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Research article

ERP differences in processing canonical and noncanonical finger-numeral configurations

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ABSTRACT

Finger-numeral configurations are used to represent numerosities, to count, and to do arithmetic across cultures. Previous research has distinguished between two forms of finger-numeral configurations; finger montring and finger counting. Montring refers to how people raise their fingers to show numerosities to others and usually serves a communicative function. Finger counting is used both for counting and arithmetic, and has a self-directed, facilitative function. In this study we compared the ERP markers for recognition of montring, counting, and noncanonical finger-numeral configurations with adult participants to explore differences in early perceptual and later semantic processing. Montring configurations were recognized faster and more accurately compared to counting and noncanonical. Recognition of montring configurations drew larger attentional resources, marked by higher positivity in the P1/N1 range, and montring and counting showed similar patterns of semantic processing, marked by higher positivity in the P3 range compared to noncanonical, possibly due to strategy differences (memory recall vs. counting). We also found some ERP evidence for participants' finger counting habits affecting their processing of counting configurations. Overall, the results show differences in perceptual and semantic processes involved in extracting numerical information across the three finger-numeral configurations.

1. Introduction

There is considerable evidence showing that different forms of finger processing interact with numerical cognition [1]. Previous research distinguished between two forms of finger-numeral configurations; montring and counting [2]. Montring configurations communicates number information and are usually used for communicative purposes. For example, when asked how many apples a child wants for her lunch, the child may spontaneously raise her index and middle fingers, indicating "two." Finger counting is used as an external aid for the purpose of counting quantities or for doing arithmetic.

So far there are only a few studies focusing on differences in perceptual processing of montring, counting, and noncanonical finger-numeral configurations. Di Luca and Pesenti [2] showed that there were no behavioral performance differences in identification of montring and counting configurations in a number identification task, while the behavioral performance was higher for both compared to noncanonical configurations. Within the same study, in a masked priming experiment, they also found evidence for montring configurations automatically activating number semantics (representations), while the noncanonical ones not.

In a follow-up study, where priming effects of montring and noncanonical number configurations were compared in a number naming task, Di Luca, Lefèvre, & Pesenti [3] found a distance effect (priming effect decreasing with numerical distance between the prime and the target) for the montring prime, but not for the noncanonical prime. They interpreted the results as montring configurations automatically triggering a number representation, in a way similar to number symbols. To investigate if the processing differences between montring and noncanonical representations are due to faster low-level visual processing of montring configurations. Di Luca and Pesenti [4] conducted a visual-detection experiment, where participants had to determine whether a montring configuration target was present among a varying number of distractors. The results showed that response latencies linearly increased as a function of number of distractors, showing a lack of a pop-out effect, which was then interpreted as a lack of perceptual saliency for montring representations among noncanonical ones.

The current study follows up on previous findings to explore the ERP correlates of processing montring, counting, and noncanonical finger configurations to characterize both perceptual and semantic processing differences. We predicted higher behavioral performance in extracting numerical information from canonical (montring and

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counting) configurations compared to noncanonical. Considering the communicative nature of montring configurations, we expected highest performance with the montring configurations. Since Luca and Pesenti [4] did not show perceptual saliency for montring configurations compared to noncanonical, we expected to find largest ERP differences, due to more automatic access to numerical information for montring and counting configurations compared to noncanonical, in the later semantic processing stages.

2. Materials and methods

2.1. Participants

46 right-handed, native English speaking undergraduate students, with no history of neurological illness and normal or corrected-to-normal vision, participated in the experiment. Data from eight subjects who started counting on their left hands was excluded. Data from the remaining 38 participants (20 female, M = 19.68 years, SD = 1.84) was included in the analysis. The research was approved by the Institutional Review Board of The University of Alabama.

2.2. Stimuli and experimental procedures

Finger counting data was obtained by asking participants to count on their fingers from 1 to 10 and recording the observed finger counting configurations. Finger montring data was gathered by showing participants pictures of different object collections (e.g., apples) on pieces of white paper and asking the participants to gesture how many objects they see on each picture.

The stimuli for the EEG session included 24 pictures of finger number configurations; 4 montring (MO), 4 counting (CO), and 4 noncanonical (NC), separately for left and right hands, all showing the palm and matching with numerosities from one to four (Fig. 1). The noncanonical configurations were based on a previous study comparing montring and noncanonical configurations [3]. The gesture images were shot with a digital camera and were edited to replace the background with a uniform black and to balance color and luminance.

The experiment included a total of 960 trials in 10 blocks, each block including 96 trials, generated by combining four sets of the 24 configurations, each of them randomized separately, which allowed an even distribution of different stimuli across each block while avoiding predictability. In each trial a configuration was presented for 500 ms, followed by a validation step, where a single-digit Arabic numeral was presented (Fig. 1). Participants pressed one of the two buttons on the controller using either their left or right index finger to indicate whether the Arabic numeral shown matches the number presented in the preceding configuration. To counterbalance use of response buttons, participants used one of the two (right: match, left: no-match, or, left: match, right: no-match) response button configurations in the first five blocks, and the other one in the remaining five blocks.

2.3. EEG acquisition and analysis

The EEG portion of the experiment took place in a sound attenuated experiment room. Neurobs Presentation (www.neurobs.com) was used for stimulus presentation. EEG Data was collected using a BrainVision 32 Channel ActiChamp system (www.brainvision.com), with Easy Cap recording caps using Ag/AgCl electrodes. The 32 electrodes were attached according to the international 10–20 system and referenced to Cz. BrianVision Recorder was used to record data (electrode impedance < 20 kΩ, 0.5–70 Hz, 500 samples/sec). A custom MATLAB script using ERPLAB (http://erpinfo.org/erplab/) and EEGLAB (http://sccn.ucsd.edu/eeglab) functions were used to analyze data. Inferential statistics was conducted with JASP (https://jasp-stats.org/). A Logitech F310 game controller was used as the input device.

During the analysis the continuous EEG data was re-referenced to the average reference, high-pass filtered with 0.1 Hz half-amplitude cutoff and low pass filtered with a 30 Hz half-amplitude cutoff (IIR-Butterworth, 24 dB/octave) filters. EEG recordings were segmented for the epoch from 200 ms before the onset of the gesture presentation to 500 ms after (stimulus offset). The first 200 ms pre-stimulus period was used as the baseline, and all epochs were corrected to baseline.

For artifact detection a moving window peak-to-peak threshold algorithm (for eye blinks; threshold 60 μV, window size 80 ms, window step 20 ms), and a step-like artifacts algorithm (for eye movements; threshold 50 μV, window size 200 ms, window step 100 ms) were used. Epochs exceeding the thresholds indicated were excluded (4.01% of trials, SD = 4.29).Only the epochs that preceded a correct response was included in the subject-level averaged ERPs (97.5% of trials).

The raw EEG and behavioral data, and the analysis scripts are publicly available in the Harvard Dataverse data repository [5].

3. Results

3.1. Behavioral results

3.1.1. Finger counting and montring

All 38 participants included in the analysis started counting on their right hands (right-starters), and all used their right hands for montring numerosities from 1–5. All participants used the same montring configuration (1: index, 2: index and middle, 3: index, middle and ring, 4: index, middle, ring and little, 5: index, middle, ring, little and the thumb). Fingers on the right for 1–5 were symmetrically matched for fingers for 6–10 on the right for montring across all participants.

20 participants started counting from the thumb (continued by index for 2, middle for 3, ring for 4, and the little finger for 5) and the remaining 18 started counting from the index finger (continued by middle for 2, ring for 3, little for 4, and the thumb for 5). Participants were grouped into two based on their counting habits; thumb-starters (N = 20) and index-starters (N = 18). The counting configuration of the thumb-starters matched with the counting configurations included in the stimulus, whereas this was not the case for index-starters.

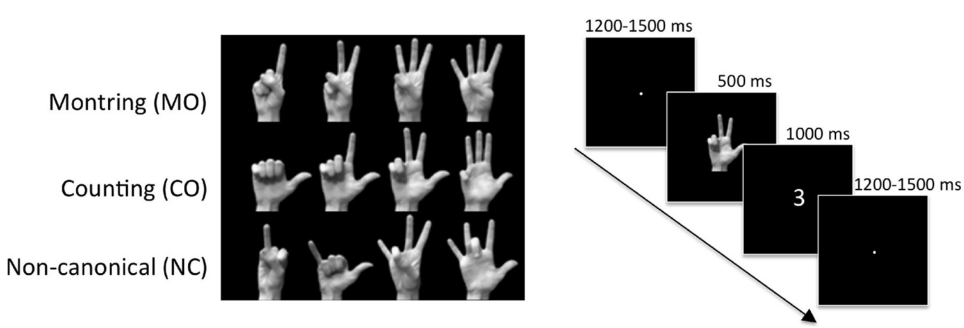

Fig. 1. Left: Stimuli for the experiment. Only right hand is shown in the figure. The left finger configurations were generated by flipping the right hand images horizontally. Right: Stimulus presentation order for each trial. The number gesture was presented on a black background for 500 ms followed by the presentation of a single-digit Arabic numeral. The inter-stimulus interval included a fixation dot, with a 1200–1500 ms random duration (jitter).

3.1.2. Accuracy & reaction time (RT)

A condition (MO, CO, NC) x hand (left, right) x group (thumb- & index-starter) repeated measures ANOVA was conducted separately on averaged accuracy rates and response times (RT). The *hand* factor was included to see if which hand was shown in the gesture stimuli (left or right) influenced behavioral performance and the group factor to test for differences between thumb- and index-starters.

For accuracy, there was only an effect of condition, [F(2, 72) = 8.903, p < .001], and no effect of hand, [F(1, 36) = .002, p = .961], and group, [F(1, 36) = .428, p = .517]. The condition x hand, [F(2, 72) = .144, p = .052], condition x group, [F(2, 72) = .077, p = .926], hand x group, [F(1, 36) = .006, p = .926], and condition x hand x group, [F(2, 72) = .006, p = .994], interactions were also not significant. Post-hoc pairwise comparisons to explore the effect of condition showed that while the accuracy for MO (M = .982, SD = .130) was significantly higher than both from CO (M = .975, SD = .156), and NC (M = .976, SD = .152), (p = .003, d = .573 & p = .009, d = .518 respectively), the difference between CO and NC was not significant (p = 1, d = .123).

For RT, similar to accuracy, there was only an effect of condition, [F (2, 72) = 34.312, p < .001], and no effect of hand, [F(1, 36) = .014, p = .907], and group, [F(1, 36) = .366, p = .549]. The condition x hand, [F(2, 72) = 1.488, p = .233], condition x group, [F(2, 72) = .657, p = .522], hand x group, [F(1, 36) = .122, p = .728], and condition x hand x group, [F(2, 72) = .967, p = .385], interactions were also not significant. Post-hoc pairwise comparisons to explore the effect of condition showed that while the RT for MO (M = 523.37, SD = 180.06) was significantly lower than both from CO (M = 552.15, SD = 198.38), and NC (M = 553.84, SD = 203.81), (p < .001, d = 1.67 & p < 001, d = 1.042 respectively), the difference between CO and NC was not significant (p = 1.000, d = .060), paralleling accuracy results. Overall, the behavioral results showed that montring configurations were more easily processed compared to counting and noncanonical configurations.

3.2. ERP results

Given the visuospatial nature of the task, and the importance of a parietal network for number representation and processing [6,7], the analysis focused on the central and posterior electrodes (Fig. 2). The 15 centroparietal electrodes were grouped into four caudal areas (Fig. 2) as O (occipital; O1/z/2), P (parietal; P7/3/z/4/8), CP (centroparietal; CP5/1/2/6), C (central; C3/z/4). Measurements for mean amplitudes across three time windows characterizing P1 (100–150 ms), N1 (150–210 ms), and P3 (250–500 ms) components were taken from each electrode for each subject. Mean amplitudes and not peak amplitudes were used both because the experimental paradigm used did not target a specific component, and because mean amplitudes are less prone to noise and were found to better characterize real effects [8].

A time (P1, N1, P3) x area (O, P, CP, C) x condition (MO, CO, NC) x group (thumb- & index-starter) repeated measures ANOVA was conducted on mean amplitude values. All of the effects and interactions involving only the within-subjects factors were significant (Supplementary Materials, Table 1, Fig. 3). There was no effect of group, [F(1, 36) = .026, p = .873], however there was an interaction between condition and group, [F(2, 72) = 3.509, p = .035], as well as an interaction across area, condition, and group, [F(6, 216) = 3.072, p = .007]. All other interactions involving the group factor were not significant (Supplementary Materials, Table 1).

3.2.1. Within-subjects effects

To explore the time, area and condition interaction an area x condition repeated measures ANOVA was conducted separately for each time interval measurement. There was an effect of both area ([F(3, 111) = 88.14, p < .001], [F(3, 111) = 10.467, p= < .001], [F(3, 111) = 50.284, p < .001]) and condition ([F(2, 74) = 32.923, p < .001], [F(2, 74) = 25.826, p < .001], [F(2, 74) = 32.588, p < .001]), as well as an interaction between condition and area ([F(6, 222) = 33.85, p < .001], [F(6, 222) = 27.978, p < .001], [F(6, 222) = 18.203, p < .001]), respectively for all intervals, P1, N1, and P3.

To further explore the area and condition interactions a one-way repeated measures ANOVA with pairwise post-hoc comparisons using Bonferroni correction was conducted to test effects of condition on each area, separately for each interval. For the first interval, P1, all areas, O [F(2, 74) = 41.292, p= < .001], P [F(2, 74) = 21.951, p < .001], CP [F(2, 74) = 4.045, p = .022], and C [F(2, 74) = 5.824, p = .004] showed an effect of condition. Similarly for the second interval, N1, all areas, O [F(2, 74) = 33.116, p < .001], P [F(2, 74) = 28.429, p < .001], CP [F(2, 74) = 3.77, p = .028], and C [F(2, 74) = 12.296, p < .001] showed an effect of condition. For the third interval, P3, O [F(2, 74) = 26.775, p= < .001], P [F(2, 74) = 32.881, p= < .001], and CP [F(2, 74) = 5.73, p = .005] showed an effect of condition, but not C [F(2, 74) = 1.661, p = .197]. The results of the pairwise comparisons are reported in Supplementary Materials, Table 2. Overall, the pairwise comparisons showed a clear pattern in occipital and parietal areas, where in the P1 interval, MO showed higher positivity compared to both CO and NC, in the N1 interval, MO showed higher positivity compared to CO and CO showed higher positivity compared to NC, and in the P3 interval, both MO and CO showed higher positivity compared to NC.

3.2.2. Between-group effects

To explore the area, condition, and group interaction an area x condition repeated measures ANOVA was conducted separately for the thumb-starter and index-starter groups. Both for the thumb and index starter groups there were effects of area ([F(3, 57) = 31.98, p < .001], [F(3, 51) = 21.25, p < .001]) and condition ([F(2, 38) = 21.65, p < .001], [F(2, 34) = 15.0, p < .001]), as well as an interaction between area and condition ([F(6, 114) = 19.49, p < .001], [F(6, 102) = 10.5, p < .001]) respectively. To further explore the area and condition interactions, a one-way repeated measures ANOVA with pairwise post-hoc comparisons using Bonferroni correction was conducted to test effects of condition on each area, separately for each group. For the thumb-starter-group, while there was an effect of condition for each area, O [F(2, 38) = 24.172, p < .001], P [F(2, 38) = 22.742, p < .001], CP [F(2, 38) = 3.603, p = .037], and C [F(2, 38) = 6.139, p = .005], for the index-starter group there was an effect of condition only for O [F(2, 34) = 14.435, p < .001] and P [F(2, 34) = 17.721, p < .001], but not for CP [F(2, 34) = 2.075, p = .141] and C [F(2, 34) = 1.973, p = .155]. The results of the pairwise comparisons are reported in Supplementary Materials, Table 3. The pairwise comparisons showed that the two groups differed in the central area, where the thumb-starter group showed higher positivity for CO compared to MO and NC, while there was no effect of condition in the same area for the index-starter group.

4. Discussion

Behavioral results have shown that montring configurations were identified faster and more accurately compared to counting and noncanonical configurations. This partially overlaps with previous research showing that montring configurations are identified faster than noncanonical ones [3]. There were no behavioral differences between the two groups.

We found differences in ERP markers across the three finger configurations. The patterns were most consistent on the occipital and parietal sites: In the P1 time range, montring showed higher positivity compared to counting and noncanonical configurations. In the N1, while the average amplitude order was the same, the comparisons across three configurations were all significant, montring having higher positivity than counting and noncanonical having the lowest. In the P3

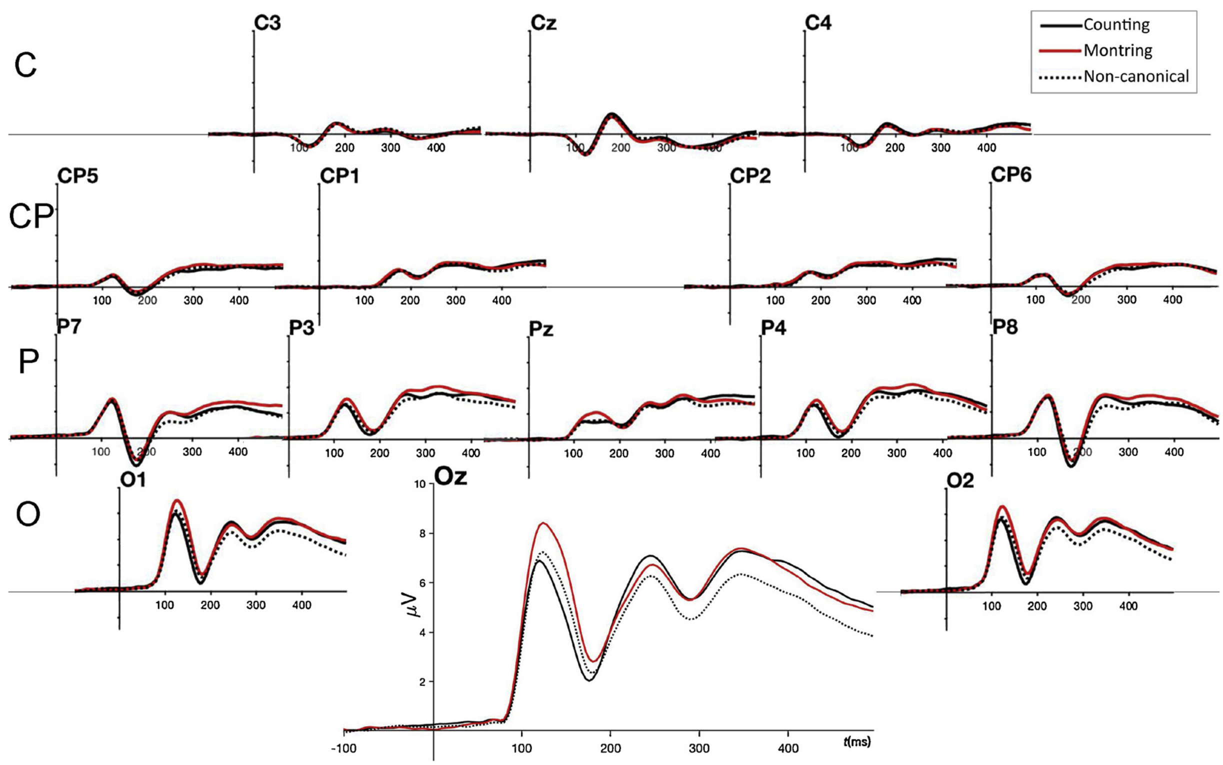

Fig. 2. ERPs across the four sites included in the analysis, C, CP, P & O. Oz is magnified to show the P1, N1 & P3 differences.

range the difference between montring and counting was not significant, where both showed higher positivity than noncanonical. The P1/N1 differences point to early perceptual processing and attention related differences, while the later P3 marks for differences in semantic processing. The overall pattern shows that while the early perceptual processing of counting configurations was similar with noncanonical, counting overlapped more with montring later, in the P3 range. The changes in the effect sizes for the difference between counting and noncanonical also reflect this gradual pattern, with weaker effect sizes in the N1 change and stronger in the P3 range.

Counting and montring configurations serve different purposes in processing and conveying numerical information, and their execution involve different types of motor programs. Montring is usually used for communicative purposes and they are generated by simultaneously raising fingers. During development, finger counting is initially used for counting and then for facilitating arithmetic processing. Finger counting involves a sequential motoric component. The counting process does not heavily rely on recognition of the values represented by each configuration, whereas both spontaneous generation and recognition of a montring configuration requires having associated the matching finger configuration with the numerosity presented. Nevertheless, the visual system plays an important role in the use of

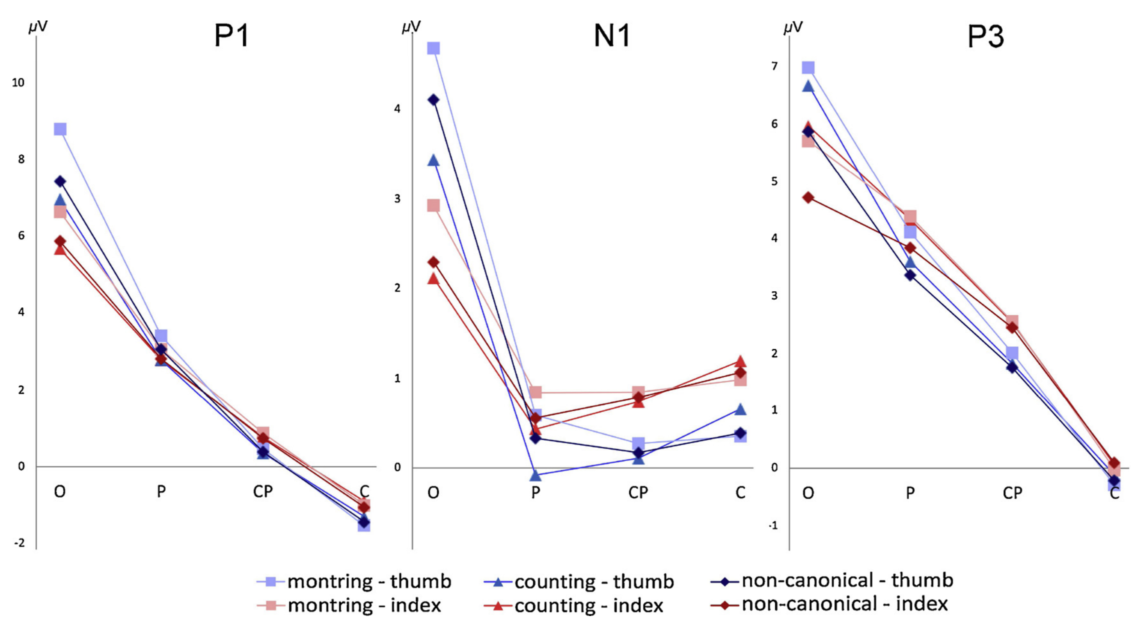

Fig. 3. Average amplitudes (μV) for the three conditions (montring, counting, noncanonical), across the three intervals (P1, N1, P3) and four electrode sites (O, P, CP, C), separately for the thumb- (blue) and index-starter (red) groups.

both types of configurations [9].

The behavioral results reported here show that montring configurations are processed faster and more accurately compared to counting and noncanonical ones. Di Luca and Pesenti [2] reported similar results with a naming task (verbally indicating the number represented in a finger-numeral configuration), where montring configurations showing the palm side of the hand were named faster than the counting ones, while for the back side of the hand, there were no differences between the two configurations. Within the same study in a second experiment, where number comparison judgments with Arabic numerals were primed with finger-numeral configurations, stronger priming effects were found with configurations involving only one hand (representing numbers up to five) compared to two hands, implying that finger configurations involving one hand are more strongly associated with matching number representations.

The ERP results can help with interpreting the behavioral findings. The P1 and N1 waves are known to be modulated with the level of attention [10]. The larger P1/N1 for the montring condition is possibly due to modulation of the feature-based attention system. The process of identifying the numerical information presented in a number gesture involves activation of a template [similar to ones described in visual search experiments; see 11 for a review], which is used to guide attention to focus on features matching with the template. The visual features that are part of this template are based on previous experiences with recognizing finger configurations, which most strongly applies to montring configurations. The higher P1/N1 positivity for montring followed by counting and then noncanonical is therefore likely to be due to more extensive experiences with perceiving and generating montring configurations, due to their communicative use. In a previous study, using fMRI data to model the location of neural generators, the source of P1 and the posterior N1 were shown to be two dipole pairs, one in the middle occipital gyrus and the other in the ventral fusiform gyrus. For the anterior N1 there was a dipole pair in the intraparietal sulcus (IPS) [12]. The model showed that attention influenced only later activity coming from the anterior N1 source in the IPS and the feedback signals in area V1. The authors argued that the input into the parietal areas from attended visual sources are enhanced by spatial attention. The higher P1/N1 positivity for montring, which indicates enhanced visual information input to parietal areas, might therefore partially explain the higher behavioral performance for recognition of montring configurations.

The results show that montring and noncanonical representation differ in early perceptual processing, both based on behavioral and ERP data. This is unlike what was suggested by Di Luca and Pesenti [4] in a visual-detection study, where no pop-out effect was found for montring gesture targets among noncanonical distractors, showing that the montring representations have no saliency effect. However, the task used in this study did not involve extracting numerical information from finger-numeral configurations. Therefore, the differences in the results might be due to the differences in the tasks –deciding if there is a canonical configuration among noncanonical ones vs. extracting the numerical value presented– since task context was shown to modulate early perceptual processes and the attention system [13,14].

For P3, montring and counting seemed to overlap and showed higher positivity compared to noncanonical. The later convergence of montring and counting might indicate overlapping semantic processes for representing numerical magnitude. In previous studies P3 was found to be related to resource allocation in dual-task paradigms [15], and memory recall in memory tasks [16]. Localization studies showed that in the context of memory recall P3 is associated with attentional resource activations to promote memory operations in temporal-parietal regions [17]. The larger P3 waves for montring and counting are possibly due to some form of retrieval of numerosity information associated with the configurations involved. This is unlike the noncanonical configurations where subitizing, counting, or estimation is used to extract the numerosity information presented in the gesture. Di Luca et al. [3] argued that montring configurations acquire a symbolic status and provide faster access to number semantics, while noncanonical configurations are processed similar to any other collection of objects, requiring subitizing, counting, or estimation processes. The results presented here also point to diverging semantic processing for canonical (montring and counting) and noncanonical configurations, and symbol like processing of montring and counting configurations.

4.1. Differences between thumb- and index-starter groups

We did not observe differences in the behavioral performance of the two groups. However, there was an interaction across area, condition, and group in the ERP analysis. The results showed that while the thumb-starters showed an effect of condition in the central area, the index-starters did not. More specifically, for the thumb-starter group, counting showed higher positivity compared to both montring and noncanonical, while noncanonical and montring did not differ. This effect might be due to the differences in how the thumb- and index-starter groups process counting configurations. For the thumb-starters the counting configurations presented matched with their finger counting habits, which means that they had extensive previous experiences in generating these configurations with their fingers. Previous research show use of motor simulations –partial activation of motor circuitry that is associated with the execuation of action during observation– for processing gestures and in general for understanding others' actions [18,19]. Further, it was also shown that these motor simulations take place especially when the observed actions are part of the motor repertoire of the observer [20,21]. Therefore, it is possible that the thumb- and index-starter groups process the counting configurations differently, due to the differences in their repertoire of motor programs for counting. For the thumb-starter group a motor simulation mechanism might be more readily engaged while processing the counting configurations, whereas this may not be the case for the index-starter group, since the generation of the counting configurations presented is not part of their motor repertiore. This also applies to noncanonical configurations for both groups. The motor simulation hypothesis was in fact previously proposed as a possible explanation for the behavioral performance differences in processing canonical and noncanonical configurations [4].

We would expect the motor simulations to play a role in the later, semantic stages of processing. However, given that time interval (P1, N1, P3) was not a factor in the interaction, the motor simulation explanation is not fully supported. However, the ERP design used in this study is not well suited to test hypotheses on the involvement of motor simulations.

Overall, even though the two groups did not differ in behavioral performance, there seems to be subtle differences in processing of counting configurations between thumb- and index-starters. In future research, if finger counting habits modulate the involvement of the motor system in extracting numerical information from finger configurations should be investigated either with an EEG paradigm focusing on Mu suppresion [22] or with an fMRI paradigm, both of which can more clearly test the motor simulation hypotheses.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.neulet.2019.04.032.

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