Processing of numerical representation of fingers depends on their location in space

Sébastien Vanstavel, Yann Coello, Sandrine Mejias

Sébastien Vanstavel, Yann Coello, Sandrine Mejias

Processing of numerical representation of fingers depends on their location in space

Affiliation: Univ. Lille, CNRS, UMR 9193 - SCALab - Sciences Cognitives et Sciences Affectives, F-59000 Lille, France

Corresponding author: Sandrine Mejias

e-mail address of the corresponding author: sandrine.mejias@univ-lille.fr

ORCID ID:

Yann Coello: 0000-0002-7148-0561

Sandrine Mejias: 0000-0003-1293-7637

Declarations

Funding: This work was funded by the French National Research Agency (ANR-11-EQPX-0023) and also supported by the European funds through the program FEDER SCV-IrDIVE. SV was financed by the Region Hauts-de-France and the University of Lille.

Conflicts of interest/Competing interests: Not applicable

Ethics approval : The protocol received approval by the Institutional Ethics Committee (Ref. Number 2018-308-S65) and was conducted according to the ethical principles of the Declaration of Helsinki (World Medical Association 2014).

Consent to participate: All participants gave their informed written consent.

Consent for publication: Not applicable

Availability of data and material: https://osf.io/9e7sm/?view_only=31f5727f46c34b13b01884743a39b500

ABSTRACT

Fingers can express quantities and thus contribute to the acquisition and manipulation of numbers as well as the development of arithmetical skills. As embodied entities, the processing of finger numerical configurations should therefore be facilitated when they match shared cultural representations and are presented close to the body. To investigate these issues, the present study investigated whether canonical finger configurations are processed faster than noncanonical configurations or spatially matched dot configurations, and whether their location in the peripersonal or the extrapersonal space is involved. Analysis of verbal responses to the enumeration of small and large numerosities showed that participants (N = 30) processed small numerosities faster than large ones and dots faster than finger configurations despite visuo-spatial matching. Canonical configurations were also processed faster than noncanonical configurations but for finger numerical stimuli only. Furthermore, the difference in response time between dots and fingers processing was greater when the stimuli were located in the peripersonal space than in the extrapersonal space. As a whole, the data suggest that, due to their motor nature, finger numerical configurations are not processed as simple visual stimuli but in relation to corporal and cultural counting habits, in agreement with the embodied framework of numerical cognition.

INTRODUCTION

In everyday life, culturally determined finger representations are commonly used to manipulate quantities and to communicate socially about them (Previtali et al. 2011). For example, fingers are used to keep track of counted items such as the number of days remaining until Friday. It is also the case when a specific quantity is shown by using fingers, as when a barman is asked to bring "three more beers" by lifting the hand and extending three fingers (Fuson 1988; Pika et al. 2009). Although using fingers to express quantities may feel natural, finger-counting and finger-montring strategies are culturally determined, e.g., the fingers used to express the number three differ between Europe and Asia (Butterworth 1999a; Ifrah 1981; Wiese 2003a, 2003b) but also in Europe between Germany and the UK (as nicely illustrated in Quentin Tarantino's "Inglorious Bastards" where a British spy outs himself simply by ordering a drink with three fingers up!). If these examples depict well the fact that canonical finger configurations are frequently used as embodied cognitive tool, an outstanding challenge is to understand to what extent the access to the semantic representation of numerosity is facilitated by the culturally determined and the embodied nature of this type of biological numerical stimuli. To address this issue, the current study aimed to investigate enumeration facilitation through different types of analog representations which, to the best of our knowledge, have not yet been compared, that is finger and dot representations.

Beyond the cultural differences in the use of fingers in relation to numerical representations (Di Luca and Pesenti 2011; Domahs et al. 2010), fingers are known to play an important role in reinforcing the understanding of our number system (Anghileri 2006; Fuson 1988; Gelman and Gallistel 1978; Hughes 1986; Jordan et al. 1992). Indeed, fingers may provide the sensory-motor roots onto which the number concept grows (Di Luca and Pesenti 2011; Tschentscher et al., 2012) and thus may play a functional role in the development of a mature counting system (Butterworth 1999b, 2005; Fuson 1988; Fuson et al. 1982; Gelman and Gallistel 1978). Furthermore, it has been suggested that the embodied aspect of numerical cognition allows the emergence of a routine to link fingers to objects in a sequential culture-specific order (Fischer 2008; Wiese 2003a), relatively stable over time and which adapts to the situation (Hohol et al., 2018). Fingers also play a role in the development of arithmetical skills (Butterworth 1999a; Gracia-Bafalluy and Noël 2008; Hilton 2019; Noël 2005), as small addition problems (e.g., 5 + 3) can be solved by representing the operands separately on the left and right hands (Geary 1994), thus enabling the child to keep track of segments of connected words ("five, … six, seven, eight" ; Fuson et al., 1982), and suggesting that relying on fingers for the acquisition of numerical knowledge has a causal influence on the learning process itself (Long et al. 2016; Noël 2005). Referring to fingers has also been found to facilitate basic arithmetical problem-solving (Domahs et al. 2008; Guedin et al. 2017; Jordan et al. 1992, 1994). Accordingly, teaching children to use their hands during arithmetical problem-solving enhanced their performance significantly as compared to children who were told to keep their hands still (Broaders et al. 2007; Cook et al. 2008). Similarly, rudimentary finger-counting strategies in adults were found to co-occur with limited numerical knowledge, as observed in speakers of Mundurukú, an Amazonian language with a very small lexicon of number words (Pica et al., 2004). Therefore, as a bodily anchored self-experience, finger representation provides natural embodied expressions of numerical quantities (Di Luca and Pesenti 2011; Fischer and Brugger 2011; Sixtus et al. 2017), that may facilitate numerical operations such as counting and calculation, in both children and adults (Hilton 2019; Moeller et al. 2011; Penner-Wilger and Anderson 2013).

Evidence of the interplay between numbers and finger representations is also provided by functional imaging studies and neuropsychological cases. The assumption of a link between numbers and finger representations came initially from the observation of Gerstmann syndrome in neuropsychological patients who, in association with bilateral parietal cortex damage, exhibited concurrent dyscalculia and finger agnosia, together with dysgraphia and left-right confusion (Ardila et al. 2000; Gerstmann 1940; Mayer et al. 1999; Rusconi et al. 2010). Other patients such as those suffering from Apert syndrome are similarly affected. Children with Apert syndrome are born with syndactyly, i.e. their fingers and toes are fused as a result of a mutation of the fibroblast growth factor receptor 2 (FGFR2) gene (Stark et al. 2015; Wilkie et al. 1995). Such children often undergo several surgical procedures in early life, which may include separation of the fingers. A recent study suggested that if these children are provided with some form of activity to help them develop their finger gnosis and fine motor skills, they are more likely to be able to use their fingers appropriately when learning arithmetical skills (Hilton 2019). Concerning neuroimaging, fMRI studies have provided evidence of a shared neural network for number processing and finger control (Tschentscher et al. 2012). This network involves the parietal cortex (in particular the left angular gyrus, Göbel et al., 2004; Liu et al., 2006; Pesenti et al., 2000; Piazza et al., 2002; Pinel et al., 2004; Zago et al., 2001), in association with the precentral gyrus (De Jong et al. 1996; Dehaene 1996; Jäncke et al. 2000; Kuhtz-Buschbeck et al. 2003; Liu et al. 2006; Numminen et al. 2004; Pesenti et al. 2000; Pinel et al. 2004; Venkatraman et al. 2005), and the premotor cortex (Butterworth 1999a; Hanakawa et al. 2003; Rusconi et al. 2005; Sato et al. 2007; Tschentscher et al. 2012). Accordingly, it was found that regions associated with finger representation within the left parietal lobe are activated during a variety of mathematical tasks (Penner-Wilger and Anderson 2013). Zago et al. (2001) also found activation of a finger representation circuit in the left parietal lobe when adults performed basic arithmetic. These data confirm the close link between finger representation and numerical processing. Accordingly, the capacity to execute tasks requiring access to finger representation and numerical judgments was found to be disrupted after transient damage of the left angular gyrus using transcranial magnetic stimulation (Butterworth 2005; Rusconi et al. 2005).

In support of the shared network hypothesis, the processing of numerical symbols through finger representation was facilitated when it corresponded to subjects' finger-counting habits, i.e., canonical finger representation (Di Luca et al. 2006; Di Luca and Pesenti 2008). Accordingly, adults made fewer errors and were faster in mapping Arabic digits (1-to-10) to finger configurations when the mapping situation was congruent with participants' finger-counting habits (Di Luca et al. 2006). The authors hypothesized that canonical finger configurations allow a direct access to the semantic representation of numerosity, while noncanonical finger configurations require explicit elaboration to access semantics (Di Luca et al. 2010; Di Luca and Pesenti 2008). In line with this, by using either canonical finger gestures or vertical bars to present results of simple arithmetical problems, Badets et al. (2010) demonstrated that simple arithmetical operations are based on finger representation even in adults. However, like other types of analogical representations, canonical and a fortiori noncanonical finger configurations are not defined only by numerosity. Indeed, sets of objects are also characterized by other features such as the area occupied by the elements, which often covary with numerosity (Di Luca et al. 2010; Fornaciai et al. 2017; Guillaume et al. 2018). Furthermore, the visual enumeration of numerosities might be different regarding canonical finger configurations as in this case, visual enumeration might involve automatic (visual) recognition of particular hand shapes (see Crollen et al., 2011), that are not present in noncanonical finger configurations and other analogical representation such as randomly arranged dot patterns.

Regarding embodied stimuli, the processing of body-related information has often been found to be influenced by its location in space. For example, Ter Horst, van Lier, and Steenbergen (2011) showed that the mental rotation of back view of left-right hand presented at different orientations was modulated by whether the hand image was presented in the participants' peripersonal (i.e., near to the participants' body) or extrapersonal (*i.e.,* far from the participants' body) space. In their study, while the task was simply to judge the laterality of a hand image, an increase in response time was observed when the orientation of the hand was incompatible with biomechanical constraints, although only when the hand image was presented in the peripersonal space. It is indeed acknowledged that stimuli in the peripersonal space receive special attention and involve multisensory processing in relation to the motor system (Coello 2018; Làdavas 2015; Rizzolatti et al. 1981). Accordingly, the processing of embodied numerical stimuli such as finger representation may depend on the location of those stimuli in space, i.e., in the peripersonal or extrapersonal space.

In this context, the present study investigated numerical processing (small and large numerosities) depending on stimuli (fingers vs dots), space (peripersonal vs extrapersonal), and configuration (canonical vs noncanonical). According to the embodied cognition theoretical framework, visual stimuli endowed with functional properties activate sensorimotor representations that contribute to the perceptual and cognitive processing of those stimuli (Coello and Fischer 2015; Fischer and Coello 2016). Assuming the embodied processing of finger representations, we expected the enumeration of numerosities to be facilitated with finger configurations instead of sets of dots. We also expected small numerosities to be processed faster than large ones. Moreover, enumerating canonical finger configurations, congruent to participants' culture, should be processed faster than noncanonical ones because only canonical configurations favor automatic access to the semantic representation of numerosity (Di Luca et al. 2010; Di Luca and Pesenti 2008). Finally, the advantage of cultural-dependent canonical representations of numerosities should be essentially observed for stimuli presented in the peripersonal space.

METHOD

Participants

Thirty French undergraduate students (mean age: 22.9 years old, range: 18 - 43, 21 females) from the University of Lille participated in the study and received course credit for their participation. All participants had a normal or corrected-to-normal vision, reported no motor deficits or developmental disorders and were right-handed (Oldfield, 1971). They were naive as to the purpose of the study and gave their informed written consent prior to inclusion. The protocol received approval by the Institutional Ethics Committee (Ref. Number 2018-308-S65) and was conducted according to the ethical principles of the Declaration of Helsinki (World Medical Association 2014).

Apparatus and Stimuli

The stimuli were displayed on a laptop screen (HP ProBook, 17-inch with 1400 x 900 resolution) using E-Prime software (Psychology Software Tools, Pittsburgh, PA). A microphone was used to record participants' responses. The stimuli were two human hands with the same color and luminance (Di Luca and Pesenti 2008) or two sets of dots presented simultaneously and used as control stimuli. Each hand could express numbers through the extension of 1 to 4 fingers. The sum of the fingers of both hands corresponded to small (3 - 4) or large (6 - 7) numerosities. Finger configurations could be either *canonical*, i.e., related to personal finger counting habits (for example, representing numerosity 6 by coupling the index and middle fingers of the left hand (numerosity 2) with the fingers of the index finger to the little finger of the right hand (numerosity 4); see figure 1A). Or they could be noncanonical, i.e., unrelated to personal finger-counting habits (for example, representing numerosity 6 by coupling the index and ring fingers of the left hand (2) with the fingers of the middle finger to thumb with the pinky of the right hand (4); see Figure 1B). The spatial equivalent of finger configurations was used in the form of dots located at the same location as the fingertips in both the canonical and noncanonical configurations (see Figure 1C-D). The set of dots thus corresponded the same small and large numerosities as those represented with the hands.

For both the canonical and non-canonical finger configurations, the two hand stimuli always displayed different quantities (e.g. 1 and 3 for numerosity 4), whatever the selected numerosity (3, 4, 6, 7). Accordingly, two symmetrical configurations were selected for each numerosity in the canonical and noncanonical configurations, as well as for their spatial equivalents (dots). Overall, 16 stimuli with fingers were retained (8 combinations of canonical configurations and 8 combinations of noncanonical configurations) and 16 patterns of dots (8 canonical spatial equivalents and 8 noncanonical spatial equivalents of finger configurations).

To present the stimuli in the peripersonal and extrapersonal space, the laptop's screen was positioned for each participant at either a distance corresponding to 50% or 150% of their arm length. The peripersonal space was defined as the space easily reachable with the hand without moving the chest, whereas the extrapersonal space was defined as the space reachable only as a result of whole-body displacement (Coello 2018; Rizzolatti et al. 1981).

/Insert Figure 1 about here /

Fig. 1 Example of stimuli presented to participants: Canonical finger configurations (panel a); noncanonical finger configurations (panel b); dot configuration representing spatial equivalent to canonical and noncanonical finger configurations (panel c and d). Upper panel represents time sequence of presentation of finger configuration (peripersonal space condition), a central fixation cross was presented for 1 s followed by finger configurations displayed until participants provided their response (with a maximum time of 3 s, canonical configuration then noncanonical configuration). Lower panel represents time sequence of dot configurations (spatial equivalents of canonical / noncanonical configurations). Participants were instructed to enumerate verbally, as fast and accurately as possible, the numerosity associated with finger or dot configuration. Courtesy of Di Luca and Pesenti, University of Leuven, Belgium, for images depicting finger configurations.

Procedure

Participants were seated comfortably in front of a table with a laptop screen placed horizontally on top, while keeping their hands on their lap under the table (palm up). Before starting the experiment, their arithmetical abilities were assessed by a battery of arithmetical tests composed of addition, subtraction, multiplication and division problems of increasing difficulty as proposed by Rubinsten and Henik (2005), but using the French version adapted by Mejias, Grégoire and Noël (2012). In the present study, the usual French finger-counting configurations were used as all participants had completed their schooling in France and had the same finger-counting habits.

Once the arithmetical evaluation was completed, the experimental task was administered. Each trial began with a central fixation cross lasting for 1 s followed by the hands/sets of dot stimuli displayed until participants provided their response recorded through the microphone in a maximum time of 3 s. They were instructed to provide verbally, as quickly and accurately as possible, the numerosity corresponding to the fingers or dot configurations. Each response provided by the participant was reported manually on a response sheet by the experimenter for accuracy analysis (after comparison with the audio files).

The task was divided into two blocks of trials, one for each type of stimulus (fingers or dots), with each stimulus being presented 8 times in each block. Accordingly, each block (fingers or dots) included 128 trials with 4 Numerosities (3, 4, 6, 7) x 2 Configurations (canonical vs noncanonical – or spatial equivalents) x 2 Symmetrical presentations (Num1-Num2, Num2-Num1) x 8 repetitions. The participants performed each block twice: once with the stimulus displayed in the peripersonal space, and once with the stimulus displayed in the extrapersonal space. The order of presentation of the four blocks was counterbalanced between participants and the trial order in each block was randomized. Overall, 512 trials were conducted by each participant. Rest periods were proposed between the different blocks, and the full experiment lasted around 1.5 hours.

Data recording and processing

Arithmetical tests

To account for both response time and the proportion of correct answers in the arithmetical tests, we computed the inverse efficiency score (IES) to obtain an indicator of participants' arithmetical abilities while controlling for speed-accuracy trade-off. The IES was obtained by dividing the total time to complete all the subtests by the accuracy (Snodgrass et al., 2006), according to:

$$\text{IES}=\text{Total response time in arithmetical tests}\text{Proportion of Correct answer}$$

A high IES corresponded to lower arithmetical ability. We then included the IES as co-variable in the statistical analysis to account for the variability of participants' arithmetical abilities.

Experimental task

Response times (RTs) were analyzed from verbal response recordings on correct answers only. For data analysis, numerosities were pooled with respect to small (3, 4) and large (6, 7) numerosities. Because normality criteria was not achieved in the data distribution, RTs were analyzed statistically using Mixed-effect models (Jaeger 2008; Kristensen and Hansen 2004). The augmented Mixed-effect model included the variables Stimulus (fingers, dots), Space (peripersonal, extrapersonal), Configuration (canonical, noncanonical, or spatial equivalents), and Numerosity (small, large), as well as their respective interactions as fixed effects, and with participants and their respective scores in arithmetical tests (*i.e.,* the IES) as random intercepts. This augmented model was compared to reduced models (i.e., without the fixed effects of interest), using −2LogLikelihood Ratio, which follows a χ^2 distribution with degrees of freedom equal to the number or parameters used). Parameter estimates of the models were provided by t values. Effect sizes were estimated using the Rm2 and Rc2 corresponding respectively to the variance explained by fixed factors and the part of the variance explained by both fixed and random factors. Both were computed with the r.squared GLMM function of the MuMIn 1.15.6 package (MuMIn 2018) using R (version 3.0).

Response accuracy was analyzed from the information reported by the experiment on the response sheet. Response accuracy calculated as the inverse of proportion of errors (see Table 1). As for RTs, statistical analysis of response accuracy was conducted using the −2LogLikelihood Ratio Test in order to compare the augmented Mixed-effect model (including Stimulus, Space, Configuration and Numerosity) to reduced models, with subjects and IES as random intercepts.

RESULTS

Arithmetical tests

IES score, computed for individual results in the arithmetical tests, was on average 23.3 (SD: 11.8, range: 8 - 69). It correlated negatively with participants' accuracy score obtained in the experimental tasks (accuracy mean 99.8%; $r = -.502$). Therefore, IES increased as response accuracy decreased.

Experimental task

A total of 15,360 trials were recorded. After having excluded noisy trials (*i.e.,* trials with noise in the room not related to participants' responses) or with no recording (2.8%), 14,931 trials were considered in the data analysis. From these trials, 4.5% were discarded for response error and another 4.3% of the data were discarded from analysis due to a response time above or below 2.5 standard deviations from the individual mean in each condition. Overall, 13,588 trials were retained for the statistical analysis corresponding to 88.5 % of all data recorded.

Response time

Mean RTs are shown in Table 1. The statistical analysis revealed a main effect of Configuration [$\chi^2(1) = 446$, $Rm^2 = .417$, $Rc^2 = .543$, $p < .001$]. RTs for canonical (and spatial equivalents) configurations were shorter than for noncanonical configurations (estimate = 94 ms, $t = 21.30$, $SE = 4.39$, $p < .001$). There was also a main effect of Stimulus [$\chi^2(1) = 1856$, $Rm^2 = .367$, $Rc^2 = .493$, $p < .001$]. RTs for fingers were longer than for dots (estimate = 196 ms, $t = 44.6$, $SE = 4.39$, $p < .001$). Furthermore, there was a main effect of Space [$\chi^2(1) = 7945$, $Rm^2 = .429$, $Rc^2 = .554$, $p < .001$]. RTs for extrapersonal space were shorter than for peripersonal space (estimate = 45 ms, $t = 1.22$, $SE = 4.4$, $p < .001$). The analysis also showed a main effect of Numerosity [$\chi^2(1) = 7945$, $Rm^2 = .800$, $Rc^2 = .202$, $p < .001$]. RTs for small numerosities were shorter than for large ones (estimate = 454 ms, $t = 103.95$, $SE = 4.4$, $p < .001$). There was an interaction between Numerosity and Stimuli [$\chi^2(1) = 94$, $Rm^2 = .447$, $Rc^2 = .573$, $p < .001$]. The difference in RTs between small and large numerosities was greater for dots [$\chi^2(1) = 5285$, $Rm^2 = .460$, $Rc^2 = .605$, $p < .001$] than for fingers [$\chi^2(1) = 2909$, $Rm^2 = .298$, $Rc^2 = .451$, $p < .001$; estimate = 84 ms, $t = 9.72$, $SE = 8.6$ ms, $p < .001$]. Numerosity also interacted with Configuration [$\chi^2(1) = 209$, $Rm^2 = .444$, $Rc^2 = .570$, $p < .001$]. The difference in RTs between small and large numerosities was greater for noncanonical (and spatial equivalents) [$\chi^2(1) = 3530$, $Rm^2 = .356$, $Rc^2 = .482$, $p < .001$] than canonical [$\chi^2(1) = 3728$, $Rm^2 = .362$, $Rc^2 = .503$, $p < .001$; estimate = 93 ms, $t = 1.76$ ms, $SE = 8.6$, $p < .001$] configurations (see Table 1).

/Insert Table 1 about here /

Furthermore, Space interacted with Stimulus [$\chi^2(1) = 21.7$, $Rm^2 = .450$, $Rc^2 = .575$, $p < .01$], due to the fact that Space influenced RTs for fingers [$\chi^2(1) = 5.2$, $Rm^2 = .006$, $Rc^2 = .153$, $p < .001$], more than for dots [$\chi^2(1) = 7.8$, $Rm^2 = .009^{-1}$, $Rc^2 = .145$, $p < .01$]. Indeed, the difference in RTs between the extrapersonal and the peripersonal space was greater for fingers than for dots (estimate = 39 ms, $t = 4.59$, $SE = 8.6$ ms, $p < .001$). Configuration interacted with Stimulus [$\chi^2(1) = 330.4$, $Rm^2 = .440$, $Rc^2 = .566$, $p < .001$], due to the fact that RTs were shorter for canonical than noncanonical configurations with fingers [$\chi^2(1) = 410$, $Rm^2 = .051$, $Rc^2 = .197$, $p < .001$; estimate = 157 ms, $t = 18.3$, $SE = 8.6$ ms, $p < .001$], but not with spatial equivalents stimuli [$\chi^2(1) = 2.9$, $Rm^2 = .003^{-1}$, $Rc^2 = .144$, $p > .05$; see Figure 2]. Finally, the 3-way interaction between Stimulus, Space and Configuration was not significant [$\chi^2(3) = .95$, $Rm^2 = .450$, $Rc^2 = .576$, $p = .759$]. No other main effects or interactions were found.

/Insert Figure 2 about here /

Fig 2 Mean RTs in milliseconds as a function of Stimulus (fingers, dots) and Configuration (canonical, noncanonical – and spatial equivalents) in (a) the peripersonal space and (b) the extrapersonal space

Response accuracy

Statistical analysis of accuracy showed a main effect of Configuration [$\chi^2(1) = 6.98$, $Rm^2 = .162$, $Rc^2 = .459$, $p < .01$], participants being more accurate for combinations of canonical finger with spatially matched dot configurations than combinations of noncanonical finger with spatially matched dot configurations (estimate = $2.148e^{-4}$, $t = -2.92$, $SE = 7.367e^{-4}$, $p < .01$). Furthermore, Configuration interacted with Numerosity [$\chi^2(1) = 5$, $Rm^2 = .171$, $Rc^2 = .469$, $p < .05$], the difference in accuracy between small and large numerosities being greater for combinations of noncanonical finger with spatially matched dot configurations [$\chi^2(1) = 62.55$, $Rm^2 = .155$, $Rc^2 = .492$, $p < .001$] than for combinations of canonical finger with spatially matched dot configurations [$\chi^2(1) = 47.56$, $Rm^2 = .138$, $Rc^2 = .38$, $p < .001$; estimate = $2.148e^{-3}$, $t = 2.06$, $SE = 1.042e^{-3}$, $p < .05$]. No other effect was found using the augmented model. Furthermore, participants' mean accuracy was negatively correlated with mean RT ($r = -.347$). This indicates that the data did not simply result from speed-accuracy trade off (see Table 2).

/Insert Table 2 about here /

DISCUSSION

The aim of the present study was to assess whether numerical processing benefits from using stimuli in the form of finger numerical representations compared to sets of dots used as control stimuli (i.e., spatially matched dots), but depending on their location in space, i.e., in the peripersonal or the extrapersonal space. According to the embodied cognition theoretical framework, visual stimuli endowed with functional properties activate sensorimotor representations that contribute to the perceptual and cognitive processing of those stimuli (Coello and Fischer 2015; Fischer and Coello 2016). However, it was shown that the activation of sensorimotor representations occurs predominantly when the visual stimuli are located in the peripersonal space (Bartolo et al. 2014; Wamain et al. 2016). For example, Ter horst et al. (2011) showed that the mental imagery associated with the laterality judgment of a hand picture was modulated by whether the stimuli were located in either the peripersonal or extrapersonal space. Accordingly, by assuming embodied processing of finger numerical representation, we expected in the present study that numerosity processing would be facilitated when finger representation was used instead of sets of dots, but essentially when the former corresponded to culturally dependent canonical configurations and were presented in the peripersonal space. Although the data revealed an interesting pattern of results, our assumptions were not overall validated. With finger configurations, participants were faster in enumerating small quantities in the presence of canonical rather than noncanonical configurations, thus confirming previous observations (e.g., Di Luca et al. 2010). Interestingly, this effect was not observed when finger spatial equivalents (i.e., dots) were considered. This suggests that the difference observed between canonical and noncanonical finger configurations was not exclusively due to the spatial distribution of the stimuli (i.e., the spatial contiguity of the fingers). Accordingly, in contrast with noncanonical configurations, finger canonical configurations seem to involve the specific encoding of numerical representations as a result of the cultural use of fingers to express quantities (Bender and Beller 2012; Domahs et al. 2010). This interpretation is in agreement with the embodied framework of numerical cognition (e.g., Andres and Pesenti, 2015; Sixtus et al., 2020). In addition, dots were processed faster than fingers, which is a novel finding. Although Badets et al. (2010) have demonstrated that simple arithmetical operations can be facilitated when using finger representation instead of wooden blocks, major differences need to be pointed out between the procedure used in this study and the present one. In Badets et al. (2010), the authors used a response-effect compatibility paradigm where the participant's verbal answer triggered the presentation of configurations either of fingers or series of rods. In that case, fingers configurations were used as feedback information not as stimuli. Accordingly, fingers may have contributed to facilitate number processing by emphasizing the link between the stimuli and the sensorimotor representations, which was not possible when using the rods as feedback (see also Badets et al., 2012; Badets and Rensonnet, 2015). The present study focuses instead on visual stimuli processing, where dots were processed faster due to their apparent simplicity allowing fast enumeration. Indeed, it has been proposed that when presenting dot patterns, numerosity is a primary visual property that can be extracted easily from the visual scene (Burr and Ross, 2008). In support of this interpretation, steady-state visual evoked potentials acquired using high temporal signal resolution revealed that changes of numerosity in dot patterns are perceptually discriminated rapidly based on occipital cortex patterns of activation (Guillaume et al. 2018; Libertus et al. 2011; Park 2017). Moreover, Van Rinsveld et al. (2020) have recently overcome the issue of intrinsic relation between numerosity and nonnumerical magnitudes as visual continuous parameters (e.g. the summed area occupied by the dots, which covary with numerosity) by using a frequency-tagging EEG approach to separately measure responses to numerosity as well as to continuous magnitudes (numerosity was the only parameter varying periodically without periodic variation of continuous magnitudes). They show that numerosity presented through dot patterns can be processed at an early stage in the visual cortex, as some nonnumerical continuous magnitude. Furthermore, using a rapid event-related functional magnetic resonance imaging paradigm and controlling for non-numerical visual stimulus dimensions, DeWind et al. (2019) highlighted a specific neural sensitivity to numerosity in the occipital cortex (areas V1, V2, and V3). This neural activity contrasts with the neural responses generally associated with the processing of numerical information, as well as that relating to the representation of fingers, which involves more anterior regions like the parietal cortex (e.g., Naccache and Dehaene 2001; Nieder and Dehaene 2009; Pesenti et al. 2000; Piazza et al. 2004). Accordingly, it is very likely that the dots in the present study were discriminated at an earlier stage of information processing than the fingers, thus creating a more direct access to the corresponding numbers. As previously mentioned, being able to pronounce the number corresponding to a specific finger configuration depends on participants' culturally embedded knowledge of how finger configurations are encoded and used to express quantities (Bender and Beller 2011). This culturally dependent knowledge might therefore be subsumed by higher cognitive processes associated with conceptual representation (Di Luca et al. 2010). Moreover, the finding that the dots were processed faster than fingers was observed with both canonical and noncanonical configurations, which underlines that numbers associated with fingers call upon representations that go beyond the simple processing of the visual features of the stimuli.

Another important finding is that the difference in response time between dots and fingers processing was greater when the stimuli were located in the peripersonal space than in the extrapersonal space. This might be due to the reduction of the visual angle for stimuli presented in the extrapersonal space, which could have been more beneficial to dot processing. However, this interpretation can be ruled out since fingers and dots were spatially matched and subtended thus the same visual angle. An alternative interpretation concerns the embodied nature of finger numerical representations. Since finger representations are likely more than just a different way of mentally representing numerosities, unlike other stimuli (i.e., visual, verbal, or analogs) they rely on sensorimotor processes that provide a non-arbitrary correspondence between finger configurations and the numerosity that they express (Crollen et al. 2011; Di Luca and Pesenti 2011). Supporting this view, a number of experiments have demonstrated the interference effect of motor activity when numerical information is processed (see for a review Andres et al. 2008). For instance, passive limb movements were found to alter the accuracy of numerical processing (Imbo et al. 2011; Michaux et al. 2013 but see, Morrissey et al. 2018). The greater difference between dot and finger processing in the peripersonal space could thus be due to the motor nature of finger numerical stimuli which influences their processing when located in the peripersonal space. Indeed, objects presented in the peripersonal space are known to activate sensorimotor representations, unlike those presented in extrapersonal space (Cléry and Hamed 2018; di Pellegrino and Làdavas 2015; Iachini et al. 2016). However, according to this interpretation, one could have expected a significant difference between canonical and noncanonical finger configuration for stimuli located in the peripersonal space. However, this was not the case, perhaps because we used canonical configuration according to each hand (2 and 4 for 6, for instance), which did not necessarily correspond to the familiar canonical representation when using the two hands (1 and 5 for six, for instance). Further research would be necessary to disentangle these interpretations, in particular by combining different finger numerical configurations and different locations in space. In an educational perspective, this debate takes on its full meaning: it is common to use fingers as numerical stimuli in order to favor the understanding of abstract Arabic digits. Accordingly, a step further would be to understand if the access to the semantic representation of numerosity is facilitated by finger montring or counting configurations, according to the distance of the numerical stimuli: one could expect that in the extrapersonal space (i.e., displayed on a classroom's walls), canonical finger configurations should be used for montring as this respect daily expectancies. While in the peripersonal space (i.e., in the child's notebook), counting configurations should subserve sensorimotor representations, i.e., congruent with the use that the child makes of his own fingers as external quantifiers, according to his/her own culture. Accordingly, it would be interesting to study the processing of canonical finger configuration when used for montring (*i.e.,* for others) or counting (*i.e.,* for oneself), depending on their spatial localisation.

Two notable conclusions can thus be drawn from the present study. First, despite their embodied nature, finger representations were not processed faster than other stimuli, even in the case of canonical configurations. However, the latter were processed faster than noncanonical configurations. Second, the higher cost of finger configurations processing compared to other stimuli was even greater in the peripersonal space than in the extrapersonal space. Together, these findings indicate that finger configurations are not processed as simple visual stimuli but in relation to body/motor representations. Consequently, their processing depends on both cultural counting habits and on where they are located in space.

REFERENCES

Andres, M, & Pesenti, M. (2015). Finger-based representation of mental arithmetic. The Oxford Handbook of Numerical Cognition, 67. https://doi.org/10.1093/oxfordhb/9780199642342.013.028

Andres, Michael, Olivier, E., & Badets, A. (2008). Actions , Words , and Numbers A Motor Contribution to Semantic Processing ? *Association for Psychological Science*, *17*(5), 313–317.

Anghileri, J. (2006). Scaffolding practices that enhance mathematics learning. *Journal of Mathematics Teacher Education*, *9*(1), 33–52.

Ardila, A., Concha, M., & Rosselli, M. (2000). Angular gyrus syndrome revisited: Acalculia, finger agnosia, right-left disorientation and semantic aphasia. Aphasiology, 14(7), 743–754.

Badets, A., Koch, I., & Toussaint, L. (2012). Role of an Ideomotor Mechanism in Number Processing. Experimental psychology, 60, 1-10. doi:10.1027/1618-3169/a000171

Badets, A., Pesenti, M., & Olivier, E. (2010). Response–effect compatibility of finger–numeral configurations in arithmetical context. The Quarterly Journal of Experimental Psychology, 63(1), 16–22. https://doi.org/10.1080/17470210903134385

Badets, A., & Rensonnet, C. (2015). Une approche idéomotrice de la cognition. [An ideomotor approach to cognition]. L'Année psychologique, 115(4), 591-635. doi:10.4074/s0003503315000238

Bartolo, A., Coello, Y., Edwards, M. G., Delepoulle, S., Endo, S., & Wing, A. M. (2014). Contribution of the motor system to the perception of reachable space: An fMRI study. European Journal of Neuroscience, 40(12), 3807–3817. https://doi.org/10.1111/ejn.12742

Bender, A., & Beller, S. (2011). Fingers as a Tool for Counting ? Naturally Fixed or Culturally Flexible? Frontiers in Psychology, 2(OCT), 256. https://doi.org/10.3389/fpsyg.2011.00256

Bender, A., & Beller, S. (2012). Nature and culture of finger counting: Diversity and representational effects of an embodied cognitive tool. Cognition, 124(2), 156–182. https://doi.org/10.1016/j.cognition.2012.05.005

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. Journal of Experimental Psychology: General, 136(4), 539.

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

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

Butterworth, B. (1999b). A head for figures. *Science*, *284*(5416), 928–929.

Butterworth, B. (2005). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry*, *46*(1), 3–18.

Cléry, J., & Hamed, S. Ben. (2018). Frontier of self and impact prediction. Frontiers in psychology, 9, 1073.

Coello, Y. (2018). Action Spaces Representation in Social Contexts. In Diversity in Harmony - Insights from Psychology (pp. 230–254). https://doi.org/10.1002/9781119362081.ch12

Coello, Y., & Fischer, M. H. (2015). Perceptual and emotional embodiment: Foundations of embodied cognition. Perceptual and Emotional Embodiment: Foundations of Embodied Cognition (Vol. 1). Routledge. https://doi.org/10.4324/9781315751979

Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2008). Gesturing makes learning last. Cognition, 106(2), 1047–1058.

Crollen, V., Mahe, R., Collignon, O., & Seron, X. (2011). The role of vision in the development of finger-number interactions: Finger-counting and finger-montring in blind children. Journal of Experimental Child Psychology. https://doi.org/10.1016/j.jecp.2011.03.011

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

De Jong, B. M., Van Zomeren, A. H., Willemsen, A. T. M., & Paans, A. M. J. (1996). Brain activity related to serial cognitive performance resembles circuitry of higher order motor control. Experimental brain research, 109(1), 136–140.

Dehaene, S. (1996). The organization of brain activations in number comparison: Event-related potentials and the additive-factors method. Journal of Cognitive Neuroscience, 8(1), 47–68.

DeWind, N. K., Park, J., Woldorff, M. G., & Brannon, E. M. (2019). Numerical encoding in early visual cortex. Cortex: A Journal Devoted to the Study of the Nervous System and Behavior, 114, 76-89. doi:10.1016/j.cortex.2018.03.027

Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger–digit compatibility in Arabic numeral processing. The Quarterly Journal of Experimental Psychology, 59(9), 1648–1663. https://doi.org/10.1080/17470210500256839

Di Luca, S., Lefèvre, N., & Pesenti, M. (2010). Place and summation coding for canonical and non-canonical finger numeral representations. Cognition, 117(1), 95–100. https://doi.org/10.1016/j.cognition.2010.06.008

Di Luca, S., & Pesenti, M. (2008). Masked priming effect with canonical finger numeral configurations. Experimental Brain Research, 185(1), 27–39. https://doi.org/10.1007/s00221-007-1132-8

Di Luca, S., & Pesenti, M. (2011). Finger numeral representations: More than just another symbolic code. *Frontiers in Psychology*, *2*(NOV), 1–3. https://doi.org/10.3389/fpsyg.2011.00272

di Pellegrino, G., & Làdavas, E. (2015). Peripersonal space in the brain. Neuropsychologia, 66, 126–133.

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(4), 359–367. https://doi.org/10.1016/j.cortex.2007.08.001

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H. C. (2010). Embodied numerosity: Implicit hand-based representations influence symbolic number processing across cultures. *Cognition*, *116*(2), 251–266. https://doi.org/10.1016/j.cognition.2010.05.007

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex*, *44*(4), 386–392.

Fischer, M. H., & Brugger, P. (2011). When digits help digits: Spatial-numerical associations point to finger counting as prime example of embodied cognition. Frontiers in Psychology, 2(OCT), 1–7. https://doi.org/10.3389/fpsyg.2011.00260

Fischer, M. H., & Coello, Y. (2016). Foundations of embodied cognition: Perceptual and emotional embodiment. Routledge, Taylor & Francis Group.

Fornaciai, M., Brannon, E. M., Woldorff, M. G., & Park, J. (2017). Numerosity processing in early visual cortex. NeuroImage, 157(March), 429–438. https://doi.org/10.1016/j.neuroimage.2017.05.069

Fuson, K. C. (1982). An analysis of the counting-on solution procedure in addition. *Addition and subtraction: A cognitive perspective*, 67–81.

Fuson, K. C. (1988). Book review: Children's Counting and Concepts of Number. *British Journal of Developmental psychology*, *6*, 395–397.

Fuson, K. C., Richards, J., & Briars, D. J. (1982). The acquisition and elaboration of the number word sequence. In Children's logical and mathematical cognition (pp. 33–92). Springer.

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

Gelman, R., & Gallistel, C. R. (1978). The child's concept of number. *Cambridge, MA: Harvard*.

Gerstmann, J. (1940). Syndrome of finger agnosia, disorientation for right and left, agraphia and acalculia: Local diagnostic value. Archives of Neurology \& Psychiatry, 44(2), 398–408.

Göbel, S. M., Johansen-Berg, H., Behrens, T., & Rushworth, M. F. S. (2004). Response-selection-related parietal activation during number comparison. Journal of Cognitive Neuroscience, 16(9), 1536–1551.

Gracia-Bafalluy, M., & Noël, M. P. (2008). Does finger training increase young children's numerical performance? Cortex, 44(4), 368–375. https://doi.org/10.1016/j.cortex.2007.08.020

Guedin, N., Thevenot, C., & Fayol, M. (2017). Des doigts et des nombres. Psychologie Française, 63(4), 379–399. https://doi.org/10.1016/j.psfr.2017.07.001

Guillaume, M., Mejias, S., Rossion, B., Dzhelyova, M., & Schiltz, C. (2018). A rapid, objective and implicit measure of visual quantity discrimination. Neuropsychologia, 111(February), 180–189. https://doi.org/10.1016/j.neuropsychologia.2018.01.044

Hanakawa, T., Honda, M., Okada, T., Fukuyama, H., & Shibasaki, H. (2003). Differential activity in the premotor cortex subdivisions in humans during mental calculation and verbal rehearsal tasks: a functional magnetic resonance imaging study. Neuroscience Letters, 347(3), 199–201.

Hilton, C. (2019). Fingers matter: the development of strategies for solving arithmetic problems in children with Apert syndrome. In *Frontiers in Education* (Vol. 4).

Hohol, M., Wołoszyn, K., Nuerk, H.-C., & Cipora, K. (2018). A large-scale survey on finger counting routines, their temporal stability and flexibility in educated adults. PeerJ, 6, e5878. doi:10.7717/peerj.5878

Hughes, M. (1986). *Children and number: Difficulties in learning mathematics*. Wiley-Blackwell.

Iachini, T., Coello, Y., Frassinetti, F., Senese, V. P., Galante, F., & Ruggiero, G. (2016). Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age. Journal of Environmental Psychology, 45, 154–164.

Ifrah, G. (1981). *Histoire universelle des chiffres*. Seghers Paris.

Imbo, I., Vandierendonck, A., & Fias, W. (2011). Passive hand movements disrupt adults' counting strategies. Frontiers in Psychology, 2(SEP), 201. https://doi.org/10.3389/fpsyg.2011.00201

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. Journal of Memory and Language, 59(4), 434–446. https://doi.org/10.1016/j.jml.2007.11.007

Jäncke, L., Loose, R., Lutz, K., Specht, K., & Shah, N. J. (2000). Cortical activations during paced finger-tapping applying visual and auditory pacing stimuli. Cognitive Brain Research, 10(1–2), 51–66.

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1992). Differential Calculation Abilities in Young Children From Middle- and Low-Income Families. *Developmental Psychology*, *28*(4), 644–653. https://doi.org/10.1037/0012-1649.28.4.644

Jordan, N. C., Huttenlocher, J., & Levine, S. C. (1994). Assessing early arithmetic abilities: Effects of verbal and nonverbal response types on the calculation performance of middle-and low-income children. Learning and Individual Differences, 6(4), 413–432. https://doi.org/10.1016/1041-6080(94)90003-5

Kristensen, M., & Hansen, T. (2004). Statistical analyses of repeated measures in physiological research: a tutorial. Advances in Physiology Education, 28(1), 2–14. https://doi.org/10.1152/advan.00042.2003

Kuhtz-Buschbeck, J. P., Mahnkopf, C., Holzknecht, C., Siebner, H., Ulmer, S., & Jansen, O. (2003). Effector-independent representations of simple and complex imagined finger movements: a combined fMRI and TMS study. European Journal of Neuroscience, 18(12), 3375–3387.

Làdavas, E. (2015). Neuropsychologia Peripersonal space in the brain. Neuropsychologia, 66, 126–133.

Libertus, M. E., Brannon, E. M., & Woldorff, M. G. (2011). Parallels in Stimulus-Driven Oscillatory Brain Responses to Numerosity Changes in Adults and Seven-Month-Old Infants. Developmental Neuropsychology, 36(6), 651–667. https://doi.org/10.1080/87565641.2010.549883

Liu, X., Wang, H., Corbly, C. R., Zhang, J., & Joseph, J. E. (2006). The involvement of the inferior parietal cortex in the numerical Stroop effect and the distance effect in a two-digit number comparison task. Journal of cognitive neuroscience, 18(9), 1518–1530.

Long, I., Malone, S. A., Tolan, G. A., Burgoyne, K., Heron-Delaney, M., Witteveen, K., & Hulme, C. (2016). The cognitive foundations of early arithmetic skills: It is counting and number judgment, but not finger gnosis, that count. Journal of Experimental Child Psychology, 152, 327–334. https://doi.org/10.1016/j.jecp.2016.08.005

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

Mejias, S., Grégoire, J., & Noël, M.-P. (2012). Numerical estimation in adults with and without developmental dyscalculia. Learning and Individual Differences, 22(1), 164–170.

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. https://doi.org/10.1027/1618-3169/a000188

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. Frontiers in Psychology. https://doi.org/10.3389/fpsyg.2011.00328

Morrissey, K., Hallett, D., Wynes, R., Kang, J., & Han, M. (2018). Finger-counting habits, not finger movements, predict simple arithmetic problem solving. Psychological Research, 1–12. https://doi.org/10.1007/s00426-018-0990-y

MuMIn, B. K. (2018). Multi-model inference. R package version 1.15. 6.; 2016.

Naccache, L., & Dehaene, S. (2001). The priming method: imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes. Cerebral cortex, 11(10), 966-974.

Nieder, A., & Dehaene, S. (2009). Representation of Number in the Brain. Annual Review of Neuroscience, 32(1), 185–208. https://doi.org/10.1146/annurev.neuro.051508.135550

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

Numminen, J., Schürmann, M., Hiltunen, J., Joensuu, R., Jousmäki, V., Koskinen, S. K., et al. (2004). Cortical activation during a spatiotemporal tactile comparison task. Neuroimage, 22(2), 815–821.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. Neuropsychologia, 9(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Park, J. (2017). A neural basis for the visual sense of number and its development: A steady-state visual evoked potential study in children and adults. Developmental Cognitive Neuroscience, 30, 333–343. https://doi.org/10.1016/j.dcn.2017.02.011

Penner-Wilger, M., & Anderson, M. L. (2013). The relation between finger gnosis and mathematical ability: Why redeployment of neural circuits best explains the finding. Frontiers in psychology, 4, 877.

Pesenti, M., Thioux, M., Seron, X., & Volder, A. De. (2000). Neuroanatomical Substrates of Arabic Number Processing, Numerical Comparison, and Simple Addition: A PET Study. Journal of Cognitive Neuroscience, 12(3), 461–479. https://doi.org/10.1162/089892900562273

Piazza, M., Izard, V., Pinel, P., Le Bihan, D., & Dehaene, S. (2004). Tuning curves for approximate numerosity in the human intraparietal sulcus. Neuron, 44(3), 547–555. https://doi.org/10.1016/j.neuron.2004.10.014

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

Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. Science, 306(5695), 499–503.

Pika, S., Nicoladis, E., & Marentette, P. (2009). How to Order a Beer Conventional Gestures for Numbers. *Journal of Cross-Cultural Psychology*, *40*(1), 70–80. https://doi.org/10.1177/0022022108326197

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

Previtali, P., Rinaldi, L., & Girelli, L. (2011). Nature or nurture in finger counting: A review on the determinants of the direction of number-finger mapping. *Frontiers in Psychology*, *2*(DEC), 1–5. https://doi.org/10.3389/fpsyg.2011.00363

Rizzolatti, G., Scandolara, C., Matelli, M., & Gentilucci, M. (1981). Afferent properties of periarcuate neurons in macaque monkeys. I. Somatosensory responses. Behavioural Brain Research, 2(2), 125–146. https://doi.org/10.1016/0166-4328(81)90052-8

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: A study of developmental dyscalculia. Neuropsychology, 19(5), 641–648. https://doi.org/10.1037/0894-4105.19.5.641

Rusconi, E., Pinel, P., Dehaene, S., & Kleinschmidt, A. (2010). The enigma of Gerstmann's syndrome revisited: a telling tale of the vicissitudes of neuropsychology. Brain, 133(2), 320–332.

Rusconi, E., Walsh, V., & Butterworth, B. (2005). Dexterity with numbers: rTMS over left angular gyrus disrupts finger gnosis and number processing. Neuropsychologia, 43(11), 1609–1624. https://doi.org/10.1016/j.neuropsychologia.2005.01.009

Sato, T., Ito, M., Suto, T., Kameyama, M., Suda, M., Yamagishi, Y., et al. (2007). Time courses of brain activation and their implications for function: a multichannel near-infrared spectroscopy study during finger tapping. Neuroscience research, 58(3), 297–304.

Sixtus, E., Fischer, M. H., & Lindemann, O. (2017). Finger posing primes number comprehension. Cognitive Processing, 18(3), 237–248. https://doi.org/10.1007/s10339-017-0804-y

Sixtus, E., Lindemann, O., & Fischer, M. H. (2020). Stimulating numbers: Signatures of finger counting in numerosity processing. Psychological research, 84(1), 152–167.

Snodgrass, J. G., Townsend, J. T., & Ashby, F. G. (2006). *Stochastic Modeling of Elementary Psychological Processes*. *The American Journal of Psychology* (Vol. 98). CUP Archive. https://doi.org/10.2307/1422636

Stark, Z., McGillivray, G., Sampson, A., Palma-Dias, R., Edwards, A., Said, J. M., et al. (2015). Apert syndrome: temporal lobe abnormalities on fetal brain imaging. Prenatal diagnosis, 35(2), 179–182.

Ter Horst, A. C., Van Lier, R., & Steenbergen, B. (2011). Spatial dependency of action simulation. Experimental Brain Research, 212(4), 635–644. https://doi.org/10.1007/s00221-011-2748-2

Tschentscher, N., Hauk, O., Fischer, M. H., & Pulvermüller, F. (2012). You can count on the motor cortex: Finger counting habits modulate motor cortex activation evoked by numbers. *NeuroImage*, *59*(4), 3139–3148. https://doi.org/10.1016/j.neuroimage.2011.11.037

Van Rinsveld, A., Guillaume, M., Kohler, P. J., Schiltz, C., Gevers, W., & Content, A. (2020). The neural signature of numerosity by separating numerical and continuous magnitude extraction in visual cortex with frequency-tagged EEG. Proceedings of the National Academy of Sciences, 117(11), 5726-5732.

Venkatraman, V., Ansari, D., & Chee, M. W. L. (2005). Neural correlates of symbolic and non-symbolic arithmetic. Neuropsychologia, 43(5), 744–753.

Wamain, Y., Gabrielli, F., & Coello, Y. (2016). In press Cortex EEG μ rhythm in virtual reality reveals that motor coding of visual objects in peripersonal space is task dependent. Cortex, 74, 1–36.

Wiese, H. (2003a). *Numbers, language, and the human mind*. Cambridge University Press.

Wiese, H. (2003b). Iconic and non-iconic stages in number development: the role of language. *Trends in cognitive sciences*, *7*(9), 385–390.

Wilkie, A. O. M., Slaney, S. F., Oldridge, M., Poole, M. D., Ashworth, G. J., Hockley, A. D., et al. (1995). Apert syndrome results from localized mutations of FGFR2 and is allelic with Crouzon syndrome. Nature genetics, 9(2), 165–172.

World Medical Association, G. A. (2014). World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. The Journal of the American College of Dentists, 81(3), 14.

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