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Visual experience influences the interactions between fingers and numbers

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Abstract

Though a clear interaction between finger and number representations has been demonstrated, what drives the development of this intertwining remains unclear. Here we tested early blind, late blind and sighted control participants in two counting tasks, each performed under three different conditions: a resting condition, a condition requiring hands movements and a condition requiring feet movements. In the resting condition, every sighted and late blind spontaneously used their fingers, while the majority of early blind did not. Sighted controls and late blind were moreover selectively disrupted by the interfering hand condition, while the early blind who did not use the finger-counting strategy remained unaffected by the interference conditions. These results therefore demonstrate that visual experience plays an important role in implementing the sensori-motor habits that drive the development of finger-number interactions.

Keywords: finger-counting, blindness, grounded cognition

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1. Introduction

The finger-based representation of numbers has often been advocated as an instance of grounded cognition (e.g., Fischer & Brugger, 2011; Wilson 2002). Since performance on finger discrimination tasks was shown to be a good predictor of arithmetic abilities (Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005), it has indeed been argued that fingers may be the “missing tool” (Andres, Di Luca & Pesenti, 2008) that sustains the assimilation of basic numerical abilities or the “missing link” (Fayol & Seron, 2005) that permits the connection between non-symbolic numerosities and symbolic arithmetic. Developmental (Butterworth, 1999a; Costa, Silva, Chagas, Krinzinger, Lonneman, Willmes, Wood, & Haase, 2011), neuroimaging (Harrington, Rao, Haaland, Bobholz, Mayer, Binderx, & Cox, 2000; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Tschentscher, Hauk, Fischer, & Pulvermüller, 2012), and neuropsychological (Barnes, Smith-Chant, & Landry, 2005; Gerstmann, 1930; Thevenot, Castel, Danjon, Renaud, Ballaz, Baggioni, & Fluss, 2014) evidence demonstrating the close intertwining between fingers and symbolic numbers have accordingly been accumulated over the last two decades.

Recently, however, it has been highlighted that blind children used the finger-counting strategy less spontaneously than their sighted peers despite achieving similar level of counting and finger gnosis (i.e., finger recognition and localization) performance (Crollen, Mahe, Collignon, & Seron, 2011a). This study has far-reaching implications since it presumes that the development of finger-number interactions (i.e., the associations between symbolic numerical processing and finger movements) relies on sensori-motor habits that are driven by vision. In this paper, we examined the impact of hand interference on the counting performance of blind adults. This experiment will therefore allow us to exclude the idea that finger-counting develops later in blind people on the basis of non-visual cues (e.g., kinematic/proprioceptive). It will also allow us to exclude the idea that finger-counting was present in blind children but that it did not manifest by an explicit motor behavior (e.g., absence of voluntary motor activity but increased cortico-spinal activity of hand muscles; Andres, Seron & Olivier, 2007). If finger and number representations actually share common cognitive and/or brain resources, a motor interference task involving the fingers should disrupt counting abilities by adding noise in the shared system.

In the present research, early blind (EB), late blind (LB) and sighted control adults (SC) were tested with 2 counting tasks and 1 memory task carried out under 3 different conditions: 1) a control ‘resting’ condition; 2) a condition requiring the realization of hand movements unrelated to finger-counting; and 3) a condition requiring the realization of feet movements. If early vision does not shape the interaction between fingers and the symbolic representation of numbers, all participants should spontaneously use their fingers to count and should manifest a hand interference effect (i.e., the hand interfering condition should be more disrupting than the feet condition). In contrast, if early vision is important for the development of the finger-number interactions, early blind individuals should less use their fingers and the hand interfering condition should not be more disrupting than the feet condition in this population. Moreover, as participants were also involved in a working memory task (listening span test) under the same control and sensori-motor interference conditions, our experiment allowed us to test whether hand interference effects (Imbo, Vandierendonck, & Fias, 2011; Michaux, Masson, Pesenti, & Andres, 2013) would disrupt participants' counting performance more than their performance in the listening span test.

2. Method

2.1 Participants

One group of 15 sighted and two groups of blind participants (11 early and 14 late blinds) took part in the study (see supplemental table 1 for a detailed description of the different groups). In terms of age, the SC did not statistically differ from the EB ($p > .2$) and LB ($p > .1$) groups. Unlike the EB, all LB participants had experienced functional vision before sight loss. At the time of testing, the participants in both blind groups were totally blind or had, at the utmost, only rudimentary sensitivity for brightness differences and no patterned vision. In all cases, blindness was attributed to peripheral deficits with no additional neurological problems. Procedures were approved by the Research Ethics Boards of the University of Montreal. Experiments were undertaken with the understanding and written consent of each participant. Sighted participants were blindfolded when performing the tasks.

2.2 Conditions

Each of the three tasks (see the tasks section below) was performed in three different conditions. In a control condition, participants were required to perform the tasks without any constrain. In the hand interference condition, participants had to perform the tasks while pressing a ball placed in each hand. Finally, in the foot interference condition, participants had to perform the tasks while pressing a ball placed beyond each foot.

The rhythm of the interference movements was irregular (between 1500 and 2400 ms) and imposed by a vibro-tactile bracelet which was carried on the wrist in the hand interference condition and on the ankle in the foot interference condition (see supplemental data for a detailed description of the bracelet).

Before the realization of the experimental tasks, a 5-minutes training session was performed with the bracelet alone so that participants could train themselves on the movements. During the experimental tasks, the tactile stimulations stopped as soon as participants reported the completion of one trial and started as soon as a new trial was initiated.

2.3 Tasks

2.3.1 Enumeration task

In order to test the ability to keep track of a number of enumerated items, participants were required to name a specific number of exemplars from 10 different target categories (e.g., can you give me 9 names of boys). The target number ranged from 5 to 9. Three lists of items were created and counterbalanced across participants and conditions. Within a list, each target number was repeated twice, once in a semantic condition (e.g., can you give me 7 names of tools) and once in a phonological condition (e.g. can you give me 7 words which begin with the letter O). Four training trials were presented before the experimental ones. During the instructions, experimenter emphasized that participants had to stop the enumeration process (by saying "STOP") as soon as they thought achieved the required target number of words. Participants were instructed to emphasize accuracy over response speed. Experimenter noted the number of words uttered by the participants. As the three lists of stimuli involved different reaction times in the baseline condition of the task, only accuracy scores (i.e., number of trials correctly completed – maximum score of 10) were analyzed for each participant in each condition.

2.3.2 Ordered series manipulation task

In order to test participants' ability to count a particular number of items, participants were asked 15 questions requiring the manipulation of the letters of the alphabet (e.g., how many letters are there between 'c' and 'h'?) and 15 questions requiring the manipulation of the months of the year (e.g., how many months are there between March and September?).

The questions were presented randomly. The same list of 30 questions was used in the three different conditions. The target responses were comprised between 5 and 9 and repeated three times with the letters and three times with the months of the year. Four training trials were presented before the experimental trials. Accuracy scores (i.e. number of trials correctly completed

– maximum score of 30) and reaction times were collected for each participant in each condition. Timing began when the stimulus was presented and ended when participants gave their response.

2.3.3 Listening span task

In order to test participants' ability to use their working memory, an auditory adaptation of the French version (Desmette, Hupet, Schelstraete, & Van der Linden, 1995) of the reading span test (Daneman & Carpenter, 1980) was presented. This task was used as a control task to make sure that the potential differences observed in the other tasks were not due to differences in working memory. Participants had to listen to a set of recorded sentences (from 2 to 7) and were instructed to recall the last word of all the sentences presented in the set. The task comprised a set of 2 training sentences and 27 experimental sentences (one set of 2 sentences, one set of 3 sentences, and so on up to the set of 7 sentences). The inter-sentences interval was 1000ms. Each trial started and ended with a 500ms pink noise. Participants were required to give their answers after the second warning tone was emitted. Three lists of sentences were created and counterbalanced across participants and conditions. The number of words correctly recalled was calculated for each participant in each condition (maximum score of 27).

2.4 Procedure

The completion of the experimental procedure involved two one-hour testing sessions (realized approximately in a week of interval). The control condition was always performed first in order to examine whether participants would spontaneously use their fingers to perform the tasks. Order of the two interference conditions as well as order of the tasks was counterbalanced across participants.

3. Results

While all SC and LB participants spontaneously used their fingers to complete the control and foot conditions of the enumeration and ordered series manipulation tasks, only 4 EB did so (see supplemental videos 1 and 2). A Chi-squared test demonstrated that the EB distribution into finger-counter and non-finger counter was significantly different from the distribution observed in the SC and LB groups, $p_s < .001$. Two subgroups of EB were therefore identified: EB who never used their fingers (EB-) and EB who always used their fingers (EB+) (see supplemental Table 1).

3.1 Enumeration task

Accuracy scores were submitted to a 3 (conditions: control, hand and foot interference) x 4 (groups: EB-, EB+, LB and SC)[1] ANOVA with repeated measures on the first factor. The group effect was not significant, $F(3, 36) = 1.17$, $p > .3$, $\eta^2 = .09$. There was, in contrast, a significant effect of condition, $F(2, 72) = 17.67$, $p < .001$, $\eta^2 = .33$, which was modulated by a condition x group interaction, $F(6, 72) = 2.59$, $p < .05$, $\eta^2 = .18$. The condition effect was significant in the SC group, $F(2, 28) = 12.36$, $p < .001$, $\eta^2 = .47$: accuracy scores were lower in the hand interference condition by comparison to the control and foot interference conditions. The same data were observed in the LB group, $F(2, 26) = 15.41$, $p < .001$, $\eta^2 = .54$, as well as in the EB+ group[2], $F(2, 6) = 7.87$, $p < .05$, $\eta^2 = .72$. By contrast, in the EB- group[2], participants performed similarly in the three conditions of the task, $F(2, 12) = 0.06$, $p > .9$, $\eta^2 = .01$ (see Figure 1).

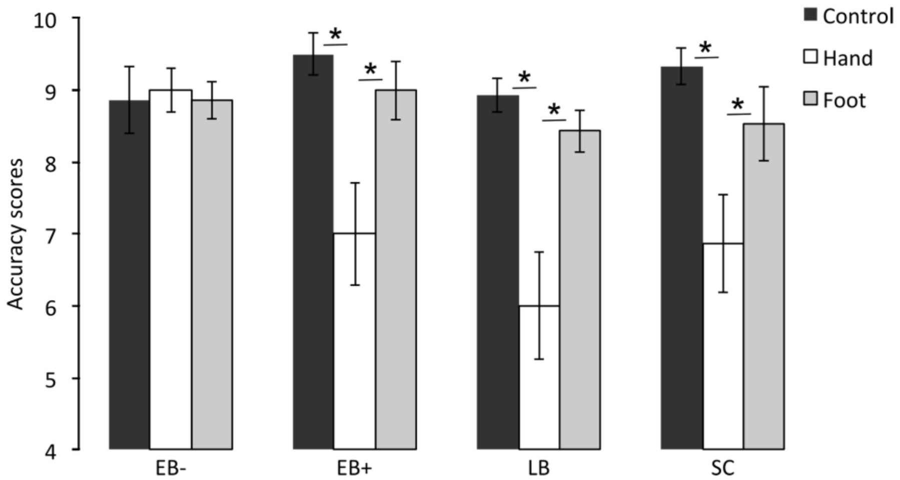

Figure 1. Results of the enumeration task (maximum score = 10). Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

3.2 <u>Ordered series manipulation task</u>

In order to obtain a general index of performance that discounts possible criterion shift or speed/accuracy tradeoff effects, response speed and accuracy were combined into inverse efficiency scores (IES: response times (RT)/correct response rates; Townsend & Ashby, 1978). As for RT, the lower the score, the better the performance.

A 3 (conditions: control, hand interference and foot interference) x 4 (groups: EB-, EB+, LB and SC)[1] repeated measures ANOVA with group as the between-subject factor and condition as the within subject factor was carried out on the IES measure. We first observed a main effect of condition, $F(2, 66) = 13.62$, $p < .001$, $\eta^2 = .29$. Importantly, we also witnessed a significant condition x group interaction, $F(6, 66) = 3.94$, $p < .01$, $\eta^2 = .26$, revealing that in SC and LB, the hand-interference condition had a particularly negative impact on performance (when compared to the control condition) while in EB- and EB+ the performance was identical in every condition (see Figure 2). The EB+ seem however to be more disturbed by the hand movements than the EB-[2].

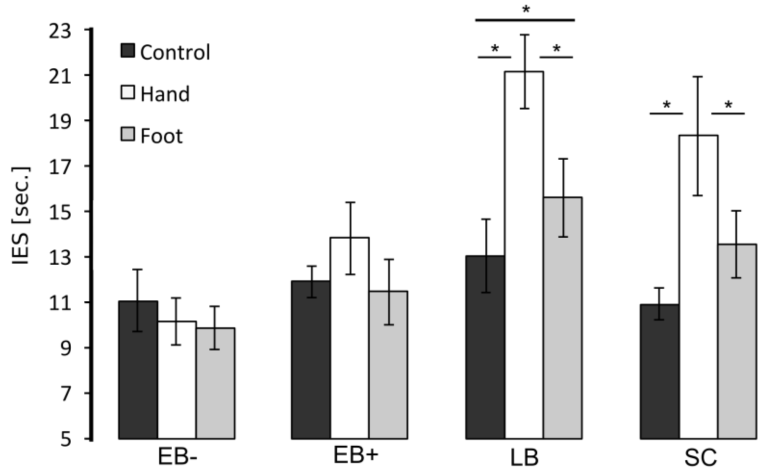

Figure 2. Results of the ordered series manipulation task. Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

3.3 <u>Listening span task</u>

A repeated measures ANOVA with condition (control, hand interference, foot interference) as the within-subject factor and group (EB+, EB-, LB, SC)[1] as the between subject factor was run on the accuracy scores. Results only showed a marginally significant effect of group, $F(3, 36) = 2.42$, $p = .08$, $\eta^2 = .17$. EB- ($M = 24.76 \pm 0.83$) performed better than LB ($M = 22.33 \pm 0.58$) and SC ($M = 22.67 \pm 0.57$). No other difference was significant (see Figure 3).

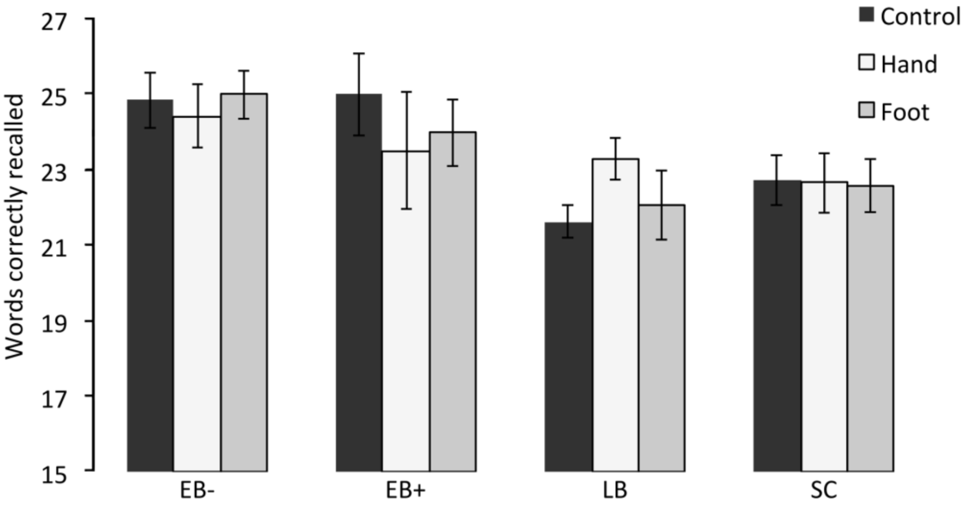

Figure 3. Results of the listening span test (maximum score = 27). Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

4. Discussion

The study of blind individuals offers the unique opportunity to examine how visual experience shapes cognition in the context of extreme changes in the environmental input (Bedny & Saxe, 2012; Crollen, Dormal, Seron, Lepore, & Collignon, 2013). Here, we studied visually deprived individuals in order to obtain new insights into the origins of the interactions between fingers and symbolic numbers.

While all SC and LB participants used their fingers to perform the counting tasks, the majority of EB did not. Moreover, hand movements interfered with counting in SC and LB but not in the EB who did not use their fingers in the enumeration tasks. All together, these results suggest that developmental vision is instrumental in implementing the close connection between fingers and counting. However, since a minority of EB uses their fingers to count and shows specific manual interferences (EB+), blindness does not seem to, by itself, skim off finger-number interactions.

Interestingly, all EB (EB- and EB+) stated that they never learned finger-counting at school or with their parents. So, we do not know why four of the EB used a finger counting strategy. It is possible that non-visual cues (kinematic/proprioceptive) are employed to develop the finger counting habit. Several classes of afferent signals from the periphery may indeed provide information about the location of the limbs, including receptors in joints signaling flexion or extension, from the skin signaling stretch, and from muscle spindles signaling contraction or lengthening (Proske & Gandevia, 2012). However, the fact that the majority of EB do not spontaneously use their fingers and do not suffer from specific hand interference suggests that these cues are less efficient than the visual ones to implement finger-counting strategies. Vision thus probably provides an important but not mandatory interface to confer to fingers a useful value as a tool to support counting.

On another hand, the fact that EB- realize the task with equal performance as the 3 other groups suggests that the development of the symbolic numerical system is flexible enough to rely on different kinds of sensory and cognitive strategies. Among the hypotheses that still need to be tested, it may be presumed that EB make a more appropriate use of working memory capacities

(Castronovo & Delvenne, 2013; Crollen et al., 2011a; Crollen, Seron, & Noël, 2011b; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013).

In the literature, several brain mapping studies suggest that there is a shared neural network for number and finger processing, including the parietal areas, the precentral gyrus and the primary motor cortex (Andres et al., 2007; Andres, Michaux, & Pesenti, 2012; Harrington et al., 2000; Piazza et al., 2004; Tschentscher et al., 2012; Zago, Pesenti, Mellet, Crivello, Mazoyer, & Tzourio-Mazoyer, 2001)[3]. Two prevailing views have been recently debated in order to explain the origin of this neuro-anatomical overlap: the functionalist and the redeployment hypotheses. According to the functionalist view, neuronal activations for number processing and finger movements are correlated in adulthood because fingers are used by children while learning counting and basic arithmetic operations (Butterworth, 1999b). The redeployment view assumes that functional circuits originally evolved for finger representation have since been redeployed to support the representation of number and now serves both uses (Penner-Wilger & Anderson, 2008, 2013). For the functionalist theory, re-use happens over the course of development whereas it happens over the course of evolution for the redeployment hypothesis (Anderson, 2010; Penner-Wilger & Anderson, 2013). One key prediction of the redeployment hypothesis is therefore that individuals with intact finger gnosis who did not use their fingers to represent quantities during development should nevertheless show activation in the finger circuit during tasks requiring the representation of numbers (Penner-Wilger & Anderson, 2013). Our observation that EB- are not impaired in the interfering hand condition (which should induce noise in the pre-existing overlapping circuits for number and finger processing) compellingly argues against the redeployment view. We therefore suggest that vision provides an ideal interface to trigger the development of finger-number interactions. In the absence of vision, the development of this association is less likely, and other sensory/cognitive strategies are used to support counting. Our prediction is that EB- would not show overlapping brain circuitry representing fingers and counting. It could therefore be highly interesting to investigate how the well-known crossmodal reorganization of the occipito-parietal network in early blind individuals (Collignon, Davare, Olivier, & De Volder, 2009; Collignon, Vandewalle, Voss, Albouy, Charbonneau, Lassonde, & Lepore, 2011; Collignon, Voss, Lassonde, & Lepore, 2009; Dormal, Lepore, & Collignon, 2012) affects the circuitry representing space, number and finger processing.

In summary, our study provides some breakthroughs in our understanding of the relation between fingers and counting by demonstrating that : (1) the use of fingers is not mandatory to achieve optimal performance in counting, (2) vision plays an important role in the establishment of finger-number interactions, probably because it provides an ideal platform to relieve the memory load during counting; (3) the development of this intertwining depends on experience and is not the product of and inherited redeployment of function.

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Footnotes

[1] The analyses were also performed on 3 groups (EB, LB, SC) instead of 4 (EB+, EB-, LB, SC). In this case, no hand interference effect was observed in the EB group.

[2] As our groups of EB- and EB+ were quite small, we also applied the method recently described by Masson (2011) to compute the posterior probabilities for H0 and H1. In the ordered manipulation task, this analysis indicated that the posterior probabilities were .81 for H0 (i.e., the null hypothesis has 81% chance of being true) and .19 for H1 in the EB- group. According to Raftery's (1995) classification of evidence into «weak» (.50–.75), «positive» (.75–.95), «strong» (.95–.99), and «very strong» (>.99), the probability values obtained for this group therefore provide positive support for H0 hypothesis. In the EB+ group, the posterior probabilities were .60 for H0 and .40 for H1 thus providing only weak support for H0. In the enumeration task, the posterior probabilities in the EB- group were .93 for H0 and .07 for H1. In the EB+ group, the posterior probabilities were .04 for H0 and .96 for H1. These analyses therefore support the idea that the EB+ are more disturbed by the hand interference condition than the EB-.

[3] While some studies did not involve any explicit finger movements (Tschentscher et al., 2012), many of the above mentioned research used tasks which are spatial in nature by involving movements of fingers (Harrington et al., 2000), pointing/grasping (Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002), or mapping finger locations to a spatial position (Andres et al., 2012). It

is therefore difficult to strongly argue that the parietal cortex is involved in finger representation per se.

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Figure caption

Figure 1. Results of the enumeration task (maximum score = 10). Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

Figure 2. Results of the ordered series manipulation task. Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

Figure 3. Results of the listening span test (maximum score = 27). Error bars denote standard error of the mean. EB- are the early blind who did not use their fingers; EB+, the early blind who used their fingers; LB, the late blind and SC, the sighted controls.

Supplemental data

Supplemental table 1. Characteristics of the blind participants

Participants	***Gender***	***Age***	***Handedness***	***Onset***	***Cause of blindness***
EB1-	M	21	R	0	Detachment of the retina
EB2-	M	47	R	0	Congenital glaucoma
EB3-	F	31	A	0	Detachment of the retina
EB4-	M	61	R	0	Congenital cataracts + optic nerve hypoplasia
EB5-	F	30	R	0	Leber's congenital amaurosis
EB6-	M	54	R	2 months	Medical accident
EB7-	M	23	R	0	Congenital malformation
EB8+	F	35	R	10 months (left eye) 3 years (right eye)	Retinoblastoma
EB9+	M	50	A	0	Thalidomide
EB10+	M	43	R	0	Retinopathy of prematurity
EB11+	M	43	R	0	Leber's congenital amaurosis
LB1	F	54	L	40	Detachment of the retina
LB2	F	49	R	44	Glaucoma + Cataract
LB3	F	56	R	19	Aniridia
LB4	M	50	R	32	Accidental detachment of the retina
LB5	F	57	R	30	Congenital degneration
LB6	F	63	R	52	Stevens Johnson Syndrome + Sulfa Antibiotics
LB7	F	64	R	11	Wagner disease
LB8	M	66	R	0 (right eye) 40 (left eye)	Medical accident at birth
LB9	F	61	R	53	Retinitis pigmentosa
LB10	F	70		23	Virus of the mother during pregnancy
LB11	M	56	L	26	Bilateral section of optical nerve
LB12	F	60	R	50	Retinitis pigmentosa
LB13	M	58	R	52	Retinitis pigmentosa
LB14	M	40	R	23	Diabetic retinopathy

Note. M = male; F = female; L = left-handed; R = right-handed; A = ambidextrous; EB participants were sub-categorized regarding the use (EB+) or not (EB-) of their fingers during the baseline condition of the enumeration and ordered series manipulation tasks.

Description of the bracelet.

The bracelet was equipped with an eccentric rotating mass vibrating motor driven by a microcontroller connected to the computer through a USB connection. During the experimental tasks, the computer controlled the moment of the tactile stimulation, but also its intensity by sending to the microcontroller the width of the impulse to be sent to the engine.

A light indicator switched on when the bracelet was vibrating so that the experimenter was able to control “on-line” whether the participants respected the imposed rhythm. On-line control of participants’ compliance to the imposed rhythm demonstrated that one LB and two SC were unable to correctly follow the instructions of the ordered series manipulation task. These participants were therefore removed from all further analyses; involving a final sample of 11 EB, 13 LB and 13 SC participants. No participant was discarded from the analyses of the enumeration and listening span tasks. The computer also registered the number of stimulations produced by the bracelet and the balls recorded the number of actual presses produced by the participants. Both measures were used “off-line” to ensure that there was no trade-off in performance with the control condition of our counting tasks. To do so, we calculated the participants’ compliance to the hand and feet interference conditions (number of presses made by the participants/number of stimulations sent by the bracelet). A 4 (groups: EB+, EB-, LB, SC) * 2 (conditions: hand vs. feet) repeated measures ANOVA was then run on this compliance measure. In the ordered manipulation task, there was no main effect of condition, $F(1, 33) = 0.01$, $p > .9$, $\eta^2 = .001$, no group effect, $F(3, 33) = 0.22$, $p > .8$, $\eta^2 = .02$, and no group x condition interaction, $F(3, 33) = 1.74$, $p > .1$, $\eta^2 = .14$,. The same results were observed in the enumeration task: $F(1, 36) = 0.41$, $p > .5$, $\eta^2 = .01$ for the condition effect; $F(3, 36) = 0.90$, $p > .4$, $\eta^2 = .07$ for the group effect and $F(3, 36) = 0.66$, $p > .5$, $\eta^2 = .05$ for the group x condition interaction. Since a similar compliance measure was found in the 4 groups of participants and in both conditions of every task, these results strongly support our main analyses and therefore argue against a trade-off in performance between the primary and the secondary (interfering) task.

Videos

The videos were recorded during a pilot experiment (not reported here) involving an enumeration task. The stimuli used were not the same as the one used for the present paper. No video was recorded during the experimental data collection in order to avoid any nuisance during the experiment. Video 1 presents a sighted control participant, video 2 an EB-, video 3 an EB who was required to show some numbers with his fingers.