267). New York: Psychology Press.

Geary, D.C., Hoard, M.K., Byrd-Craven, J., & DeSoto, M.C. (2004). Strategy choices in simple and complex addition: Contributions of working memory and counting knowledge for children with mathematical disability, *Journal of Experimental Child Psychology*, *88*, 121-151.

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

Imbo, I., Vandierendonck, A., & Fias, W. (2011). Passive hand movements disrupt adults‘ counting strategies. *Front. Psychology 2:201*. doi: 10.3389/fpsyg.2011.00201.

Jordan, N.C., Hanich, L.B., & Kaplan, D. (2003). Arithmetic fact mastery in young children: A longitudinal investigation. *Journal of Experimental Child Psychology, 85*, 103–119.

Jordan, N.C., Huttenlocher, J., & Levine, S.C. (1992). Differential calculation abilities in young children from middle- and low-income families. *Developmental Psychology*, *28*, 644–653.

Jordan, N.C., Levine, S.C., & Huttenlocher, J. (1994). Development of calculation abilities in middle- and low-income children after formal instruction in school. *Journal of Applied Developmental Psychology*, *15*, 223–240.

Lafay, A., Thevenot, C., Castel, C., & Fayol, M. (2013). The role of fingers in number processing in young children. *Front. Psychol., 4:488.* doi:10.3389/fpsyg. 2013.00488.

Michaux, N., Masson, N., Pesenti, M., & Andres, M. (2013). Selective interference of finger movements on basic addition and subtraction problem solving. *Experimental Psychology, 60(3),* 197–205.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27,* 272–277.

Moeller, K., Martignon, L., Wessolowski, S., Engel, J., & Nuerk, H.C. (2011). Effects of finger-counting on numerical development – the opposing views of neurocognition and mathematics education. *Front. Psychology, 2:328.* doi:10.3389/fpsyg.2011.00328.

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

Noël, M.P. (2009). Counting on working memory when learning to count and to add: A preschool study. *Developmental Psychology, 45(6),* 1630–1643.

Noël, M.P., Seron, X., & Trovarelli, F. (2004). Working memory as a predictor of addition skills and addition strategies in children. *Current Psychology of Cognition, 22(1),* 3–25.

Ostad, S. A. (1997). Developmental differences in addition strategies: A comparison of mathematically disabled and mathematically normal children. *British Journal of Educational Psychology, 67,* 345–357.

Ostad, S. A. (1999). Developmental progression of subtraction strategies: A comparison of mathematically normal and mathematically disabled children. *European Journal of Special Needs Education, 14,* 21–36.

Siegler, R.S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General, 116(3),* 250–264.

Siegler, R.S., & Jenkins, E. (1989). *How children discover new strategies*. Hillsdale, NJ: Erlbaum.

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

Figure caption

Figure 1. Results of Experiment 1. (A) Children's accuracy scores in the control, hand interference and foot interference conditions of the one-target and two-target counting tasks; (B) children's finger use measure in the control and foot interference conditions of the one-target and two-target counting tasks. Bars denote standard errors of the mean.

Figure 2. Results of Experiment 2. (A) First graders' accuracy scores in the control, hand interference and foot interference conditions of the addition task (first testing session); (B) First graders' accuracy scores during the second testing session; (C) Fourth graders' performances in the control, hand interference and foot interference conditions of the addition task. Bars denote standard errors of the mean.