Canonical finger-numeral configurations facilitate the processing of Arabic numerals in adults: An Event-Related Potential study

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**ABSTRACT**

Various studies claim that early-learned, culture-typical (canonical) finger configurations used to communicate or represent numerosity, have stronger connections to numerical concepts stored in long-term memory than cultural-unfamiliar finger configurations, thereby allowing for faster access to their numerical meaning. The current study investigated whether presentation of canonical finger configurations gesturing numerosities 1–4 or 6–9 would facilitate young adults’ behavioral and neural processing of Arabic numerals. Thirty-one adults performed a number comparison task in which they had to decide whether simultaneously presented Arabic numerals or canonical and non-canonical finger configurations showed the same or a different numerosity, while measuring their performance and Event-Related Potentials (ERPs). The results showed faster responses when comparisons involved canonical (versus non-canonical) finger configurations, but only on numerosity-congruent trials where finger configuration and Arabic numeral matched in number identity. Canonical, and small-number finger configurations 1–4 in general (irrespective of their canonicity), also elicited enhanced amplitude of the early right-parietal P2p, and the later centro-parietal P3 on numerosity-congruent trials. We suggest these P2p and P3 findings respectively reflect facilitated numerical access and easier categorization of canonical finger-numeral configurations. The current results provide behavioral and neurophysiological evidence for the embodiment of culture-specific, canonical, finger-numeral configurations, and their link with other number representations in the adult brain, likely emerging from their more frequent use in daily life communication and/or in early childhood during number symbol acquisition.

1. Introduction

Humans possess the unique ability to represent numerosity in the form of number words or symbols (e.g., Arabic numerals like 3 or 6). How young children learn to associate these words/symbols with the quantities that they represent is still largely unknown, but it has been shown to be a lengthy and complex process (Wynn, 1992). There is evidence that learning involving the use of (parts of) the body can make it easier to attach semantic meaning to symbols and abstract concepts (Lindemann and Fischer, 2015; Tran et al., 2017). With regard to numeracy development, an example of this is children’s intuitive use of fingers when learning to count, or when performing simple addition or subtraction (Butterworth, 1999; Fuson, 1988; Moeller et al., 2012; Siegler and Shrager, 1984). During the early learning of number words or symbols, fingers might play a special facilitating role by providing concrete (and always available) referents of numerosity, thereby facilitating the process of associating number words or symbols with the numerosity that they represent (Butterworth, 1999; Fischer and Brugger, 2011; Fuson, 1988; Knudsen et al., 2014).

Whereas some suggest that fingers only act as temporary helpful aids during early number symbol acquisition (see Moeller et al., 2011 for a review), there is increasing evidence from behavioral studies that internalized (embodied) finger-numeral representations still influence or facilitate number symbol processing in adults (for a review see Di Luca and Pesenti, 2011). This points to the existence of interlinked finger- and other symbolic or non-symbolic number representations. The current study aimed to add to the understanding of the processing and internalization (embodiment) of canonical finger-numeral configurations, and their potential facilitating effects on the processing of other numerals (e.g., Arabic digits) in young adults, by measuring Event Related brain Potentials (ERPs). To that aim, we investigated whether early-learned, culture-specific (also called canonical) finger-numeral configurations (versus unfamiliar, non-canonical configurations) facilitate the processing of Arabic numerals in a same-different number...
comparison task, and whether this is accompanied by electrophysiological evidence of facilitated semantic processing in the brain, which would be evidence for their embodiment.

Fingers can be used to represent numerosities in different ways, one way is during counting when fingers are raised or lowered sequentially in a certain order and one finger represents one numerosity. Another way is the use of fingers to represent or communicate a numerosity by holding up a hand with a pattern of fingers raised simultaneously, also called ‘montring’ by Di Luca and Pesenti (2008). Both counting and montring finger configurations have been shown to conform to culture-specific habits, although especially counting configurations have been reported to show some variation within cultures, such as in starting hand (left/right) and/or starting finger (in Western samples with thumb or index finger). Fairly consistent counting habits have however been reported among Western (European) samples (Hohol et al., 2018). Several behavioral studies have compared the processing of canonical and non-canonical finger-numeral configurations by presenting them via pictures in different number processing tasks. These studies have reported facilitating effects of canonical finger-numeral configurations on numerical processing in adults (Badets et al., 2018; Di Luca et al., 2006; Di Luca and Pesenti, 2008). Di Luca and Pesenti (2008) investigated differences in verbal number naming between two types of canonical (i.e. counting and montring), and non-canonical configurations representing numerosities 1–5. The counting and montring configurations differed from each other in that counting configurations included the thumb, whereas montring configurations did not. No differences in numerical naming speed were found between counting and montring finger configurations for numerosities 1–5, but both canonical configurations were named faster than non-canonical ones showing the same numerosity. Other studies that have included one or both types of canonical finger-numeral configurations have reported similar facilitating effects in other symbolic number processing tasks, or on other number processing skills in adults or children (Di Luca and Pesenti, 2010, 2008; Lafay et al., 2013; but see Soylu et al., 2019, who reported behavioral facilitation of only montring and not counting configurations 1–5). Since the majority of previous studies found facilitating effects of both canonical (counting and montring) finger-configurations when presented in the form of pictures, in the present study we will not distinguish them and use the more general term canonical finger-numeral configurations.

Several authors have suggested that the facilitated processing of canonical finger-numeral configurations are caused by canonical patterns becoming embodied, and developing links with other numerical representations due to their frequent encounter and use in daily life (Di Luca and Pesenti, 2011; Fischer, 2012). Di Luca and Pesenti (2008) presented the first evidence that adults were faster in retrieving the number words for canonical finger-numeral configurations than for their non-canonical counterparts (e.g., thumb, index finger and pinky showing number three). In the same paper, the authors also demonstrated that being primed by a picture of a canonical (as opposed to non-canonical) finger-numeral configuration led to faster naming of subsequently presented Arabic numerals. In a follow-up study, Di Luca et al. (2010) further demonstrated that the larger the numerical distance was between the numerosities represented by the canonical finger-numeral prime and the target (the Arabic numeral), the smaller the priming benefits, and no such priming-distance effects were found for non-canonical configurations. Based on these findings, the authors concluded that only canonical configurations activate representations with the same place coding properties as activated by other symbolic number notations (e.g. verbal or Arabic numerals). Sixto et al. (2017) demonstrated similar priming effects when participants produced the finger-numeral gestures themselves (instead of viewing them in a picture as in Di Luca et al., 2010). Finally, Badets et al. (2010) reported facilitating effects of presentation of pictures showing canonical finger-numeral configurations on the speed with which one could verbally provide the solution to earlier presented simple, one-digit, addition sums. Adults were faster when, upon the onset of their verbal response, the correct solution to the earlier presented sum was shown in the form of a canonical finger-numeral configuration instead of in the form of several rods. This facilitating effect of canonical finger-numeral configurations versus rods only occurred when the numerosity shown by the fingers was congruent with the outcome of the addition sum. In a recent study we replicated these facilitating effects of canonical finger-numeral configurations on number processing, but now in a math verification task (van den Berg et al., 2021). More specifically, in this study we compared canonical-with non-canonical finger configurations, instead of with rods as in the Badets et al. (2010) study. The behavioral results from above discussed studies suggest that canonical finger-numeral configurations have a special status as learned patterns stored in long-term memory, that are quickly accessible and capable of automatically activating other numerical representations, thereby possibly facilitating their processing (Di Luca and Pesenti, 2011).

Brain studies could provide more direct evidence of embodiment of canonical finger-numeral configurations and their link to other representations of number. However, there are to the best of our knowledge only three prior studies that have used Event-related brain potentials (ERPs) to investigate the cerebral processing of different finger-numeral configurations. In a study by Proverbio and Carminati (2019), adults performed a math verification task in which participants determined the correctness of the solution to a math problem presented in Arabic numerals in the 0–10 range. Task-irrelevant finger-counting configurations flanked the solution (Arabic numeral), showing either a congruent (same as the Arabic numeral), or incongruent numerosity. In contrast to the above discussed behavioral studies that all reported facilitating effects of perception or production of canonical finger-numeral configurations on number symbol processing, Proverbio and Carminati (2019) reported a decrease in accuracy when congruent finger-counting patterns flanked sum solutions, which is indicative of performance interference. The behavioral interference effect was accompanied by an enhanced positivity above the fronto-central cortex between 700 and 900 ms after stimulus presentation in the ERPs. These contrasting results are likely explained by differences in task design; in the Proverbio and Carminati (2019) study finger-counting configurations were irrelevant to the task, and did not require active processing. All above discussed studies that did find facilitated processing of canonical finger-numeral configurations used task paradigms that demanded active processing of the numerosity that finger configurations conveyed. Additionally, the conclusion that only early-learned, canonical, finger-numeral configurations have acquired a special status in long-term memory requires a design that includes a direct comparison between the brain processing of canonical and non-canonical finger configurations, which was not the case in Proverbio & Carminati’s study.

Soylu et al. (2019) did compare ERP responses to pictures of canonical and non-canonical finger-numeral configurations communicating numerosities 1–4. In their study, participants determined whether canonical/non-canonical finger configurations showed the same or a different number than a subsequently presented Arabic numeral. Replicating results from earlier behavioral studies by Di Luca et al. (2006; 2008), montring configurations 1–4 led to faster and more accurate responses than counting- or non-canonical configurations, which was accompanied by enhanced amplitude of early exogenous P1 and N1 ERP components, indexing higher automatic attraction of attention by the montring patterns. The later centro-parietal-occipital P3, measured in 500–500 ms post-stimulus time window, showed enhanced amplitude to both counting and montring configurations, which was, based on the prior P3 memory literature (Donchin, 1981), interpreted as indexing the retrieval of the represented numerosity from memory. The posterior location and timing of this finger-numeral canonicality effect on the ERP overlaps with that reported in earlier magnetoencephalography (MEG) studies investigating the semantic processing of other (non-numeric) culturally meaningful hand gestures (Avikainen et al., 2003; Nakamura et al., 2004). These combined findings thus suggest that posterior
activity in this mid-latency time window indexes the processing stage in which one has first access to, or extracts the semantic meaning of, culturally meaningful hand gestures, including number gestures.

The studies discussed above either studied the processing of pictures showing finger-numeral configurations representing small numerosities 1–4 (Di Luca et al., 2010; Soylu et al., 2019), or did not distinguish between single- and double-handed configurations of respectively numbers 1–5 and 6–10 in their analyses (Di Luca and Pesenti, 2008; Proverbio and Carminati, 2019). Since there might be differences in the frequency of use, and thus the embodiment, of canonical-finger-numeral configurations for numerosities 1–4 represented on a single hand, and higher numerosities 6–9 represented on both hands, they might also have different facilitating effects on number symbol processing. In a recent study we did investigate such processing differences between canonical and non-canonical configurations of numerosities 2–4 and 7–9 on reaction time and P3 amplitude (and on the not earlier studied P2p-ERP component), using a math verification paradigm (van den Berg et al., 2021). In this study, adult participants mentally computed the solutions to a simple addition problem and had to compare their solution (that they kept in memory) with the presented sum solution, which could be the correct or incorrect solution. We found that compared to non-canonical configurations, viewing pictures of both one-hand and two-hand canonical finger configurations facilitated (sped up) the number comparison process to the same extent, and this went along with an enhanced parietal P3 response indicative of facilitated categorization/memory retrieval for both small and large canonical finger configurations. A response of the earlier P2p-ERP component was however only elicited by pictures of one-hand canonical (and not non-canonical), finger configurations showing numbers 2–4. Based on the prior number processing-ERP literature (Dehaene, 1996; Hyde and Spelke, 2012; Libertus et al., 2007; Temple and Posner, 1998), this enhanced early parietal-occipital P2p response to only canonical finger configurations 2–4 was suggested to reflect the automatic activation of associated representations of magnitude that have been acquired due to the more frequent use of culture-typical finger configurations early in development and life.

The aim of the present study was to see if we could replicate these P2p and P3 results in a same-different number comparison paradigm in which finger configurations and Arabic numerals 1–4 and 6–9 were presented within one stimulus display (instead of sequentially as in Soylu et al. (2019), and in van den Berg et al. (2021). Proverbio and Carminati (2019) also presented Arabic numerals and finger-numeral stimuli within one stimulus display, but in a math verification task in which finger-stimuli were task-irrelevant and also only canonical configurations were shown. In the present study participants had to actively compare simultaneously presented (canonical/non-canonical) finger configurations and Arabic numerals (in numerical ranges 1–4 and 6–9), in order to decide whether both showed the same or a different numerosity. The current same-different comparison task was chosen because of its comparability to number comparison tasks as they are used in the number processing literature to study magnitude processing/representation. In regular number comparison tasks, participants are required to decide whether different symbolic (e.g., number words or Arabic numerals), or non-symbolic (e.g., arrays of dots) number stimuli represent the same or a different magnitude. In the present study same/different comparisons had to be made between the numerosity shown by (canonical/non-canonical) finger configurations and Arabic numerals. In line with the above reviewed finger-numeral processing studies (Badets et al., 2010; Soylu et al., 2019; van den Berg et al., 2021), we expected pictures of canonical finger-numeral configurations to elicit faster number comparison responses than pictures of non-canonical configurations. In earlier studies, canonicity effects were primarily reported in conditions where Arabic numerals and finger-numeral configurations indicated the same numerosity (Badets et al., 2010; Sixtus et al., 2017; van den Berg et al., 2021). Additionally, in line with the above discussed finger-number ERP studies and the number comparison-ERP literature, we expected two specific ERP components to be modulated by the canonicity of the finger configurations, the first being the P2p. In the number processing ERP literature, modulations of the amplitude of the P2p are associated with the process of automatic activation of semantic (magnitude) information associated with numerals (Dehaene, 1996; Libertus et al., 2007; Temple and Posner, 1998). Based on our earlier findings in the math verification paradigm, we expected the P2p amplitude to be enhanced when comparing the numerosity of canonical (compared to non-canonical) finger-numeral configurations and Arabic numerals, and more strongly so to small (1–4), than large (6–9) finger configurations (van den Berg et al., 2021). The second ERP component we expected to be modulated by the canonicity of finger configurations was the later endogenous P3 component occurring in a window between approximately 300–500 ms after stimulus presentation, with highest amplitude above central-parietal electrodes. In earlier number- and finger processing studies enhanced centro-parietal P3 amplitude has been linked to easier stimulus evaluation/categorization processes, likely due to better memory representations of the stimuli evoking the enhanced P3 (Dehaene, 1996; Jiang et al., 2010; Libertus et al., 2007; Soylu et al., 2019; Turconi et al., 2004; van den Berg et al., 2021). In line with our earlier findings, we expect enhanced centro-parietal P3 amplitude to both canonical finger configurations 1–4 and 6–9, as indicative of their faster recognition and easier categorization due to their storage in memory.

2. Method

2.1. Participants

Participants were thirty-one young adults recruited from the student population at Maastricht University (mean age: 21yrs 8mo [SD 1yr 6mo]; 5 males). All adults provided written informed consent after being informed about the study, and participants received university course credits for their participation. The faculty’s local Ethical Committee approved all study procedures (ERCNLP_RP_2027_2018_34). All procedures were in accordance with the Declaration of Helsinki.

2.2. Procedure

Testing took place in dedicated EEG labs at the university in a soundproof booth and started with explaining the procedure, followed by attachment of the electrodes. Participants first performed the modified computerized Same/Different Task (see below) during which EEG was measured. Before the Same/Different Task, participants underwent a practice session until they reached a performance criterion of 70–80% correct, followed by a simple, timed, arithmetic paper and pencil test (not reported in the current paper). Instructions were to respond as fast and as accurately as possible and minimize eye blinks and (eye) movements during the tasks.

2.3. Finger-numeral same/different task

In the finger-numeral same/different task, participants were presented with Arabic numerals (either in the numerical range 1–4, or 6–9) presented in the center of the screen, flanked by hands showing numerosity-congruent (same as the Arabic numeral) or numerosity-incongruent (different from the Arabic numeral) finger-numeral configurations. Hands presented either canonical (culturally familiar) or non-canonical (unfamiliar) finger-numeral configurations (see Fig. 1 for a full trial, including timing information and with examples of the task stimuli). The participants’ task was to press the left button on a Cedrus RB-844 button box as fast and accurate as possible when the finger configuration and Arabic numeral indicated the same numerosity, and the right button in case of both presenting a different numerosity.
The canonical finger configurations use Western European, single-handed conventions (e.g., thumb, index, and middle finger for three), but see paragraph 3.2.1. for a more elaborate description of the procedure of selection of canonical and non-canonical finger configurations. Non-canonical configurations used a similar single-handed convention (e.g., thumb, middle finger, pinky finger to communicate ‘three’) in order to keep the stimuli perceptually similar, and to avoid confounding due to a change in number of hands to represent small numbers 1–4 between canonical and non-canonical conditions. The lower numerical range (1–4) for canonical and non-canonical trials was accompanied by a closed hand (denoting zero), whereas the higher range (6–9) used an open hand (denoting five); the position of presentation of these closed hand and full hand stimuli (respectively indicating zero and five) was counterbalanced, meaning that they occurred left from the Arabic numeral on 50% of the trials and right on the other 50% of trials. Finger configurations of number five (one hand with all fingers raised and one hand with closed fingers) were excluded since single-handed non-canonical representations of five are not possible.

The same/different task consisted of 288 unique trials, presented in six blocks of 48 trials. To balance the numerical distance and the frequency of numerals and hands, 40 out of 288 trials consisted of a stimulus presenting an Arabic numeral in the low (1–4) numerical range paired with finger-numeral configurations in the high (6–9) range or vice versa. Because of the aim to distinguish between finger configuration - Arabic numeral comparisons within low (1–4) and high (6–9) numerical ranges (see introduction), these 40 cross-range ‘different’ trials were excluded from the analysis, which led to 58% (144) same trials and 42% (104) different trials. These remaining 248 trials were still balanced to have 50% canonical/non-canonical and 50% low/high range trials in same and different conditions. Stimulus presentation was quasi-random, with the restrictions of identical Arabic numerals never being presented directly after each other, and one type of hand stimulus (canonical/non-canonical) never being shown more than four times in a row. All stimuli were presented on a grey background inside a white box at the center of a 19-inch monitor at a viewing distance of 57 cm.

2.3.1. Selection of finger pattern stimuli

The selection of the non-canonical and canonical finger-numeral configurations included in the present study was based on a small pilot questionnaire study with N = 14 students, all with a similar Western background as the current study sample. All participants were presented with a row of four pictures showing different finger configurations representing the same numerosity. The lower two configurations were non-canonical, and the other two were the two possible canonical patterns with adjacently raised fingers. One of these canonical configurations included the thumb (often called a ‘counting’ configuration), and the other canonical configuration did not include the thumb (often called a ‘montring’ configuration). The students were asked to rate the four finger configurations on the likelihood that they would use them to communicate a number to someone else (scale 1–4, with 1 highest likelihood and 4 lowest likelihood). For each of the four included numerosities 1, 2, 3, and 4, out of the two non-canonical finger configurations we chose the one that was rated as most unlikely being used for communicating the number for inclusion in the task. Of the two canonical configurations, we (for each number) chose the canonical pattern that was indicated by the majority as the most likely used to
communicate the numerosity (although both canonical finger configurations did not differ much in rating, but both differed strongly in rating from both non-canonical configurations). This resulted in the choice of non-canonical and canonical finger configurations as shown in Fig. 1 (note that the same finger configurations for 1, 2, 3 and 4 were used for higher numbers 6, 7, 8, 9, only accompanied by a full-hand indicating 5, whereas in the case of 1, 2, 3, 4 a second hand was also shown, but with a closed fist representing zero).

2.4. EEG/ERP acquisition and analyses

Electro-Encephalographic (EEG) data were recorded using an elastic EEG-electrode cap (EasyCap; Nellcor-Puritan Bennet, Hayward, CA) with a 38 tin electrode set-up (FP1, FP2, F7, F3, Fz, F4, P7, P3, Pz, F8, FC5, FC1, FCZ, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CPz, CP2, CP6, P7, P3, Pz, P4, P8, PO7, O1, Oz, O2, A2, AFZ, A1). The data were filtered online at 0.01–225 Hz and continuously sampled at a rate of 500 Hz using a BrainAmp amplifier system and software (Brain Products GmbH, Munich, Germany). The AFz electrode served as ground, and the left mastoid (A1) acted as the online reference; the right mastoid (A2) was included as an extra active electrode. Horizontal and vertical EOG was measured by electrodes placed on each eye’s outer canthus and above/ below the left orbit. All electrode impedances were kept below 10 kOhm and were frequently checked during testing.

For offline analyses of the EEG data, Matlab 2019a/EEGLab2019/ERPLABv8.0.0 software was used. The data was first resampled to 250 Hz and re-referenced to the average signal. Next, a Butterworth band-pass 0.1 Hz–70 Hz half-amplitude filter (roll-off 12 dB/dec - 40 dB/dec order 2) was applied to the data before execution of Independent Component Analysis (ICA) for removal of horizontal eye movements and blinks. The ocular artifact-free data was filtered using a Butterworth 30 Hz half-amplitude low-pass filter (roll-off 12 dB/dec - 40 dB/dec order 2), after which the data was epoched (based on the event-codes associated with the numerosity indicated by the finger-configuration and the Arabic numerals, excluding epochs with incorrect responses) into 300 ms pre-stimulus and 1500 ms post-stimulus time windows. Baseline correction was performed using the pre-stimulus -300 – 0 ms interval. Next, an automatic artifact detection procedure was applied to the remaining epochs (only at electrodes PO7, PO8, and Pz that were included in the analyses), rejecting trials with activity exceeding a ±75 µV criterion. An average of 0.98% (min. 0% and max. 25%) of the total number of trials in the task were rejected based on artifacts. Participants were only included in the subsequent analyses if at least 50% of trials for each bin (each combination of Canonicity, Same/Different, and Numerical Range) remained for averaging (after removal of incorrectly responded and artifact trials); since ERP data of all participants fulfilled this criterion, all were included in the analysis.

The choice of electrodes and time-windows to be included in the statistical analyses was based on previous ERP studies that used similar number comparison paradigms with Arabic numerals, or non-symbolic number stimuli (e.g. dot arrays) (Dehaene, 1996; Hyde and Speilke, 2012; Libertus et al., 2007; Temple and Posner, 1998), and a previous ERP study from our lab with a similar research question and similar finger-numeral stimuli, but using another task paradigm (van den Berg et al., 2021). All these studies have shown the P2p to occur above lateral parietal-occipital electrode locations. Because the more precise location above lateral parietal-occipital cortex at which the P2p reaches maximum amplitude varies between studies based on, amongst others, differences in populations, head-sizes, and cap fittings, the more precise location and timing of the P2p (above lateral parietal-occipital cortex) and P3 in the current task and sample was determined on the basis of visual inspection of the ERP signal averaged across all conditions (and associated topo maps in P2p and P3 time windows). This led to the P2p amplitude and latency analyses being performed at left and right Parietal-Occipital electrodes (PO7 and PO8) in a 220–350 ms time window. Because of a clear latency shift between small (1–4) and large (6–9) numerical range stimuli, the P2p amplitude data was analyzed in two separate time windows (220–275 ms and 280–350 ms; for grand average ERPs and topo-maps of the P2p in these two different time windows see Figs. 3 and 4). The P3 amplitude-latency analyses were performed at the Pz electrode (based on the prior number comparison literature: Dehaene, 1996; Jiang et al., 2010; Libertus et al., 2007; Turconi et al., 2004; van den Berg et al., 2021), in a 400–600 ms time window (see Fig. 5 for the grand average ERPs and topo-maps in this time window). For the amplitude analyses mean amplitude scores within the above mentioned time windows were computed and entered in the analyses. The P2p and P3 latency analyses included the automatically scored peak latencies in the 220–350 ms window for the P2p and the 400–600 ms time window for the P3.

2.5. Statistical analysis

To analyze the dependent measures RT, P2p amplitude (in two time windows), P2p peak latency, P3 amplitude and latency, Linear Mixed-effects models were constructed. For the accuracy data, Generalized Estimation Equation (GEE) models were constructed because of severe normality violations. The models for RT and accuracy data included within-subject factors Canonicity (2 levels: Canonical and Non-Canonical finger-numeral configurations), Congruency (2 levels: Congruent and Incongruent, with Arabic numerals and finger configurations respectively indicating the same or a different numerosity), and Numerical Range (2 levels: Low [numerosities 1, 2, 3, 4] and High [numerosities 6, 7, 8, 9]).

The P2p and P3 amplitude and latency analyses were performed separately for numerosity-congruent and incongruent trials, so only included factors Canonicity and numerical Range and the P2p analyses included an additional factor Hemisphere (2 levels: Left and Right). This choice of performing the ERP analyses separately for congruent and incongruent trials is based on several considerations: 1) the outcome of the RT and accuracy analyses only yielded statistically significant canonicity effects (facilitated comparison performance for canonical finger configurations) in numerosity-congruent trials (as is also reported in earlier finger-numeral processing studies; Badets et al., 2010; Di Luca et al., 2006; Di Luca and Pesenti, 2008; Sixtus et al., 2017). Since the main aim of the present study was to study neural processes underlying this behavioral facilitation (see introduction), only ERP analyses in the numerosity congruent trials (where such facilitation was found) can address this aim. 2) stimulus-response incongruency evokes additional processes like conflict monitoring and inhibition that also affect comparison performance and evoke specific ERP components that might overlap in time with P2p and P3 canonicity effects. For completeness the ERPs and analyses will be also reported for incongruent trials.

Assumptions were checked using a Compound Symmetry covariance structure, removing single observations (single data-points) as outliers if residuals exceeded three standard deviations from the mean. A single outlier was removed for the behavioral Accuracy data and also for the P3 amplitude data, no observations were removed from the RT and P2p amplitude analyses. In the P2p latency analyses 17 data-points from 7 participants were excluded because of problems of the automatic peak-scoring routine to detect a P2p peak within the 220–350 ms time-window (in these cases the program yielded latency scores of 220 at the lower border of the time window where after further inspection of the signal no P2p peak occurred). In the P3 latency analysis, only one data-point from one participant was excluded from the analysis because of problems with finding a peak within the 400–800 ms time window. Assumptions of normality and homoscedasticity were met in all analyses. For dependent variables RT and ERP amplitude, various covariance matrices were compared using AIC to determine the best fitting model. For the RT models, an Unstructured matrix showed the best fit. For ERP amplitude analyses, both the early and late P2p models showed the best fit with the Unstructured matrix, while the P3 (400–600 ms) data fitted best with the Toeplitz covariance matrix. ERP latency
analyses were run with an ARMA(1.1) covariance structure for the P2p and P3 windows. All models were subsequently reduced by removing non-significant interactions.

3. Results

3.1. Behavioral results

3.1.1. Reaction time (RT)

The response time analysis yielded significant main effects of Canonicity (F[1,30] = 14.04, p < .001), Congruency (F[1,30] = 51.55, p < .001), and numerical Range (F[1,30] = 176.87, p < .001), and three two-way higher-order interactions between Canonicity*Congruency (F[1,30] = 8.34, p = .007), Canonicity*Range (F[1,30] = 7.19, p = .012), and Range*Congruency (F[1,30] = 12.39, p = .001). The means and SE’s in all conditions (all cells of the task design) are presented in Table 1, and the three two-way interactions on RT are visualized in Fig. 2.

Further testing of the Canonicity*Congruency interaction showed a statistically significant canonicity effect on numerosity-congruent trials, where finger configurations and Arabic numerals represented the same numerosity (M_diff = 21.83 ms; t(30)_Ncan-Can = 4.71, p < .001), with faster comparison times for canonical than non-canonical finger configurations (M_RT_Can_Can = 788.42 ms, SE = 18.9 ms, and M_RT_Can_Noncan = 810.25 ms, SE = 19.2 ms). No statistically significant canonicity effect was found on numerosity incongruent trials (M_diff = 5.49 ms; t(30)_Ncan-Can = 1.19, p = .242). Further testing of the Canonicity*numerical Range interaction showed that participants’ finger configuration – Arabic numeral comparisons were faster than non-canonical trials in the low (1–4) numerical range (M_RT_Can_Low = 754.14, SE = 17.29, M_RT_Noncan_Low = 779.11, SE = 18.47, M_diff = 24.97 ms; t(30)_Ncan-Can = 4.59, p < .001), but there was no canonicity effect for finger configurations representing a numerosity in the high (6–9) range (M_RT_Can_High = 877.98, SE = 18.5, M_RT_Noncan_High = 880.34, SE = 20.89, M_diff = 2.36 ms; t(30)_Ncan-Can = 0.41, p = .683). Finally, the Range*Congruency interaction indicated that whereas statistically significant congruence effects (faster responses on numerosity-congruent than incongruent trials) were found for both small (1–4) and large (6–9) finger configurations, the effect was larger in the low numerical range (M_RT_Can_Low = 734.62, SE = 17.02, M_RT_Incon_Low = 798.64, SE = 18.74, M_diff = 64.02 ms; t(30)_Incon_Incon = 8.16, p < .001), than in the high numerical range (M_RT_Can_High = 864.05, SE = 21.05, M_RT_Incon_High = 894.27, SE = 19.90, M_diff = 30.22 ms; t(30)_Incon_Incon = 3.59, p = .001). Hence, the RT data showed a processing advantage for congruent and low-range canonical finger configurations (Fig. 2).

3.1.2. Accuracy

For accuracy means in all conditions, see Table 1. The analysis of accuracy only showed statistically significant main effects of Congruency (X^2[1] = 6.15; p < .013), and numerical Range (X^2[1] = 29.38; p < .001). Number comparison accuracy was higher on congruent trials where finger configuration and Arabic numeral presented the same numerosity, than on incongruent trials (MAcc_Can = 97.32%; MAcc_Incon = 92.71%; SE = 0.89%), but there was no canonicity effect compared to the higher (6–9) numerical range (M_RT_Can_High = 94.78%; SE = 0.65%), MAcc_High = 92.02%; (SE = 0.90%), M_RT_Incon_High = 92.76%; t(1)_Low_High = 4.55, p < .001). There was a trend towards a significant Canonicity effect (X^2[1] = 2.77; p = .096). None of the interactions reached significance (all p-values > .292).

3.2. ERP results

As explained in paragraph 2.4., the P2p data was analyzed in two time windows to take into account P2p peak latency differences between the Parietal-Occipital electrodes.

Table 1

Means and Standard Errors (between brackets) for behavioral and ERP data in the four Canonicity-Numerical Range conditions separated for numerosity congruent and incongruent conditions. The P2p data is further split up for the two analyses windows and on the hemisphere factor, showing mean amplitudes at left/right parietal-occipital electrodes.

|                      | Non-Canonical | Canonical |
|----------------------|---------------|-----------|
|                      | Low Range     | High Range |
| **Reaction Times**   |               |           |
| (milliseconds: ms)   |               |           |
| Congruent            | 751.19 (17.32)| 718.05 (16.72)|
| Incongruent          | 869.32 (21.10)| 858.79 (21.00)|

| **Accuracy (%) correct** | Non-Canonical | Canonical |
|--------------------------|---------------|-----------|
| Low Range                | 94.28% (0.82%)| 96.47% (0.65%)|
| High Range               | 92.34% (0.99%)| 93.25% (0.75%)|

| **P3 amplitude (μV)** at Pz in 400–600 ms time window | Non-Canonical | Canonical |
|-------------------------------------------------------|---------------|-----------|
| Low Range                                             | 6.25 (0.55)   | 7.00 (0.55)|
| High Range                                            | 5.15 (0.55)   | 5.50 (0.55)|

| **P3 peak latency (ms)** at Pz in 400–600 ms time window | Non-Canonical | Canonical |
|----------------------------------------------------------|---------------|-----------|
| Low Range                                               | 526.71 (9.49) | 509.28 (8.89)|
| High Range                                              | 510.52 (10.18)| 516.65 (10.4)|

Values shown are estimated marginal means with Standard Errors. | Low Range = average of 1, 2, 3 & 4; High Range = average of 6, 7, 8 & 9
finger configurations 1–4 and 6–9 (see also paragraph 3.2.2). Further, as explained in paragraph 2.5, the ERP analyses were performed separately for numerosity congruent and incongruent trials.

3.2.1. P2p amplitude between 220 and 275 ms

In this early P2p time-window, numerosity congruent trials (see Fig. 3) showed main effects of Canonicity (F(1,30) = 14.95; p = .001) and Hemisphere (F(1,30) = 6.25; p = .018); the P2p amplitude was larger on Canonical than Non-canonical trials (M_diff = 0.59 μV; t(30)_Can-Ncan = 3.87; p = .001) and was higher above the right (PO8) than left (PO7) parietal-occipital cortex (M_diff = 1.57 μV; t(30)_Right-Left = 2.50; p = .018). There were no other statistically significant main or interaction effects (all p’s > .175).

Numerosity incongruent trials (see Fig. 4) only showed a trend towards a Hemisphere effect (F(1,30) = 3.64, p = .066), no other significant main or interaction effects of factors Canonicity, numerical Range, or Hemisphere on P2p amplitude were found in this early time window (all p-values > .188).

3.2.2. P2p amplitude between 280 and 350 ms

In this late P2p window (Fig. 3), numerosity congruent trials showed main effects of Canonicity (F(1,30) = 8.59; p = .006), numerical Range (F(1,30) = 48.55; p < .001), and Hemisphere (F(1,30) = 4.87; p = .035), but none of these factors interacted with each other (all p-values > .471). The main effect of canonicity showed larger P2p amplitude on Canonical than Non-canonical trials (M_diff = 0.55 μV; t(30)_Can-Ncan = 2.93; p = .006). The main effect of numerical Range showed larger P2p amplitude on trials showing numerosities in the lower (1–4) than the higher (6–9) numerical range (M_diff = 1.90 μV; t(30)_Low-High = 6.97; p < .001). Finally the main effect of Hemisphere showed higher P2p amplitude above the right (PO8) than the left (PO7) parietal-occipital cortex (M_diff = 1.51 μV; t(30)_Right-Left = 2.21; p = .035).

Numerosity incongruent trials (Fig. 4) only showed a main effect of numerical Range (F(1,30) = 52.73; p < .001), which interacted with Hemisphere (F(1,30) = 5.54; p = .025). Further testing of the interaction showed that the numerical range effect (larger P2p amplitude in response to low range (1–4) than high range (6–9) number stimuli) was larger above the right (M_diff = 2.42 μV; t(30)_Low-High = 6.90, p < .001), than the left (M_diff = 1.41 μV; t(30)_Low-High = 4.31, p < .001) parietal-occipital hemisphere. None of the main or interaction effects reached significance (all p-values > .191).

3.2.3. P2p latency between 220 and 350 ms

Mean P2p latencies are depicted in Table 1. A statistically significant main effect of numerical Range with delayed P2p latency in response to low range (1–4), compared to high range (6–9), stimuli was found in both numerosity congruent (M_diff = ; F[1183.36]_Low = 43.80, p < .001; see Fig. 3), and numerosity incongruent trials (M_diff = ; F(1, 200.91)_Low = 12.37, p = .001; see Fig. 4). Further, in numerosity congruent trials no main effects of Hemisphere, Canonicity or any interactions between Range, Hemisphere and Canonicity factors were found (p-values ranging between 0.491 and 0.961). In numerosity incongruent trials a main Canonicity effect on P2p latency just fell short of significance (F[11145.75] = 3.67, p = .057). No statistically main effect of Hemisphere or interactions between Canonicity, Range or Hemisphere were found on P2p latency (p-values ranging between 0.097 and 0.793).

3.2.4. P3 amplitude (at Pz) between 400 and 600 ms

For numerosity congruent trials (Fig. 5) main effects of Canonicity (F[1,18.51] = 5.89; p = .026) and numerical Range (F(1,40.85) = 40.33; p < .001) were found; P3 amplitude was larger on Canonical than Non-canonical trials (M_diff = 0.55 μV; t(18.51)_Can-Ncan = 2.43) and P3 amplitude was enhanced when Arabic numerals and finger configurations represented numerosities in the lower (1–4) numerical range than the higher (6–9) range (M_diff = 1.30 μV; t(40.85)_Low-High = 6.35). The Canonicity*Range interaction was not significant (F(1,14.50) = 1.03; p = .326).

Numerosity incongruent trials (Fig. 5) only showed a significant main effect of numerical Range (F(1,48.04) = 6.35, p = .015); P3 amplitude was larger on trials in which Arabic numerals and finger configurations both represented a numerosity in the low (1–4) numerical range, compared to the high (6–9) numerical range (M_diff = 0.74 μV; t(48.04)_Low-High = 2.52; p = .015). No significant main effect of Canonicity (F(1,25.51) = 0.42; p = .524) or Canonicity*Range interaction (F(1,30.36) = 0.20; p = .657) was found.

3.2.5. P3 latency (Pz) in 400–600 ms window

The P3 latency analysis for numerosity congruent trials showed no significant main Canonicity or Range effects (p = .410 and .574 respectively). There was an interesting, yet non-significant, Canonicity*Range interaction (F(1,81.44) = 3.02, p = .086). Bonferroni-corrected comparisons indicated a marginally significant canonicity effect only for congruent-low numerical range (1–4) trials (t(77.41) = 1.82, p = .072), with a 17.4 ms delayed P3 latency for non-canonical finger-configuration - Arabic numeral comparisons compared to comparisons involving canonical stimuli (canonicity effects for the other three categories s had p-values > .511).
For numerosity incongruent trials there only was a borderline significant main effect of numerical Range ($F[1,30.96] = 4.14, p = .050$). The main effect of Canonicity and the Canonicity*Range interaction were non-significant ($p = .585$ and .806 respectively).

4. Discussion

The current study investigated whether culture-typical (canonical) finger-numeral configurations representing numerosities 1–4 or 6–9...
have facilitating effects on the processing of Arabic numerals in a same/different ( numerosity congruent/incongruent) comparison task, by collecting behavioral and Event-Related Potential (ERP) data.

4.1. Effects of the canonicity of finger-numeral configurations on number comparison performance

A significant canonicity*congruency interaction effect on reaction time showed that participants were faster in deciding that a
simultaneously presented Arabic numeral and a finger configuration represented the same numerosity when finger configurations were canonical (as compared to non-canonical). When the numerosity indicated by the Arabic numeral and finger configuration did not match (i.e., were numerosity incongruent), number comparison times did not differ in a statistically significant way between canonical and non-canonical finger configurations. As reviewed in the introduction, similar facilitating effects of culture-typical finger-numeral configurations on reaction time have been reported in other number processing tasks (Di Luca et al., 2010, 2006; Di Luca and Pesenti, 2008; Sixtus et al., 2017; Soylu et al., 2019; van den Berg et al., 2021). The present study found that canonical finger-numeral configurations only facilitated finger – Arabic numeral

Fig. 5. Grand Average ERPs in numerosity congruent (top ERP figure) and numerosity incongruent (bottom ERP figure) conditions, with the grey colored bar indicating the 400–600 ms time window across which mean P3 amplitude was computed. Topography maps show the mean P3 activity across the scalp in the 400–600 ms time-window in numerosity congruent (top row) and incongruent (bottom row) conditions in the four Canonicity-numerical Range categories: Canonical-Low, Non-Canonical-Low, Canonical-High, Non-Canonical-High.
comparison in numerosity-congruent conditions. This is in line with findings in two prior studies of Di Luca et al. (2010, 2006; 2008), suggesting that these processing benefits of canonical finger configurations are due to their storage in long-term memory, allowing for faster recognition and retrieval of the numerosity that they represent.

The current study further investigated this by also measuring P2p and P3 ERP components, that have in prior studies been linked to different stages of number semantic processing. A P2p component localized mainly to right intraparietal regions (Dehaene, 1996; Hyde and Spelke, 2012), has, in previous number processing studies, been shown to be sensitive to numerical manipulations such as numerical distance effects. This P2p component was therefore suggested to index an early numeric semantic processing stage associated with the automatic activation of non-symbolic magnitude information associated with the to-be-processed number stimulus (Dehaene, 1996; Hyde and Spelke, 2012; Libertus et al., 2007; Temple and Posner, 1998). Numerical distance effects have also been found on the later endogenous parietal P3 component, and have been suggested to index domain-general processes related to categorical decision making (Donchin, 1981), or explicit memory recognition or retrieval (Friedman and Johnson, 2000).

4.2. Effects of the canonicity of finger-numeral configurations on ERPs

The present ERP results showed statistically significant main canonicity effects of the finger-numeral configurations on the amplitude (and not latency) of both P2p and P3-ERP components, but, in parallel with the reaction time findings, these effects were only present when the finger configuration and the Arabic numeral showed the same numerosity (i.e., were congruent in number identity). These ERP canonicity effects in numerical congruent trials entailed higher P2p and P3 amplitudes elicited by canonical than non-canonical finger patterns. Below we will further discuss the functional meaning of these ERP results.

The P2p in our study showed higher activation above the right than the left parietal-occipital cortex. A similar right-lateralized P2p was first reported by Dehaene (1996) in a number comparison task that required adults to decide whether the magnitude indicated by (verbal and Arabic) numerals 1–9 was smaller/larger than five. In their study, the P2p amplitude was modulated by the numerical distance between the target and reference number five, with P2p amplitude increasing when numerals were closer to five, and thus less easy to discriminate due to overlapping analog representations on the mental number line. The mental number line refers to numbers being organized along a horizontal line, oriented from left to right, with smaller numbers represented on the left and larger numbers on the right (Gallon, 1880). On the basis of above discussed numerical distance effects on P2p amplitude, Dehaene concluded that the P2p represents activation associated with the processing stage at which one has first access to the magnitude representations associated with the numerals. The increase in P2p amplitude when discriminating Arabic numerals that are numerically closer together was attributed to more effortful processing due to their stronger representational overlap on the number line, and is thus indicative of their more difficult discrimination. In a prior number learning study, we (van den Berg et al., 2020), reported a similar modulation of the occipital-parietal, right-lateralized, P2p when adults learned to associate new arbitrary symbols to numerosities presented in the form of dot arrays. P2p amplitude was increased above the right parietal cortex only for novel symbols that one could successfully map onto a numerosity (i.e., for those symbols that were successfully associated with corresponding magnitude information during learning), supporting the P2p-numeric access/activation view. Because the current task requires similar numerical judgments, the current higher right-lateralized (occipital-parietal) early P2p response to canonical than non-canonical finger configurations is tentatively suggested to index fast and automatic numerical access or activation of associated numeric representations for canonical configurations, most likely acquired through their frequent use in number development and daily life communication. Whereas ERP activity at the scalp cannot be directly linked to its underlying sources, in the above discussed number comparison ERP study by Dehaene (1996), the response-locked P2p distance effect was source-localized in the right parieto-occipito-temporal junction (but see Pinel et al., 2001, who localized the P2p distance effect in bilateral parietal cortex). Further, two MEG studies provide further support for a functional link between posterior/parietal activity in a time window overlapping with the P2p as observed in our study, and the automatic activation of semantic information when seeing hand gestures with culturally acquired symbolic meaning, like hand signs for ‘stop’ or ‘ok’ (Möhring et al., 2014; Nakamura et al., 2004).

Further support for the view that the current P2p canonicity effect might index canonical finger-numerals’ more direct access to numerosity meaning, comes from the study of ERP responses to ideographic or ideophonic stimuli. Ideographic or ideophonic stimuli are symbols or sounds/words that directly convey a specific meaning, idea, sensation or feeling, such as the Roman numeral III, an emoji, or the word ‘shiver’. Two ERP studies (Bien et al., 2012, 2013; Lockwood and Tuomainen, 2015) investigated processing differences between ideophones and non-ideophonic control sounds or words. Both studies reported enhanced P2 activity to ideophonic stimuli, in right intra-parietal sulcus (IPS) in the TMS study by Bien et al. (2012), and above right frontal cortex by Lockwood and Tuomainen (2015). Lockwood and Tuomainen (2015) interpreted their finding of enhanced P2 activity to ideophonic words as reflecting the recruitment of sensory integration processes between the ideophonic stimulus itself, and the sensory information/sensation automatically triggered by it in another modality. In an fMRI study, Holloway et al. (2013) studied processing differences between Arabic numerals and Chinese number ideographs in bilingual English-Chinese participants and bilingual participants with no knowledge of Chinese ideographs. Whereas the Arabic numerals (e.g., 5 or 6) elicited activation of the left intra-parietal sulcus (IPS) in both groups, the Chinese numerical ideographs (e.g., 五行 or 六) activated the right IPS, but only in Chinese speakers who had acquired the cultural meaning of these symbols that are primarily used for communicative purposes, like our canonical finger-numeral configurations. Together, these findings thus support a relation between (right) parietal cortex activation in the P2 time window and early semantic processing of ideographic or iconic symbols. Although speculative at this stage, the current right-lateralized P2p canonicity effect, that we also found in our earlier study (van den Berg et al., 2021), might point to the canonical number gestures having acquired a similar iconic status in our adults. It has however to be noted that similar right IPS activation has been reported in fMRI studies in which adults had to make magnitude comparisons between two symbolic (e.g., Arabic numerals) or two non-symbolic (arrays of dots) number stimuli (Chochon et al., 1999; Eger et al., 2003; Holloway et al., 2010). Based on this, the latter studies concluded that right-IPS houses an analog representation of magnitude and is involved in automatic or voluntary semantic processing of the magnitude dimension, which might point to discrete, analogue (instead of iconic), representations driving the current right-lateralized P2p canonicity effect.

Canonical finger-numeral configurations also elicited a higher central-parietal P3 amplitude between 400 and 600 ms than non-canonical configurations, but only on numerosity-congruent trials, which corroborates the reaction time results. As reviewed in the introduction, a similarly enhanced parietal P3 in response to canonical (compared to non-canonical) finger-numeral configurations 1–4 was reported in previous studies by Soylu et al. (2019), and to both canonical configurations 2–4 and 6–9 in a previous study from our lab using a math verification task (van den Berg et al., 2021). In these two former studies, finger- and Arabic numeral stimuli were presented sequentially whereas in the present study finger configurations and Arabic numerals were presented simultaneously within one stimulus. Proverbio and Carminati (2019) used similar stimuli, with finger configurations flanking Arabic numerals, but in their study finger stimuli were irrelevant to the task (no active comparison needed). Further, these authors
made no comparison between canonical and non-canonical finger-numeral configurations, which is important for drawing conclusions about specific facilitating effects of canonical finger-numeral configurations, and finally, in this previous study no P2p or P3 components were measured. Because in Soyu et al. (2019) pictures of finger configurations were presented before presentation of the Arabic numerals, the P3 canonicality effect in this study purely reflects processing related to the extraction of the numeric meaning of the finger stimulus. In contrast, in our earlier study (van den Berg et al., 2021), and in the current study, the P3 also reflects active magnitude comparison processes on the basis of which participants decided whether finger configurations and other numeric stimuli/representations displayed the same or a different numerosity. In prior number comparison ERP studies, requiring magnitude comparisons between symbolic (e.g. number words/Arabic numerals) or non-symbolic (dot arrays) numerical stimuli, P3 amplitude modulation has been associated with the confidence of one’s magnitude categorization/discrimination response (Dehaene, 1996; Libertus et al., 2007), with higher P3 amplitudes associated with easier stimulus categorization and higher response confidence. In memory recognition paradigms, enhancement of P3 amplitude has been related to facilitated memory recognition processes (Friedman and Johnson, 2000), which in turn facilitates stimulus classification and decision making processes, and enhances response confidence (Donchin, 1981; Eimer and Mazza, 2005; Polich, 2003; Verleger et al., 2005; Ye et al., 2019). Based on this prior work, we tentatively conclude that the enhanced P3 response on numerosity-congruent trials presenting canonical finger configurations, could be a manifestation of facilitated decision-making processes related to the easier classification of the numerosity conveyed by the cultural-familiar finger configurations, due to their storage in memory.

4.3. Differences in canonicality effects between finger configurations representing small versus large numerosities

The present study expands on findings from previous behavioral and ERP finger-numeral studies by distinguishing behavioral and ERP responses to finger configurations showing small (1–4) or large (6–9) numerosities, using a paradigm in which finger configurations and Arabic numerals are presented simultaneously and have to be actively compared in magnitude. A significant canonicality*numerical range interaction effect on reaction time indicated that the behavioral facilitation effect of canonical finger configurations on comparison reaction time was present only when Arabic numerals and finger configurations represented lower numerosities 1–4, whereas for the higher 6–9 range, the canonicality effect on reaction time did not reach statistical significance.

One explanation for the finding that the reaction time canonicality effect was stronger for finger configurations representing smaller numerosities 1–4, may be that canonical finger configurations have developed stronger associations with numerical meaning in early childhood, because fingers might especially provide a scaffold during the developmental stage in which children acquire the numeric meaning of the first four number words (Wynn, 1990, 1992). Such an explanation would also be in line with some recent models and findings that suggest that only the first four numerals are mapped directly onto corresponding non-symbolic representations of magnitude (Carey and Barner, 2019; Le Corre and Carey, 2007; Reynvoet and Sasanguie, 2016; van den Berg et al., 2021). As proposed by previous studies, fingers might support this initial mapping process of connecting symbolic number representations, such as number words, and later Arabic numerals, to corresponding magnitudes in the outside world (Gunderson et al., 2015; Jay and Buetenson, 2017). Thus, the fact that number learning in early childhood starts with the mapping of number words 1–4 onto their corresponding numerosities, and that finger configurations gesturing numerosities smaller than 5 are likely used more frequently in daily communication, could have led to stronger internalized semantic representations of canonical finger configurations of those first four numerosities, thereby facilitating their processing. In our previous number-finger processing ERP study we also compared facilitating effects of small one-hand vs larger two-hand canonical finger configurations on number processing, but in a math verification task (van den Berg et al., 2021). In this task, adult participants had to first mentally compute the solution to a simple addition sum that they had to compare with an afterwards presented correct or incorrect sum solution that was presented in the form of a picture of a canonical or non-canonical finger configuration. In this previous study, a three-way interaction effect was found on number comparison reaction time between canonical, numerical range of the finger configurations (2–4 versus 7–9), and whether finger patterns showed a correct or incorrect sum solution. That is, canonical (versus non-canonical) finger configurations 2–4 resulted in faster math verification performance, irrespective of whether the sum solution was correct or not, whereas canonical configurations 7–9 only facilitated math verification performance when they showed the correct sum solution (were numerosity congruent). In the current task, there were only two-way interactions of numerical range with canonicity and congruency-level, indicating that small-range finger configurations 1–4 showed stronger canonicity and congruency effects than large finger configurations 6–9, but these canonicity and congruency effects did not interact. Whereas further study is needed to determine what is causing these differences, both our former, and the current study, show evidence for canonical (versus non-canonical) finger configurations having facilitating effects on the processing of/comparison with other representations of numerosity, with facilitation being only present or stronger in numerosity congruent trials and for one-hand canonical configurations 1–4.

With respect to P2p and P3 amplitude, only main effects of numerical range were found at left and right parietal-occipital electrodes from 280 ms onwards, starting in the late P2p window, and extending into the central-parietal P3. The amplitude of the P2p and P3 was higher in response to finger configurations showing smaller numerosities 1–4, than to configurations showing larger numerosities 6–9 represented on two hands, irrespective of their canonicity or numerical congruency with the Arabic numerals. In contrast to the reaction time results, the small/large numerical range effect on P2p and P3 amplitude did not interact with the canonicity effect, suggesting additive effects of canonicity and numerical range. The P2p and P3 latency analyses only showed (strong) main effects of numerical range on P2p latency and not P3 latency, with P2p peaking later in response to finger configurations 1–4 than 6–9, irrespective of their canonicity or finger-Arabic numeral congruency. Reaction time results show that it took generally longer to process finger configurations 6–9 that are represented on two hands, than configurations 1–4 represented on one hand. In line with this, and the previous literature, we speculate that the enhanced late-P2p/P3 amplitude to all finger configurations 1–4 reflects the facilitated recognition and categorization of the numerosity that they represent, irrespective of their canonicity. This generally facilitated processing of finger configurations 1–4 might be caused by the overall easier enumeration of small numerosities via subitizing, whereas larger numerosities 6–9 can only be enumerated by slower counting processes. The delayed P2p peak in response to small numerical range stimuli 1–4 might seem counter-intuitive to the behavioral effect of faster comparisons between finger configurations and Arabic numerals within this range. Reaction times do however represent the end-result of proceeding through many processing steps, from exogenous early automatic perceptual and semantic processes, to endogenously controlled memory and decision making processes. Therefore, RT and ERP latency results do not necessarily have to go in the same direction: some early process might take longer, but might facilitate later processing with the end result of faster responding.

In summary, the results discussed above show stronger semantic connections between canonical finger-numeral configurations and stored representations of numerosity in the low (1–4) numerical range. Canonical finger-numeral configurations facilitated the processing of...
Arabic numerals, as shown by faster number comparison responses when they showed the same numerosity. The two ERP components investigated in the current study give more insight into the processes that might underlie this facilitating effect of canonical finger-numeral configurations on Arabic numeral processing. A right-lateralized P2p component showed an increased amplitude for canonical, compared to non-canonical, finger-numeral configurations, which we interpreted as being indicative of faster and automatic access to their semantic number status in memory throughout development, due to cross-modal associations might subsequently allow for faster recognition of their meaning, thereby facilitating the processing of a matching Arabic numeral in the current task.

A limitation of the present study is the lack of assessment of individual finger counting or montring habits, so that any potential variance in the data caused by potential differences herein could not be taken into account. As described in the methods section, the here used finger configurations were however tested for their canonicity (as postures most likely used when communicating a numerosity) among a small European student sample similar to that included in the present study. Further, any potential variance caused by counting or montring habit differences (e.g. in starting finger/hand for counting and starting hand for montring) did not prevent the finding of consistent canonicity effects on both the performance and ERP measures. This matches with results reported by Soylu et al. (2019) that differences in finger counting habits (starting counting with index finger or thumb) had no effects on the facilitated processing of montring configurations and the accompanying enhanced early ERP responses. It should also be noted that to limit task length, response button configuration was only counterbalanced for the most important Canonicity and numerical Range factors, but not the Congruency factor. Congruent and incongruent trials respectively required left- and right-hand (hand) responses. Whereas motor facilitation of the right hand has previously been reported for small numbers 1–5 (Sato et al., 2007), and right-handed people respond faster with their right hand, this could have provided a potential processing advantage in incongruent trials, and if we would have counterbalanced also across the congruency factor, this might have led to the finding of even stronger, instead of weaker, congruency effects.

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