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Do numbers make us handy? Behavioral and electrophysiological evidence for number-hand congruency effect

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ABSTRACT

Finger counting facilitates numerical representations and mathematical processing. The current study investigated the association between finger counting habits and number processing by employing behavioral and electrophysiological measures. We explored whether small and large numerical primes influence the recognition of embodied target hand stimuli. Twenty-four right-handed participants that were grouped into right-starters (n = 13) and left-starters (n = 11) for finger counting performed a hand recognition task that consisted of numerical magnitudes as prime and hand recognition as targets. Based on the finger counting habits, congruent (i.e., left-starters: small number/left hand or large number/right hand; right-starters: small number/right hand or large number/left hand) and incongruent (i.e., left-starters: large number/left hand or small number/right hand; right-starters: large number/right hand or small number/left hand) conditions were presented to the participants. The participants were required to indicate whether the targets were left or right hand by simply pressing the left or the right key, respectively. Results indicated faster reaction times (RTs) for congruent as opposed to incongruent trials for all participants. The mean amplitude of the centro-parietal P300 component was significantly increased for the incongruent compared to congruent condition, indicating increased mental effort. Also, analysis of the latency of the P300 in terms of congruency effect in all participants revealed significant results. These combined results provide behavioral and electrophysiological evidence indicating the embodied nature of numbers. The results are interpreted in light of the general findings related to the P300 component. This research supports the association of number-hand representations and corroborates the idea of embodied numerosity.

1. Introduction

Numbers are of significant importance to the modern world. In recent years, the experimental research into the embodied cognitive neuroscience of numerical processing has gained considerable progress (Butterworth, 1999; Fischer, 2018; Fischer & Brugger, 2011; Fischer & Hartmann, 2014; Morrissey et al., 2016). However, the underlying nature of numerical representations and their relation to embodiment is not fully understood. One of the main issues in this line of research concerns the links between sensory-motor habits and numerical representations. It has been proposed that finger counting has remarkable influences on numerical reasoning from a developmental perspective (Coolidge & Overmann, 2012), and it is still used in adulthood (Newman & Soylu, 2014). In fact, due to the ubiquitous availability of fingers, they are considered the most genuine apparatus for numerical processing (Di Luca & Pesenti, 2011; Sixtus et al., 2020). In line with the proposal that finger counting habits contribute to numerical processing, it has been suggested that our embodied mapping constrains these strategies within the sensory-motor system (Fischer & Shaki, 2018; Prete & Tommasi, 2020). This embodied mapping might indicate a close association between hands and numerical representations. Research has shown that finger counting habits influence simple arithmetic problem-solving (Morrissey et al., 2020), and training finger dissociations in elementary school children improve numerical performance (Gracia-Bafalluy & Noel, 2008). However, one outstanding question is about the neurophysiological correlates of these embodied numerical associations, which would help us to enhance our understanding of individual differences in numerical and mathematical skills.

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Earlier neuroimaging studies have suggested that the brain areas dedicated to hand movements are activated during numerical comparison (Dehaene et al., 1996; Pesenti et al., 2000), addition (Pesenti et al., 2000), and subtraction problem solving (Rueckert et al., 1996). Moreover, both starting hand for finger counting and presentation of small numbers up to five led to contralateral brain hemisphere activation (Tschentscher et al., 2012). These results highlight the association between finger counting and numbers.

It is noteworthy that several experiments have reported that numerical processing is associated with some aspects of space. This phenomenon is referred to as Spatial-Numerical Associations (SNAs; Cipora et al., 2019). The SNARC (spatial-numerical association of response codes) effect is the most studied type of SNA that suggests responses to small numbers are faster by the left hand, whereas responses to large numbers are faster by the right hand in Western cultures (Dehaene & Brannon, 2011; Dehaene et al., 1993; Cipora et al., 2019) because the numbers are represented on the left-to-right order on the mental number line. However, the link between numbers and sensory-motor activities has recently become a more powerful framework for studying numerical processing (Fischer et al., 2021; Proverbio & Carminati, 2019).

So far, only a few studies have investigated the event-related potentials (ERPs) of the embodied nature of numerical representation. Soylu et al. (2019) compared ERP markers for the recognition of montring, counting, and noncanonical (atypical) finger-digit associations. Montring is a method with which people raise their fingers to show numerical magnitudes to others and serves as a social-communicative function. However, finger counting is considered to be self-directed and has facilitative functions for magnitude representations. The results indicated that participants' performance was faster in montring configurations compared to counting and noncanonical configurations. They also found differences in the P300 component range (250–500 ms) between counting and montring compared to noncanonical conditions (Soylu et al., 2019). ERP evidence of the P300 component is also observed for internalized representation of finger-number gestures and their facilitation on math performance. The findings showed more accurate and faster simple addition performance when canonical (typical) finger patterns represented numbers. The central-parietal P300 was also modulated and revealed different amplitudes when canonical and noncanonical finger patterns were used for addition (van den Berg et al., 2021).

The centro-parietal P300 component occurs 250–500 ms after target stimuli and, in general, reflects stimulus evaluation processes and resource allocation (Isreal et al., 1980). It is reported that P300 amplitude increases when unexpected stimuli occur (Donchin, 1981; Polich, 1987, 2007). It is also assumed that the amount of mental effort allocated to a stimulus is determined by the inherent demands on 'perceptual-central' resources, and these inherent demands are reflected in the amplitude of the P300 component (Kok, 1997; Sutton et al., 1965). A high level of task difficulty is proposed to mobilize more resource allocation and evoke higher P300 amplitudes. For example, Ragot (1984) investigated the relative contributions of target evaluation and motor processes to the variability of P300 and RTs in a compatibility task. A green or red light was presented to the left or right of a fixation point, and the participants had to press the left and right keys in response to different colors. Congruency effects were determined by the spatial location of the stimulus. The more challenging conditions were those trials in which the target's spatial location was opposite to the side of the required response (spatially incongruent). Increased RTs and enhanced P300 amplitudes were recorded in conditions with spatial conflict (Ragot, 1984). In a subsequent study, Ragot and Fiori (1994) asked participants to respond with left and right hands when seeing the 'left' and 'right' words, respectively. They reported P300s with larger amplitudes to incompatible than compatible conditions (Ragot & Fiori, 1994). Several studies have also reported that the latency of the P300 component has a strong effect on RT, and it is proposed that this measure primarily influences the stage of response selection (Bashore et al., 2014; Magliero et al., 1984; Smid et al., 1992).

The current study aimed to extend the previous findings of the neurophysiological correlates of the association between finger counting and number processing. It is reported elsewhere that participants who mastered to start counting on their right hand (right-starters) associate small numbers with the right and large numbers with the left side of the space (Fischer, 2008; Fischer & Brugger, 2011; Liudmila, 2017). We investigated the related congruency effect of number-hand in two groups of left- and right-starters. In our task design, the participants had to press the keypad with their right/left hand, following the screen's visually presented right/left hands. However, the presented hands were preceded by numerical primes (small numbers: 1–4; large numbers: 6–9). This combination led to the following congruent pairs: left hand preceded by small numbers, right hand preceded by large numbers in left-starters, right hand preceded by small numbers, and left hand preceded by large numbers in right-starters. Additionally, the incongruent pairs consisted of the following conditions: left hand preceded by large numbers and right preceded by small numbers in left-start, and right hand preceded by large numbers, and left hand preceded by small numbers in right-starters.

Specifically, regardless of behavioral consequences as reflected in reaction times, we were interested in elucidating the electrophysiological responses of the brain through P300 analysis. In other words, if based on previous research (Johnson, 1988; Ruchkin et al., 1987), P300 effects stem from the target classification stage, variations in difficulties assumed in the evaluation of the target stimuli should interact with being left or right-starter because more challenging conditions in target evaluation might engage more processing resources than easy ones. Moreover, the P300 amplitude is considered an appropriate measure of stimulus evaluation independent of response-related processes (Houlihan et al., 1994).

We hypothesized the congruency effect in all participants, defined as a faster response to the congruent than incongruent number-hand pairs. This congruency effect would be reflected on P300 in the form of larger and later P300 in incongruent pairs than congruent pairs. These findings will show the association between numerical representation and finger counting habits. Because of its frequent use, the finger counting habit is internalized and hence might influence the performance of participants in motor response to visual hand stimuli when numerical primes are presented. Moreover, because both groups were among right-hand individuals (though with different finger counting habits), we might also observe between-group differences such as a stronger congruency effect in right-handed right-starters than right-handed left-starters, if we consider experience-based (handedness) and preference-based (finger counting habits) aspects (Sato & Lalain, 2008). It is proposed that a rapid and confident numerical processing called subitizing works for small numbers (smaller than 5) in comparison to larger ones (Burr & Ross, 2008) that might correspond to the starting hand as well. The data support the claim that smaller quantities might be processed with a system that depends on parallel individuation rather than estimation (Carey, 2009; Lipton & Spelke, 2004; Revkin et al., 2008), and the reaction times are significantly smaller for quantities within the range of subitizing (Lyons et al., 2012). Furthermore, fMRI results point to the stronger effects of small numbers as opposed to larger ones on the premotor cortex (Tschentscher et al., 2012). Therefore, right-handed participants might recognize their right hand faster according to their prior experience, and due to the subitizing effect of small numbers, the expected effects might be more prominent in right-starters because both experience-based (right hand) and preference-based (small numbers) effects might reinforce each other. We expect that the hand-lateralization in our sample in combination with concomitant task requirements, might strengthen the effects for right-starters.

2. Methods

2.1. Participants

A total of 30 right-handed native Farsi speakers participated in the present study. While no prior sample size calculation was conducted, our sample size was selected based on previous relevant ERP research that suggested the required number of participants and number of target trials for stabilization of the P300 component and adequate statistical power (Boudewyn et al., 2018; Cohen & Polich, 1997; Gibney et al., 2020; Yano et al., 2019). Specifically, the P300 stabilizes with approximately 20 target trials with a total number of 24 participants (Cohen & Polich, 1997; Yano et al., 2019). Handedness was tested using Edinburgh Handedness Questionnaire (EHQ), and a score above 40 indicates right dominancy (Oldfield, 1971). All participants were right-handed with handedness score of $M = 92.56$, $SD = 15.13$ (range: 42–100). They had normal or corrected-to-normal vision and no history of neurological and psychiatric disorders. They also reported the absence of motor diseases or movement due to medications. Based on their finger courting habits, the participants were divided into left- and right-starters using a finger counting questionnaire (Fischer, 2008). This finger counting questionnaire is reported to have good reliability and validity (Fischer, 2008; Lindemann et al., 2011). The data from six participants were excluded from the final analysis due to high levels of EEG artifacts. The data of 13 right-starters (10 female, mean age = 26.69, $SD = 5.94$) and 11 left-starters (eight female, mean age = 26.51, $SD = 5.70$) entered to the final statistical analysis. All participants signed a consent form and were compensated monetarily for their participation. The study was approved by the local Ethics Committee and was conducted in accordance with the Declaration of Helsinki's ethical principles for human research.

2.2. Task and stimuli

The experimental hand recognition task consisted of two stimuli: priming numbers and visually presented hand as the target. The priming numbers contained small (1–4) and large (6–9) single-digit numbers, and the target stimuli were visually presented left and right hands. Each trial started with the presentation of a fixation point (+) for 300 ms, followed by a number presented for 1200 ms, followed by the presentation of the target stimuli (either left or right hand) for 2000 ms. The inter-stimulus interval (ISI) between the priming number and the target was 1200 ms and contained the fixation point that was based on previous works on the number processing paradigm (Tschentscher et al., 2012) and lateral left-right response (Ragot & Fiori, 1994).

The combination used in our hand recognition task led to a congruent and incongruent condition that differed for the left- and right-starter participants. For the left-starters, congruent trials included small numbers (1–4) followed by the left-hand target and large numbers (6–9) followed by the right-hand target, and incongruent trials included small numbers (1–4) followed by the right-hand target and large numbers (6–9) followed by the left-hand target. For the right-starters, congruent trials included small numbers (1–4) followed by the right-hand target and large numbers (6–9) followed by the left-hand target, and incongruent trials included small numbers (1–4) followed by the left-hand target and large numbers (6–9) followed by the right-hand target (Fig. 1). A total of 160 trials were randomly presented to each participant, including 40 trials for each condition.

2.3. Procedure

Participants were tested individually while sitting approximately 70 cm from a computer screen. The participants were asked to indicate whether the targets were left or right hand by simply pressing the left or the right key on a response box, respectively. They were explicitly instructed that the numerical stimuli were irrelevant to the task. A total of ten trials with feedback to participants were presented for the practice phase. No feedback was given during the main task.

2.4. EEG recording and analysis

Electroencephalogram (EEG) measurement was conducted using a Mitsar Cap (10–20 international system). The electrode cap was equipped with 21 electrodes (Fp1, Fp2, F3, F4, C3, C4, P3, P4, F7, F8, T3, T4, T5, T6, Fz, Cz, Pz, O1, O2, and additional A1 and A2 connected to the left and right earlobes, respectively, as the reference electrodes). The EEG was recorded continuously with a sampling rate of 500 Hz with AFZ as the ground electrode and filtered online from 0.3 to 50 Hz. Impedances were kept below 10 KΩ. Off-line analyses were performed using WinEEG (version 2.130.101) and included low-pass filtering at 30 Hz and artifact detection. Eyeblink artifacts were dealt with using Independent Component Analysis (ICA). The independent components corresponding to horizontal and vertical eye movements were visually identified and rejected for each participant. Trials with voltages exceeding ±80 μv at any electrode were discarded, and the remaining 89.1 % of trials were used for further analysis. Participants were only included in the final analysis if at least 50 % of the total number of trials were artifact-free, excluding six participants.

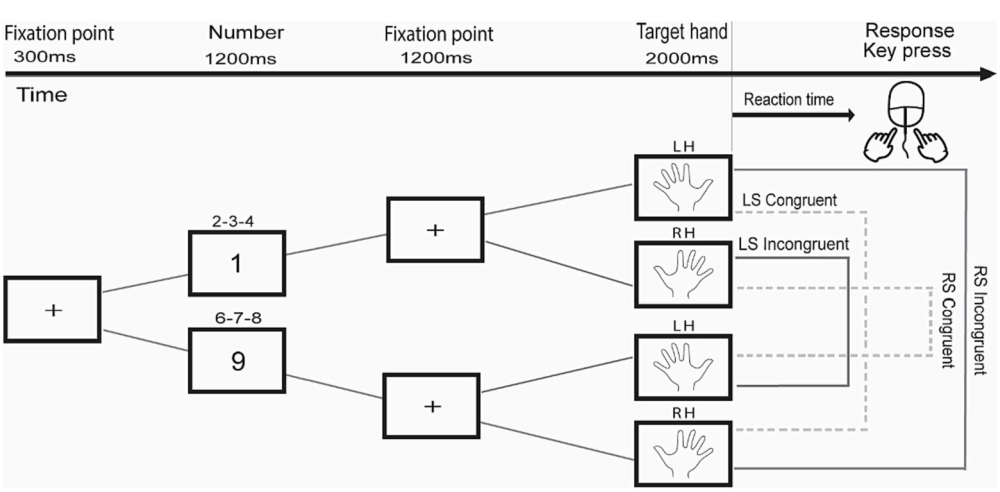

Fig. 1. Hand recognition task. The participants were instructed to ignore the presented numbers and press the right or the left key, respectively, when they saw the left hand (LH) or the right hand (RH) presented on the screen. For the left-starters (LS), congruent trials (dashed lines) included small numbers (1–4) followed by the left-hand target and large numbers (6–9) followed by the right-hand target [these trials are incongruent for a right-starter (RS) group], and incongruent trials (gray line) included small numbers (1–4) followed by the right-hand target and large numbers (6–9) followed by the left-hand target [these trials are congruent for a right-starter group]. The topmost trial is an example of a congruent trial for the left-starter, such that a small number (in this case, number 1) is presented as prime and the target is the left hand. The same trial is incongruent for a right-starters participant.

Stimulus-locked epochs were extracted offline over 1000 ms periods after stimulus onset (i.e., target hand), and an additional 200 ms was calculated prior to the stimulus onset to perform baseline correction. The ERPs were averaged for target stimuli (left and right hands). The component of interest was the P300, which has been frequently shown to be related to the congruency effect in different fields (Delle-Vigne et al., 2015; Cao et al., 2017; Rivera & Soylu, 2021). The choice of time windows and topography of the P300 analysis was based on previous literature (Dehaene, 1996; Jiang et al., 2010; Paulsen & Neville, 2008; Polich, 2007) and visual inspection of the grand average signals and related topographic maps. Accordingly, the analysis was concentrated on a time window of 250–500 ms at Cz and Pz electrodes. Mean amplitudes and latencies of P300 for the four different conditions were entered in the statistical analysis.

2.5. Behavioral and EEG analysis

The response time (RT) was calculated from the target hand offset. Incorrect and missing responses (7 %) were discarded. Additionally, we excluded noisy trials (10.9 %) based on the EEG preprocessing. First of all, a paired *t*-test was conducted to evaluate the congruency effect over all participants (n = 24) concerning RTs, amplitudes, and latencies of the P300 component. We also explored the congruency effect within each group (right starter and left starter) separately by conducting paired *t*-tests for RTs, amplitudes, and latencies of the P300 component.

Additionally, to explore the congruency effect within each group as well as evaluation of the SNARC effect, we conducted a 2 prime (small vs. large) by 2 hand (right- vs. left) repeated measure ANOVA. Furthermore, *post-hoc* analyses regarding hand-number configuration in each group are presented in the Supplementary materials and shall be considered exploratory at most. Since the task was very easy and the error rate was very low (7 %), the behavioral analysis concentrated only on RTs. All data were analyzed using GraphPad Prism version 8.4.3.

3. Results

3.1. Behavioral and ERP results for all participants

With respect to the congruency effect, paired *t*-tests revealed significant congruency effect among all participants for RT ($t(23) = 2.70$, $p = .013$, $d = 0.25$), amplitude ($t(23) = 3.82$, $p < .001$, $d = 0.47$), and latency of P300 ($t(23) = 2.43$, $p = .023$, $d = 0.29$), respectively. These results are presented in Fig. 2.

3.2. Behavioral and ERP results for left- and right-starters

The means and standard deviations of the RTs for four number-hand combinations and congruent and incongruent conditions are presented in Table 1.

In right-starters, paired t-tests revealed significant results for RT ($t(12) = 2.49$, $p = .028$, $d = 0.69$), amplitude ($t(12) = 4.08$, $p = .002$, $d = 1.13$), and latency of P300 ($t(12) = 2.84$, $p = .015$, $d = 0.79$), respectively. In left-starters, paired *t*-tests revealed non-significant results for RT ($t(10) = 1.23$, $p = .246$, $d = 0.37$), amplitude ($t(10) = 2.13$, $p = .059$, $d = 0.64$), and latency of P300 ($t(10) = 0.55$, $p = .595$, $d = 0.17$), respectively. These results are presented in Fig. 3.

The means and standard deviations of the mean amplitude of P300 for four number-hand combinations and congruent and incongruent conditions are presented in Table 2.

The grand average ERPs and P300 responses to several conditions and groups are presented in Figs. 4 and 5.

The means and standard deviations of P300 latency for four number-hand combinations and congruent and incongruent conditions are presented in Table 3.

Finally, a 3-way ANOVA concerning 2 group (left- vs. right-starter) × 2 prime (small vs. large) × 2 hand (right- vs. left) revealed significant interaction effect of Group × Prime × Hand ($F(1, 22) = 6.949$, $p = .015$). Furthermore, the effect of the presented number was significant only in right-starters when the right hand was the target ($t(12) = 3.50$, $p = .004$, $d = 0.97$), suggesting a faster reaction time to small numbers compared to large numbers. To see detailed *post-hoc* analyses regarding hand-number configuration in each group, see the Supplementary materials.

4. Discussion

The present study investigated embodied numerical processing using the number-hand congruency effect. Our research question was whether finger counting habits influence recognizing embodied target stimuli (left or right hand) in different congruent and incongruent configurations. Two groups of left and right-starters completed a hand recognition task in which they had to press the keypad with their right/left hand, following the screen's visually presented right/left hands, preceded by small and large numerical primes.

The current study's findings support the embodied nature of number processing (Fischer, 2018; Fischer & Hartmann, 2014; Fischer & Shaki, 2018; Sixtus et al., 2020). Both behavioral and neurophysiological findings showed the priming effect of numbers on response time to the target hand. In other words, the congruency of numbers and target

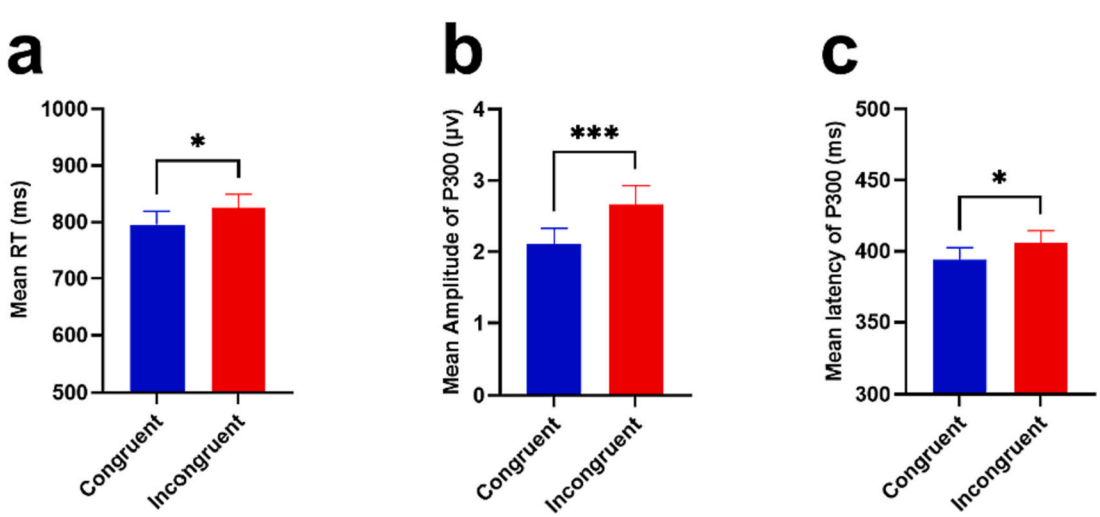

Fig. 2. Mean difference of RTs, P300 amplitudes, and latencies in all participants (n = 24). As can be seen, when the prime number and target hand were congruent, the participants responded faster to targets (a) and showed smaller P300 amplitude (b) and shorter latency (c). ($p < .05$*, $p < .001$***.)

Table 1
The means and standard deviations of the RTs (ms).

	Small – Left hand		Large – Left hand		Small – Right hand		Large – Right hand		Congruent		Incongruent	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Left-starter	836	162	847	151	804	134	792	110	814	127	826	131
Right-starter	870	131	830	127	730	116	780	100	780	111	825	111

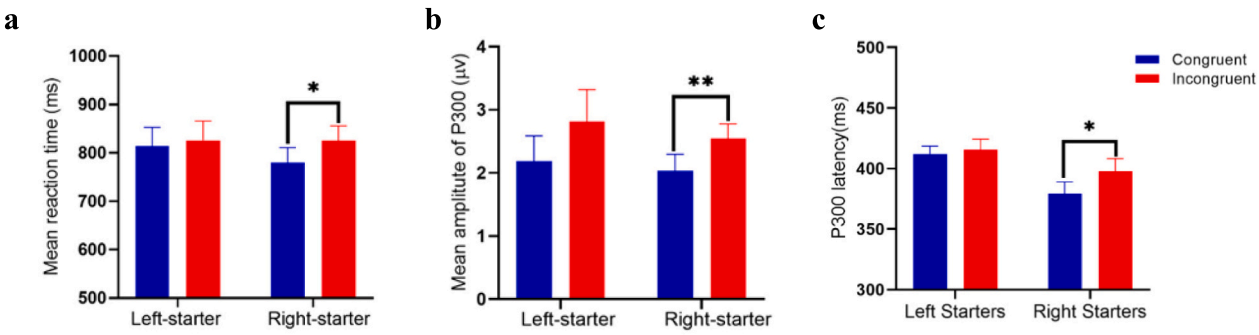

Fig. 3. The congruency effect separately within each group for RT (a), the P300 amplitude (b), and the P300 latency (c). ($p < .05$*; $p < .01$**.)

Table 2
The means and standard deviations of P300 amplitude.

	Small – Left hand		Large – Left hand		Small – Right hand		Large – Right hand		Congruent		Incongruent	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Left-starter	2.53	1.72	3.26	1.85	2.36	2.22	1.85	1.28	2.19	1.32	2.81	1.70
Right-starter	2.95	0.48	2.27	1.44	1.81	0.40	2.14	1.44	2.04	0.94	2.55	0.84

hands (e.g., small numbers followed by the right hand and large numbers followed by the left hand in right-starters) was observed in all participants. Specifically, our findings revealed faster RTs, smaller P300 component amplitudes, and shorter latencies for congruent trials. These results might be attributed to the difference in the finger counting habits of the participants and the related cognitive and motor challenges within the number-hand configurations. It means that when numerical primes associated with target hands were presented, the recognition of targets was facilitated. It seems reasonable to assume that the numerical processing preceding a left- or right-hand response contained partial target stimuli information (de Jong et al., 1988; Rüsseler & Rösler, 2000). This partial information was probably determined by the finger counting habits of the participants. Hence, one might conclude that the numerical primes within congruent trials that contained such partial information prepared the related hand and led to faster responses for congruent compared to incongruent number-hand trials. This finding also aligns with previous works in other fields that used preparatory signals before an imperative stimulus. In these paradigms, the first stimulus provides in advance information and allows the participants to prepare the corresponding response for targets (Brown et al., 2011; Kato et al., 2004).

Of note, motor responses in priming tasks can be facilitated by a prime congruent with targets or degraded when prime and target are incongruent. The related switch costs are robust and reported in several tasks and stimuli, including finger presses (Nakata et al., 2005) and arm movements (Craighero et al., 1996). There are two explicit and implicit systems of priming: The explicit system is rule-based and relevant to the expected task, while the implicit system is irrelevant to the expected task but consists of informational content. Even in the latter case, the participants rely on the informational contents (in our case, finger counting habits) to associate them with the targets (hand recognition). In the current study, the numerical primes might have engaged cortical motor areas related to information contents of finger counting habits that associate with hand recognition.

The current research also measured ERPs to obtain more profound insight into the nature of perceptual processes underlying the effects of number-hand configurations. Interestingly, when all participants were taken into account, the most prominent effect size was observed for the amplitude of the P300 component. This congruency effect has been frequently reported in the P300 component in many different fields, such as numerical cognition (Salillas et al., 2008), language (Andres et al., 2011; Bellegarda & Macizo, 2021), and executive functions (Kałamała et al., 2018; Leuthold, 2011). The sensitivity of the P300 amplitude might be attributed to the fact that the participants had fewer cognitive challenges in the congruent trials than in the incongruent trials. Specifically, in line with the finger counting habits of the participants, when the numerical primes were incongruent with the hand associated with them, the P300 amplitudes were larger. The finding is consistent with previous research on the P300 component that has shown that the amplitude of this component is highly related to informational qualities such as the difficulty of a task (Johnson, 1988; Li et al., 2019; Polich, 1987, 2007). Enhanced amplitudes of the P300 in response to incongruent trials showed effects of the mental efforts in line with finger counting habits. In general, these results demonstrate that the stage of cognitive evaluation reflected by the mean amplitude of the P300 increases in response to the trials that require more processing resources (Ghani et al., 2020).

An additional mental effort was also observed in P300 latencies for all participants. In line with the behavioral response times, this effect suggested faster responses when numerical primes were congruent with target hands. This finding is consistent with previous studies that reported an association between response time and P300 latency (Ford et al., 1982; Hohnsbein et al., 1991). The observed P300 latencies also suggest an association between embodied congruency effect and motoric response execution in the current study. The fact that P300 latencies were in line with behavioral response times supports the studies

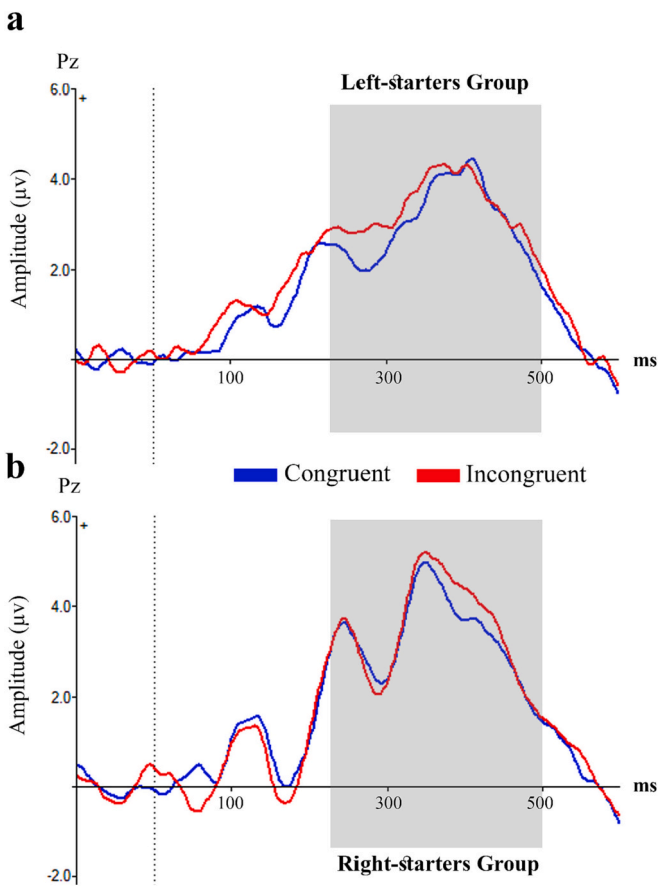

Fig. 4. Grand average ERPs for the centro-parietal electrode (Pz) with the P300 time window (gray color) for the congruency effect in each group of left (a) and right-starters (b). The X-axis indicates the time in milliseconds (ms).

that have shown the latencies are more related to response selection processes (Ford et al., 1979; Osman et al., 1992; Zeef et al., 1996). For instance, Smulders et al. (1995) reported that the participants who responded to congruent and incongruent trials for the 'left' and 'right' words revealed longer response times and P300 latencies in incongruent trials as opposed to congruent trials.

Our pilot analysis within groups showed a significant difference in response times between congruent and incongruent trials observed in right-starters (but not left-starters). This might be interpreted in light of the fact that the right-handed right-starters have already dealt with hand dominancy and finger counting habits at the same time, which is not the case of right-handed but left-starters in the current study. Indeed, the shortest and longest response times (see Table 1) were obtained for the right-starter group in the least and most challenging conditions, respectively: when prime stimuli were small numbers (congruent with finger counting habit) and the target was the right hand (congruent with handedness), and when prime stimuli were small numbers (incongruent with counting habits) and the target was the left hand (incongruent with handedness).

Regarding the SNARC effect (Chochon et al., 1999; Dehaene & Brannon, 2011; Dehaene et al., 1993), one might indeed expect to produce a left-to-right response increasing from small to large number in both congruent and incongruent trials. Differently from those expectations, our task did not produce any significant lateral bias known as the SNARC effect, even in the left-starters. We propose that the direct mapping of the SNA was violated in the current study for four possible reasons. First and most importantly, the results might be interpreted by the fact that the finger counting habits of the participants induced a remapping of SNA. It has been reported that finger counting habits seem to influence SNA (Fischer, 2008; Wood et al., 2008). Fischer (2008) proposed that a systematic link might exist between the hand one starts counting and the SNA is modulated by number-hand associations. Therefore, finger counting in our work somehow suppressed the SNA. Second, previous literature suggested that SNA is influenced by several cultural factors, such as reading direction (Wood et al., 2008). Hence, one might expect an influence of reading direction in our right-to-left Farsi-speaking participants. For instance, Dehaene et al. (1993) reported that the right-to-left Farsi speakers reveal a weaker SNARC than the left-to-right French speakers (Dehaene et al., 1993; see also Rashidi-Ranjbar et al., 2014). Third, our participants were university students who are frequently exposed to the English language and literature, that might have also induced the findings. For instance, a recent study on Farsi speakers showed that the original SNARC effect that has been frequently observed in Western left-to-right languages (Mazhari et al., 2019; see also Ito & Hatta, 2004). Fourth, the reading directions for words and numbers are inconsistent for Farsi speakers like Hebrew. From this perspective, our work indicates that there might be no relation between reading direction and SNA.

Furthermore, it is reported that different paradigms other than the original SNARC task might present different spatial associations. For example, the original SNARC effect (left-to-right association) is reversed in tasks requiring participants to imagine an analog clock (Bächtold et al., 1998). Also, Di Luca et al. (2006) showed faster right-hand responses to small numbers that were not consistent with the left-to-right orientation of SNARC (Di Luca et al., 2006), which can be explained by the finger counting strategies of participants (Di Luca et al., 2006; Fischer, 2008, 2018; Fischer & Brugger, 2011; Fischer et al., 2012).

A recent and more relevant study (Miklashevsky, et al., 2021) to our research paradigm used bimanual grip force recording to investigate the embodied aspects of number processing. Their participants processed visually presented numbers in a go/no go n-back task while passively holding small force sensors in both hands. No systematic SNA effect was found at the group level; however, in line with our findings, an effect of finger counting was observed at the later stage of encoding as measured by grip forces. These results are inconsistent with the possibility that the left-to-right direction of numbers indicates an invariant spatial representation of numbers and indicates that the assignment of spatial codes to numbers might be determined by the tasks used.

Nonetheless, these results must be interpreted with caution, and a number of limitations should be borne in mind. The first one concerns the fact that only right-handed participants took part in our research. This limitation is primarily related to the over-learned motor patterns that might constrain our findings. Future works testing left-handed and right-handed participants with different finger counting habits are thus required to investigate the association between numbers and hands.

The second limitation and, more importantly, relates to the study sample, which suggests future large-scale studies. However, while the sample size of our work was rather small, the observed congruency effects were very large. Furthermore, it is reported that increasing the number of trials is most helpful at low and intermediate levels of statistical power (Boudewyn et al., 2018). Thus, it is usually worth increasing the number of trials if there is little cost to doing so. In our research, we increased the number of target trials to 40 per condition to reach the acceptable range for ERP analysis in each group. We suggest that a larger sample might lead to more conclusive results. Although our research only includes small sample size and some results are somewhat exploratory, it introduces an informative method to study electrophysiological aspects of embodied numerical cognition.

5. Conclusion

The current study's findings contribute to the ongoing debate concerning the embodied nature of numbers. Our results support the association of number-hand representations and corroborate the idea of embodied numerosity. We observed the number-hand congruency effect

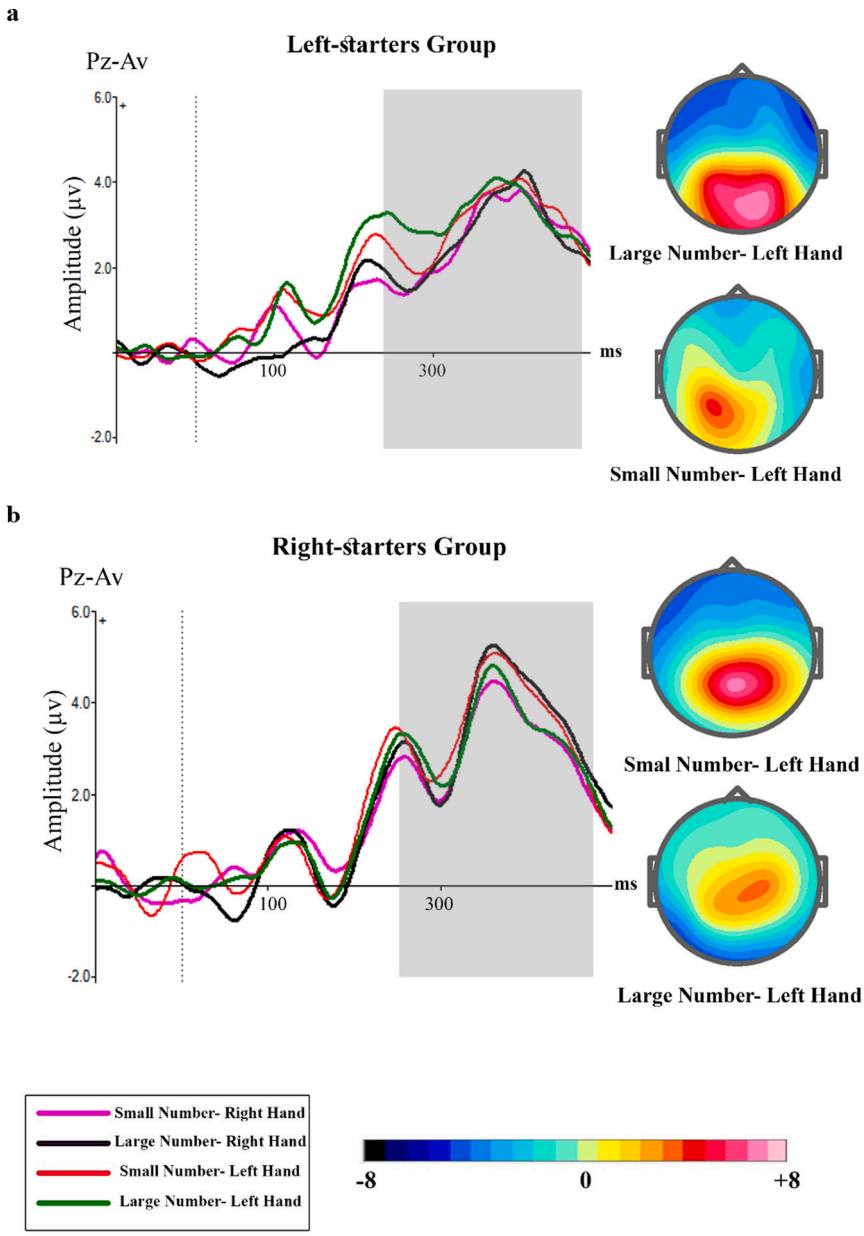

Fig. 5. Grand average ERPs for the centro-parietal electrode (Pz) with the P300 time window (gray color). Topography plots represent the differences related to the left hands for the P300 component for both groups.

Table 3
The means and standard deviations of P300 latency.

	Small – Left hand		Large – Left hand		Small – Right hand		Large – Right hand		Congruent		Incongruent	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Left-starter	412	31.0	409	37.6	423	42.0	412	30.1	412	25.8	416	34.3
Right-starter	399	37.5	382	38.5	376	62.0	396	68.0	379	46.1	398	46.1

in all participants and showed that numerical primes that prepared the related hands influenced the response times and led to faster responses in the number-hand congruent condition. The ERP analysis of the component P300 as revealed by its amplitude and latency also shed more light on this issue. To conclude, the present work provides evidence of the number-hand association in line with the general idea of embodied cognition and shows that numerical representations may at least partially influence motor processing.

CRediT authorship contribution statement

Saied Sabaghypour: Conceptualization, Methodology, Data curation, Software, Writing – original draft, Writing – review & editing. **Hassan Sabouri Moghaddam:** Conceptualization, Methodology, Writing – original draft, Supervision, Writing – review & editing. **Farhad Farkhondeh Tale Navi:** Methodology, Visualization, Formal analysis, Writing – review & editing. **Mohammad Ali Nazari:** Conceptualization, Investigation, Writing – review & editing, Validation. **Mojtaba**

Soltanlou: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Validation.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The raw EEG data supporting the conclusions of this article will be made available by the authors upon request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2023.103841.

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