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Suggested citation referring to the original publication:
Acta Psychologica 231 (2022), Art. 103791 pp. 1 - 12
DOI https://doi.org/10.1016/j.actpsy.2022.103791
ISSN 1873-6297

Journal article | Version of record

Acta Psychologica 231 (2022) 103791

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Spatial-numerical associations without a motor response? Grip force says 'Yes'

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ARTICLE INFO

Jel classification:
2330 Motor Processes
2340 Cognitive Processes

Keywords:
SNARC
Mental number line
Number processing
Embodied cognition
Grip force
Motor system

ABSTRACT

In numerical processing, the functional role of Spatial-Numerical Associations (SNAs, such as the association of smaller numbers with left space and larger numbers with right space, the Mental Number Line hypothesis) is debated. Most studies demonstrate SNAs with lateralized responses, and there is little evidence that SNAs appear when no response is required. We recorded passive holding grip forces in no-go trials during number processing. In Experiment 1, participants performed a surface numerical decision task ("Is it a number or a letter?"). In Experiment 2, we used a deeper semantic task ("Is this number larger or smaller than five?"). Despite instruction to keep their grip force constant, participants' spontaneous grip force changed in both experiments: Smaller numbers led to larger force increase in the left than in the right hand in the numerical decision task (500–700 ms after stimulus onset). In the semantic task, smaller numbers again led to larger force increase in the left hand, and larger numbers increased the right-hand holding force. This effect appeared earlier (180 ms) and lasted longer (until 580 ms after stimulus onset). This is the first demonstration of SNAs with passive holding force. Our result suggests that (1) explicit motor response is not a prerequisite for SNAs to appear, and (2) the timing and strength of SNAs are task-dependent. (216 words).

1. Introduction

Spatial-Numerical Associations of Response Codes (the SNARC effect) received much attention during the last decades following the landmark report by Dehaene et al. (1993): people press left buttons faster when responding to smaller numbers (e.g., 1 or 2) and right buttons faster when responding to larger numbers (e.g., 8 or 9). This finding inspired the hypothesis of a spatially oriented Mental Number Line: processing of numbers, similar to processing of time concepts (see von Sobbe et al., 2019) or affective information (see Phaf et al., 2014), is tightly related to the representation of space (Fias, 1996). A similar arrangement of smaller-to-larger quantities from left to right has also been demonstrated for several non-numerical domains, such as size or luminance (see Macnamara et al., 2018). Spatial-numerical associations were shown with various methods: with button presses, finger movements (Fischer, 2003), eye movements (Myachykov et al., 2015, 2016), foot responses (Schwarz & Müller, 2006), and even full-body movements (Shaki & Fischer, 2014; Winter et al., 2015; see also Wood et al., 2008, for a meta-analysis of different methods). Recent evidence points to biological underpinnings of these spatial associations of numbers (Felisatti, Laubrock, et al., 2020b; Masson et al., 2020; Rugani et al., 2015, 2020).

Yet, the automaticity of spatial-numerical associations (SNAs) and their role in semantic processing are debated. One possible interpretation is that evolutionarily inherited hemispheric specialization, together with spatially systematic sensory and motor experiences, promote and shape SNAs (Felisatti, Aagten-Murphy, et al., 2020a; Fischer, 2012). More generally, this view holds that our bodily experience is obligatorily re-activated whenever we recognize or understand objects or symbols (Barsalou, 2008; Bub et al., 2018; Fischer, 2012; Pulvermüller & Fadiga, 2010). Alternatively, Gevers and colleagues (Gevers, Ratinckx, et al., 2006a; Gevers, Verguts, et al., 2006b) suggested that the SNARC effect does not reflect the *processing* of numbers themselves but rather stems from peripheral *response-related processes* and the interaction between such response mappings and number semantics (see also Fias et al., 2001; but see Bull et al., 2013, Experiment 2, for conflicting results). Further support for this account comes from EEG-research: Keus et al. (2005) found robust SNA signatures in response-locked, but not in

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https://doi.org/10.1016/j.actpsy.2022.103791
Received 30 November 2021; Received in revised form 31 August 2022; Accepted 31 October 2022

stimulus-locked event-related potentials.

If bodily contributions to representing number meaning are merely response-related, then no SNAs should be demonstrated in studies without explicit lateralized responses. While almost all previous studies used paradigms with lateralized responses, a few attempts were made to avoid those. Myachykov et al. (2016) demonstrated SNAs in spontaneous ocular drift on a blank screen while presenting participants with small and large numbers auditorily without any explicit task. Other studies showed spontaneous SNAs in eye movements during counting (Hartmann et al., 2016; Holmes et al., 2016). Attentional shifts caused by number processing have been demonstrated by Fischer et al. (2003) but not replicated recently in a larger cross-lab study (Colling et al., 2020; see also Pellegrino et al., 2019). Shaki and Fischer (2018) documented SNAs in an implicit association test with only a central response button when number magnitude was processed explicitly.

Research on individual differences also provides mixed evidence regarding the mechanisms responsible for SNAs. If SNAs are necessary for processing number magnitude, they should correlate with individual mathematical abilities. However, studies on the relationship between SNARC and mathematical skills led to contradicting conclusions (see for a review Cipora et al., 2020). A recent analysis demonstrated that only 45 % of individuals show the SNARC effect, and this minority pulls the group mean towards significance (Cipora et al., 2019).

Along with cross-cultural (Pitt & Casasanto, 2020) or individual differences (Cipora et al., 2020; Viarouge et al., 2014), a closer examination of the timing of SNAs might provide further insights into their functional role in number processing, especially when response requirements are well controlled. As an example of this refined methodological approach, our recent study used two grip force sensors while presenting participants with smaller and larger numbers in a 1-back paradigm (Miklashevsky et al., 2021). Participants simply held the sensors with *constant pressure* throughout the session and responded verbally to number's repetitions. Otherwise, participants remained silent. Not only is this method free from lateralized motor responses, but it also provides information about *spontaneous* grip force changes in each hand with millisecond resolution. This study found systematic changes in grip force already at 100–140 ms after stimulus onset. These changes were specific for groups of left- vs. right-starters, i.e., people who started counting with their left vs. right hand in a following finger counting test. This evidence is consistent with the now widely accepted role of sensorimotor experiences in the representation of conceptual knowledge – a theoretical position known as "embodied cognition".

While the abovementioned study identified both a rapid onset and individual-related differences in number processing, it did not find systematic patterns of force that would reflect SNAs and therefore support the Mental Number Line Hypothesis. One of the reasons for this outcome, given the otherwise ubiquitous nature of SNAs, could be the 1-back task used by Miklashevsky and colleagues: while processing a number on the screen, participants also had to keep the previous number in their working memory, thus perhaps diluting specific SNAs (see Chen et al., 2008); the overall observed pattern of grip force supported this hypothesis.

In the present study, we addressed the limitation of our previous study by using a modified version of the go/no-go paradigm with bimanual force registration in two different tasks that were free of potential problems associated with the N-back task. In Experiment 1, we presented participants with single numbers or letters and asked them to respond verbally only to letters (cf. Pinto, Pellegrino, Lasaponara, et al., 2019a, Experiment 3). This instruction ensures the processing of stimulus identity (number vs. non-number) while keeping semantics less involved (cf. dicrimination of words and pseudowords in a lexical decision task). In Experiment 2, we asked participants to perform a magnitude classification task, a classical task to assess SNAs (Wood et al., 2008). This task requires deeper processing of number magnitude: Participants compare a given number to a reference point (e.g., number 5) and categorize the number as being larger or smaller than this reference. Thanks to nearly identical methodology, any differences between the two experiments can be attributed to the varying task, i.e., the depth of semantic processing of numerical stimuli.

Another advancement concerns the nature of the grip force signal and its appropriate analysis. Grip force registration is a relatively novel method, and no gold standard has been established for it yet (see Nazir et al., 2017, for methodological considerations). Most previous studies focused on linguistic (Aravena et al., 2012; da Silva et al., 2018, 2019; Labrecque et al., 2016; Nazir et al., 2017; Pérez-Gay Juárez et al., 2019) or video materials (Blampain et al., 2018). They either used unimanual grip force recording (Aravena et al., 2012; Blampain et al., 2018; da Silva et al., 2019; Labrecque et al., 2016; Nazir et al., 2017; Pérez-Gay Juárez et al., 2019) or only focused on the earlier part of the grip force effect (first 800 ms after stimulus presentation, da Silva et al., 2018). The study by Miklashevsky et al. (2021) mentioned above examined a more extended period of 1000 ms and found a complex multiphasic pattern of activity in both hands *regardless of number magnitude* (see also our Fig. 1, an adapted image from da Silva et al., 2018, where a beginning of this pattern appears for lexical stimuli; see also Miklashevsky, 2022, for an identical pattern with visually presented objects). This pattern likely reflects unspecific cognitive processes that are not directly related to number magnitude but instead to perception of the stimulus, preparation, or execution of the verbal response (or response inhibition, in no-go trials), and memory-related processes.

Crucially, both hands followed the same pattern, reflecting either central cognitive processes or bimanual coupling (Drewing & Aschersleben, 2003; Garbarini et al., 2014; Garbarini & Pia, 2013; Mathew et al., 2020). This fact might be less relevant for studies investigating motor semantics per se because they can compare two conditions (motor vs. non-motor) with each other and thus reduce the influence of these bimanual force oscillations. However, most of those studies cited above compare different conditions not with each other but with a baseline (i.e., average force prior to the moment of stimulus presentation), which is not free of the methodological problem we discuss here.

For our goal – measuring associations with left vs. right hand in order to examine the Mental Number Line hypothesis – this coupling is highly

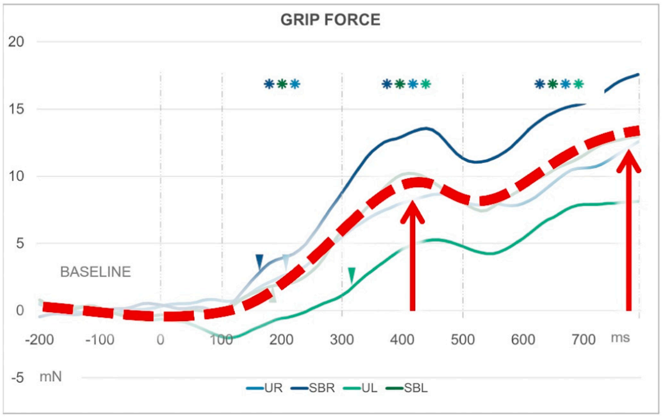


Fig. 1. Biphasic grip force pattern during word processing (adapted image from da Silva et al., 2018, Fig. 2)

Note. Grip force modulation caused by presentation of action verbs. UR: unimanual task (i.e., participants held one grip force sensor), right-hand data; SBR: symmetrical bimanual task (i.e., participants held two sensors, one in each hand), right-hand data; SBL: symmetrical bimanual task, left-hand data; UR: unimanual task, right-hand data. Asterisks indicate a significant difference between the baseline (the grip force before stimulus onset) and force change in a certain time window. The x-axis represents time in milliseconds after the word onset. The y-axis represents grip force variation in millinewtons. See da Silva et al. (2018) for details. The red dashed line and red up-pointing arrows were added by us for illustration purposes. The red line represents the pattern generally observed in all conditions. The arrows indicate peaks around 400 ms and 800 ms after stimulus onset.

problematic: if we expect to find stronger force in one hand after the presentation of some numbers, while the other hand's force increases simultaneously, the difference effect of interest can be diminished. That is why we here suggest using linear regression modeling for lateralized stimuli or stimuli with lateralized semantics and always including the contralateral hand's force as a covariate. In other words, we estimate the effect of the number on grip force beyond the variance explained by the force of the contralateral hand. With this innovation, we tackled the problem of detecting SNAs without an explicit motor response to investigate the degree to which numbers are embodied concepts.

2. Experiment 1: numerical decision task

The goal of Experiment 1 was to examine grip force changes during number processing with a task requiring merely superficial, non-semantic number processing. For this reason, we used a numerical decision task: we asked participants to differentiate between numbers (from 0 to 9) and visually similar letters of the alphabet (cf. Pinto, Pellegrino, Lasaponara, et al., 2019a, Experiment 3). Grip force was recorded bimanually throughout the experiment, and participants were instructed to keep the pressure constant, i.e., no manual motor responses were required. Instead, verbal responses to letters were needed, and all number trials were no-go trials.

2.1. Equipment, stimuli, and procedure

We applied nearly identical equipment and setting as used by Miklashevsky et al. (2021). During the whole experiment, participants held bimanually two grip force sensors (ATI Industrial Automation, www.ati-ia.com/Products/ft/sensors.aspx) resembling large metal coins with 40 mm diameter, 14 mm height, and 57 g weight each. These sensors were calibrated to record grip forces with millisecond (ms) temporal and millinewton (mN) kinetic resolution. A three-millimeter plastic cover of the same diameter as the sensor itself (40 mm) covered each sensor from both contact sides, which gives a total thickness of 20 mm and a total weight of 65 g per sensor. Only Fz force along the vertical axis through the sensors was analyzed (see Fig. 2).

Before data collection, participants learned to apply a holding force between 1.5 N and 3 N with each hand. Two circles on the screen represented the sensors. These circles changed their color from green (“too weak”) to red (“too strong”), with the acceptable force range indicated in gray. When both circles turned gray, the experimenter instructed participants to keep their grip force at this level during the experiment. Data collection started automatically when the force remained within the required range for 3 s. This calibration procedure was repeated after each break.

Single digits from 0 to 9 and Latin letters (A, D, E, G, R, S) appeared on the screen. Note that we only analyzed numbers from 1 to 4 and from 6 to 9 to keep the design similar to Experiment 2 (see below). The letters A, D, E, G, R, and S were chosen because they are not grouped exclusively at one or the other end of the alphabet since spatial associations were also demonstrated for letters: letters from the beginning of the alphabet are associated with the left side, and letters from the end of the alphabet are associated with the right side (Gevers et al., 2003).

All stimuli appeared in black font on a white background. With an approximate viewing distance of 60 cm (not strictly controlled) and a width of 0.4 cm for the digits, they occupied 0.382 degrees of visual angle (calculated by using the formula 57.3 * w/d, where w denotes the width of the object and d denotes the distance to the object). Each trial started with a fixation dot (200 ms) followed by a stimulus (either a number or a letter, for 2000 ms or until response; see Fig. 3). We used no intertrial interval. A go-nogo task was applied: participants should say

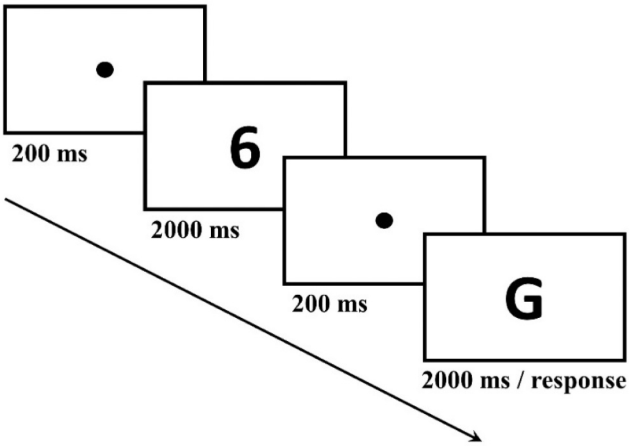


Fig. 3. Experimental procedure (Experiment 1).

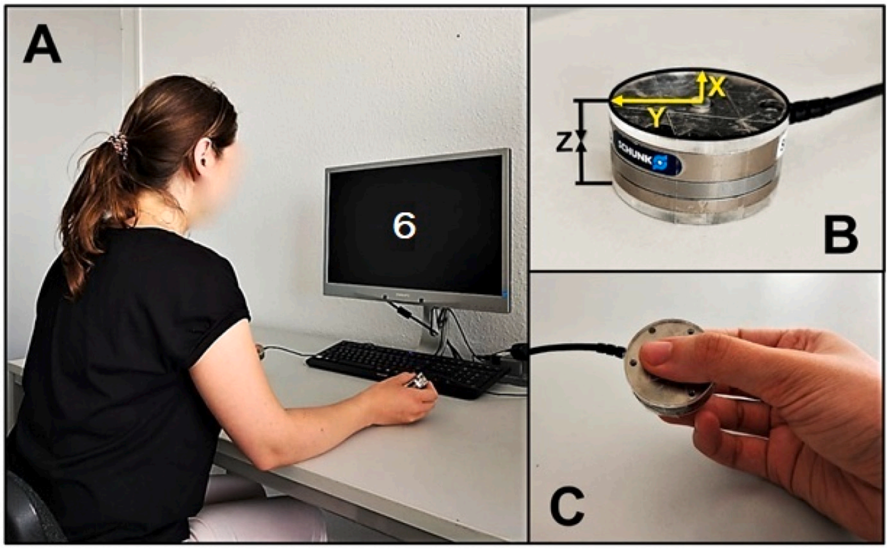


Fig. 2. Experimental setup.
Note. Panel A: Bimanual force recording setup (display stimulus not to scale). Panel B: Grip force sensor (X – longitudinal, Y – radial, Z – compression forces). Panel C: The way participants held the sensors (around 45° relative to the table surface). From Miklashevsky et al. (2021).

"yes" whenever they saw a letter while staying silent when they saw a number. In the instruction, we pointed out that there is no letter O in the experiment, but the number zero is present. The experimenter was seated at another desk and registered participants' verbal responses by mouse click. We used OpenSesame (Mathôt et al., 2012) for stimuli presentation and collected force data at a separate PC using custom-made software based on the Python-library Expyriment software (Krause & Lindemann, 2014). All instructions were given in English.

All 16 stimuli were randomly presented 64 times (4 blocks separated by obligatory breaks, 16 repetitions of each stimulus in a block, i.e., 160 number trials and 96 letter trials in each block). Overall, participants were exposed to 1024 experimental trials. A practice part preceded the main experiment: all stimuli randomly appeared once. No feedback was provided during practice, but the experimenter observed the participant's performance and resolved possible misunderstandings of instructions after the practice session. The experimental part took around 40 min. After completing it, participants filled in demographic and health-related questionnaires. The local Ethics Committee approved the study (study number 15/2019).

2.2. Participants

We initially collected data from 30 participants. Assuming a medium effect size of $d = 0.6$ (for non-semantic numerical tasks, see Table 1 in Wood et al., 2008), alpha = 0.05, and power = 0.80, our required sample size was 24 participants (G*Power v. 3.1.9.7, Faul et al., 2009). Supplementary materials at OSF (see Data Availability Statement) contain a detailed power analysis protocol. Moreover, mixed-effects models used in the present study are more powerful than usual separate analyses by participants and by items (Brysbaert & Stevens, 2018). Thus, using mixed-effects modeling additionally ensured that we were able to detect effects of interest.

All participants reported having no motor diseases or medications affecting motor control. All participants had normal or corrected-to-normal vision. Data of four participants who had >20 % of trials outside of pre-defined force thresholds (see Section 2.3 for details) were removed from the sample. The remaining sample consisted of 26 people (24 females, 2 males; mean age = 24 years, ranging from 18 to 37 years). All but two participants were right-handed according to self-report. Sixteen participants indicated German as their native language; other native languages were Georgian, Hindi, Chinese, Arabic, Hungarian, Russian, and Bulgarian. All participants spoke at least one foreign language, while most spoke two or more foreign languages.

2.3. Data preprocessing

Data preprocessing followed recommendations provided by Nazir et al. (2017): first, we filtered the raw force data at 15 Hz with a fourth-order, zero-phase, low-pass Butterworth filter. Then single epochs were extracted from the vertical Fz signal, starting from 200 ms before and ending at 2000 ms after stimulus onset. The average force was calculated for the time window of 20 ms before stimulus onset for each epoch and then subtracted from all data points of that epoch. The resulting grip force always crosses the zero point at the start of each trial; negative force values reflect a vertical grip force lower than the force at the stimulus onset and not the absence of force. Note that from now on we use the word force for simplicity, although this is not an absolute force but a relative force, i.e., force change compared to the force at the moment of stimulus presentation. Maximum and minimum thresholds were applied (±500 mN) for removing movement artifacts and identifying participants with excessive force variability. A larger range (±500 mN) compared to ±200 mN applied by Nazir and colleagues was chosen since longer epochs were selected (2000 instead of 1000 ms). With increasing epoch length, the probability also increases that force will exceed a certain threshold because of increased variability. Thus, we used wider thresholds for longer trials/epochs in order to avoid removing too much data. All trials with force exceeding one of the thresholds were excluded. In the data of 4 participants, the number of excluded trials exceeded 20 %; we completely excluded these participants' data from the analysis and the sample description above (Section 2.2). For the remaining 26 participants, on average, 5 % of trials were removed (ranging from 0 % to 15 % per participant). Accuracy was high (99 % on average, ranging from 95 % to 100 % per participant). Trials with incorrect responses were also discarded from the analysis.

Table 1
Main effect of Hand on average grip force in the time window 50–130 ms (Experiment 1).

Random effects	Name	Variance	SD
Participants	Intercept	10.97	3.313
Residual		15.85	3.981

Fixed effects	b	SE	t-value	p-value
Intercept	4.172	0.706	5.910	<0.001
Hand (right)	−0.922	0.390	−2.362	0.018

2.4. Main analysis and results

We observed multiphasic force fluctuation patterns similar to the previous study with grip force registration in number processing discussed above (Miklashevsky et al., 2021). As suggested in this earlier study, we will here also use EEG-like notations with letters H (high, stands for force peaks) and L (low, stands for force dips) followed by numbers indicating milliseconds.

In the present experiment, we observed H130 (i.e., a force peak around 130 ms after stimulus onset), followed by L250 (i.e., a force dip around 250 ms after stimulus onset) in all no-go trials (see Fig. 4B). A seemingly bimodal wave consisting of both H330 and H440 followed. The average force dropped sharply until 630 ms and remained constant until 1000 ms. After this point, the force slowly dropped until the end of the epoch.

In go-trials, the grip force did not differ from no-go-trials until 300 ms after stimulus onset, where a clear divergence point between the two averaged forces emerged (see Fig. 4A). After 300 ms, the force in go-trials increased dramatically and almost reached the level of 40 mN at around 1100 ms after stimulus onset. This force increase reflects the activity spread across the motor system when participants prepare and perform their verbal responses. Blampain et al. (2018) demonstrated that grip force registration reflects not only hand-related motor activity but also activation of other body parts, e.g., the feet. Assuming that the divergence point indicates response preparation or execution, all cognitive processing required for performing the experimental task – distinguishing between letters and numbers – should occur before this point (see General Discussion).

We used cluster permutation analysis for exploratory purposes (see Section 5.4 for the discussion of our statistical approach and more details on the cluster permutation method). This analysis aimed to identify time windows of interest since we could not formulate an a priori hypothesis regarding the timing of the effects. Force data were averaged by Number (1/2/3/4/6/7/8/9) and Hand (left/right) and submitted to a cluster permutation analysis using the R (R Core Team, 2020) package "permuco" (Frossard & Renaud, 2018) with the TFCE correction for multiple comparisons (Threshold-Free Cluster Enhancement, see Ehinger, 2019). No significant effects were found. The closest to significance were three time windows: 50–130 ms (with the effect of Hand approaching significance), 250–400 ms (with the effect of Number approaching significance), and 500–700 ms (with the interaction between Number and Hand approaching significance; the significance threshold for linear mixed-effects modeling was a standard $p = .05$, with $p < .1$ being marginally significant.).

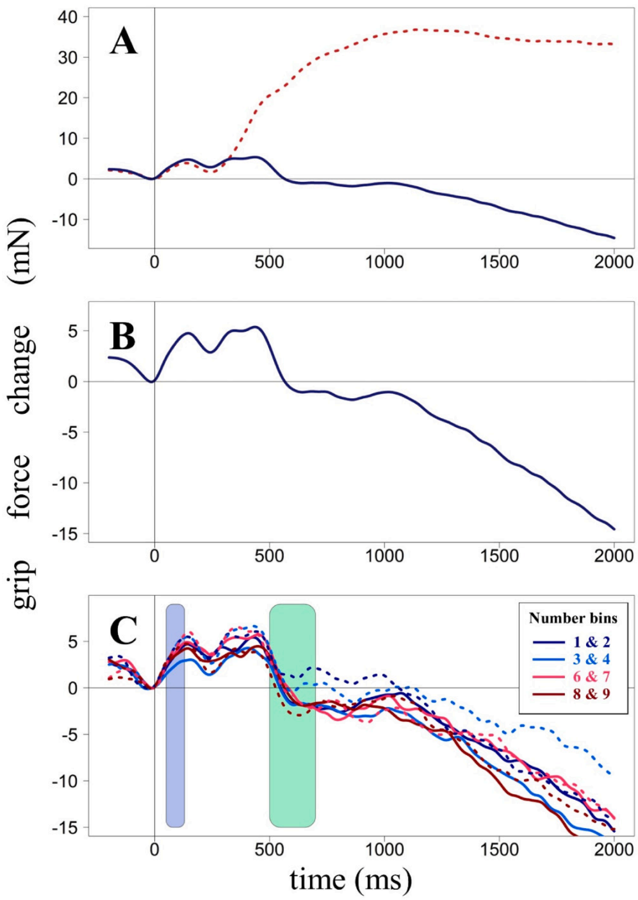


Fig. 4. Force patterns (Experiment 1).
Note. Panel A: force change in go (dotted red line) and no-go trials (solid blue line) averaged across both hands. Panel B: force in no-go trials averaged across both hands (note the magnified y-axis). Panel C: average force in left (dotted lines) and right hands (solid lines) in number bins of two for better visibility. See color coding of number bins in the legend. The blue rectangle represents the time window 50–130 ms (main effect of Hand). The green rectangle represents the time window 500–700 ms (interaction between Hand and Number, see main text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We averaged the data by Hand and Number for each participant in each time window and submitted them to a series of linear mixed models analyses using the lme4 package (Bates et al., 2015) in R. The categorical predictor Hand was sum-coded (left/right, sum-coded contrast −0.5 and 0.5, see Barr et al., 2013). All continuous predictors (Number and contralateral forces, see in this section below) were mean-centered.

2.4.1. 50–130 ms

Number (from 1 to 9 without 5, continuous) and Hand (left/right) as fixed factors and the interaction between the two were included. We included random intercepts for participants. Averaged force in the time window 50–130 ms was used as dependent variable. We performed backward elimination using the drop1 function to identify the best-fitting model; effects and interactions that did not improve model fit ($p > .1$) were successively eliminated. Only the effect of Hand remained significant, with lower force in the right hand ($b = -0.922$, $p = .018$). Marginal r-squared = 0.008; conditional r-squared = 0.414. The marginal r-squared indicates the variance explained by fixed factors (independent variables), while the conditional r-squared indicates the variance explained by the entire model, i.e., by fixed factors plus random factors (intercepts for participants, in our case; see Nakagawa & Schielzeth, 2013). See detailed results of the analysis in Table 1.

2.4.2. 250–400 ms

The same approach was applied as for the previous time window. Averaged force in the time window 250–400 ms was used as dependent variable. Neither main effect was significant, nor was the interaction between those (all p-values above 0.2).

2.4.3. 500–700 ms

The data were restructured, and the mean-centered force of each hand was used as predictor for the force of the contralateral hand (see Introduction and Section 5.4 for the discussion of this approach), along with Number (from 1 to 9 without 5, continuous) as fixed factor. Participants were included as random intercepts. We performed two analyses, one for each hand's force as dependent variable. The drop1 function was used to identify the best-fitting model; effects and interactions that did not improve model fit ($p > .1$) were successively eliminated. The main effect of interest, Number, is always reported regardless of the significance level.

When controlling for the right-hand force, we found that Number predicted left-hand force reliably: the larger the number magnitude, the lower the left-hand force ($b = -0.464$, $p = .028$; see Fig. 5; detailed results in Table 2). Marginal r-squared = 0.305; conditional r-squared = 0.588.

Even when controlling for left-hand force, we did not find a significant effect of Number on right-hand force, although its direction is as predicted: the larger the number magnitude, the higher the right-hand force ($b = 0.174$, $p = .403$; detailed results in Table 3). The marginal r-squared was 0.073, and the conditional r-squared was 0.746. Fig. 5 shows regression lines (effect of Number) for each hand separately.

2.5. Discussion

The results of Experiment 1 demonstrate that number magnitude influences grip force according to the predictions of the Mental Number Line hypothesis: smaller numbers lead to larger force in the left hand. Importantly, we observed the effect even in the absence of any semantic task related to number magnitude. The effect was, however, not significant in the right hand. Moreover, it appeared relatively late: 500–700 ms after stimulus presentation, well after the divergence point for go and no-go trials (300 ms). This observation questions the interpretation of the results: the observed SNAs might be activated automatically, i.e., in a context where magnitude information is not required for performing the task; yet they can be functionally irrelevant for number processing which should occur before 300 ms. Finally, recent work suggested that activation of SNAs requires explicit access to number meaning (Pinto, Pellegrino, Marson, et al., 2019b; Shaki & Fischer, 2018).

3. Experiment 2: magnitude classification task

We decided to explicitly investigate the spatial associations resulting from semantic processing of number magnitude and do so in a manner comparable with previous reaction time studies of the Mental Number Line (see Wood et al., 2008). Thus, we conducted a second experiment. In this experiment, we asked participants to make explicit magnitude judgments – categorize numbers as being larger or smaller than 5. Like in Experiment 1, a go/no-go paradigm was applied, and only no-go trials were analyzed.

3.1. Equipment, stimuli, and procedure

We used the same equipment, setup, and software tools as in Experiment 1. Eight Arabic digits were used as stimuli (from 1 to 9, without the number 5, the reference point). All stimuli were presented in black font on a white background. With an approximate viewing distance of 60 cm (not strictly controlled) and the width of digits 0.4 cm, the stimuli occupied 0.382 degrees of visual angle (calculated by using

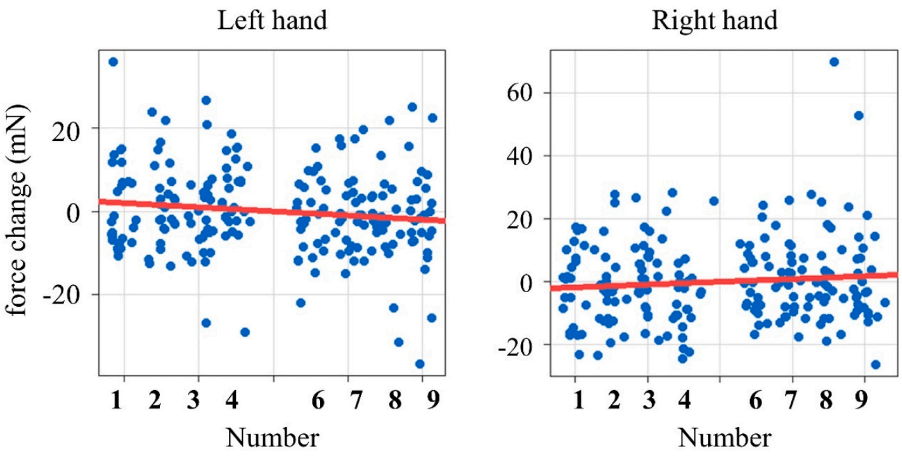


Fig. 5. Effect of Number on grip force in the left and right hands (Experiment 1, 500–700 ms).

Table 2
Main effects of Number and the contralateral hand's force on average left grip force in the time window 500–700 ms (Experiment 1).

Random effects:	Name	Variance	SD
Participants	Intercept	47.68	6.905
Residual		69.33	8.326

Fixed effects	b	SE	t-value	p-value
Intercept	0.085	1.472	0.058	0.149
Hand (right)	0.385	0.057	6.738	<0.001
Number	−0.464	0.211	2.201	0.028

Table 3
Main effects of Number and the contralateral hand's force on average right grip force in the time window 500–700 ms (Experiment 1).

Random effects	Name	Variance	SD
Participants	Intercept	175.38	13.243
Residual		66.12	8.132

Fixed effects	b	SE	t-value	p-value
Intercept	−0.545	2.658	−0.205	0.614
Hand (left)	0.301	0.068	4.410	<0.001
Number	0.174	0.208	0.837	0.403

the formula 57.3 * w/d, where w denotes the width of the object and d denotes the distance to the object). Each trial started with a fixation dot (200 ms) followed by a stimulus (a random number; 2000 ms or until response). No intertrial interval was used. In one session, participants said "yes" in response to numbers larger than five while keeping silent for smaller numbers. In another session, the instruction was reversed; the order of the two sessions was counterbalanced across participants. The experimenter was seated at another desk and coded participants' verbal responses by mouse click.

All 8 stimuli were randomly presented 50 times in each session (2 blocks separated by an obligatory break, 25 repetitions of each stimulus in a block). Overall, there were 800 experimental trials. A practice part preceded the main experiment: all stimuli appeared randomly three times. Feedback was provided during practice: after false trials, the red word "ERROR" emerged on the screen. The whole experimental part took around 40 min. After completing it, participants filled in demographic and health-related questionnaires and the Edinburg Handedness Inventory (EHI, Oldfield, 1971). The local Ethics Committee approved the study (study number 15/2019).

3.2. Participants

Initially, we collected data from 31 participants. Assuming a large effect size of $d = 1.04$ (for the magnitude classification task, see Table 1 in Wood et al., 2008), alpha = 0.05, and power = 0.80, we would require just 10 participants (G*Power v. 3.1.9.7, Faul et al., 2009). A detailed power analysis protocol is available at OSF (see Data Availability Statement).

One participant reported a motor disease (light essential tremor) which was also clearly observable in the grip force data. The data of this participant were excluded. Other participants reported having no motor diseases and taking no medications affecting motor control. All participants had normal or corrected-to-normal vision. Participants with >20 % of trials eliminated due to exceeding the pre-defined force thresholds were excluded from the analysis ($N = 1$, see Section 3.3. for details). The remaining sample consisted of 29 participants (23 females, 6 males; mean age = 25 years, range from 19 to 35 years). Fifteen participants indicated German as their native language; other native languages were Turkish, Hungarian, Chinese, Arabic, Italian, Ukrainian, Russian, Swedish, Hebrew, English, and Spanish. The mean EHI score was 75 (3 participants with EHI score lower than −50, i.e., strong left-handers; all other participants with a score between +50 and +100, i.e., strong right-handers).

3.3. Data preprocessing

The same preprocessing procedures and criteria were used as described in Experiment 1. More than 20 % of trials crossed the pre-defined force thresholds (± 500 mN) in one participant's data. We removed this participant's data from the analysis completely (also not included in the sample description). For the remaining 29 participants, on average, 4 % of trials were removed (ranging from 0 % to 16 % per participant). Accuracy was high (100 % on average, ranging from 97 % to 100 % per participant). Trials with incorrect responses were discarded from the analysis.

3.4. Main analysis and results

We observed a similar multiphasic pattern of grip force fluctuation as in our Experiment 1 and in our previous study (Miklashevsky et al. 2021). After stimulus onset, the force in no-go trials increased and reached H150, followed by a dip L200. The second peak, H380, lasted until 440 ms. A constant decrease of force until the end of the epoch followed. Force levels in go and no-go trials diverged at around 300 ms.

The force in go trials increased rapidly after this point and reached 45 mN at around 700 ms (see Fig. 6).

Force data were averaged by Number (1/2/3/4/6/7/8/9) and Hand (left / right) and submitted to a cluster permutation analysis. We deliberately excluded any time windows starting after 1000 ms from the following analysis because they do not reflect the semantic processing of numbers. However, we included effects starting before this point, even if they lasted longer and so crossed the 1000-ms point. No significant effects were found. Four time windows were the closest to significance: 10–130 ms (with the effect of Hand approaching significance), 500–1750 ms (with the effect of Number approaching significance), 180–400 ms, and 430–580 ms (with the interaction between Number and Hand approaching significance).

The data (averaged by Hand and Number for each participant in each time window) were then submitted to a series of analyses using linear mixed models with the lme4 package (Bates et al., 2015) in R (R Core Team, 2020). As in Experiment 1, the categorical predictor Hand was sum-coded (left/right, sum-coded contrast −0.5 and 0.5, see Barr et al., 2013), while continuous predictors Number, Distance-to-5 (see below), and the contralateral force were always mean-centered.

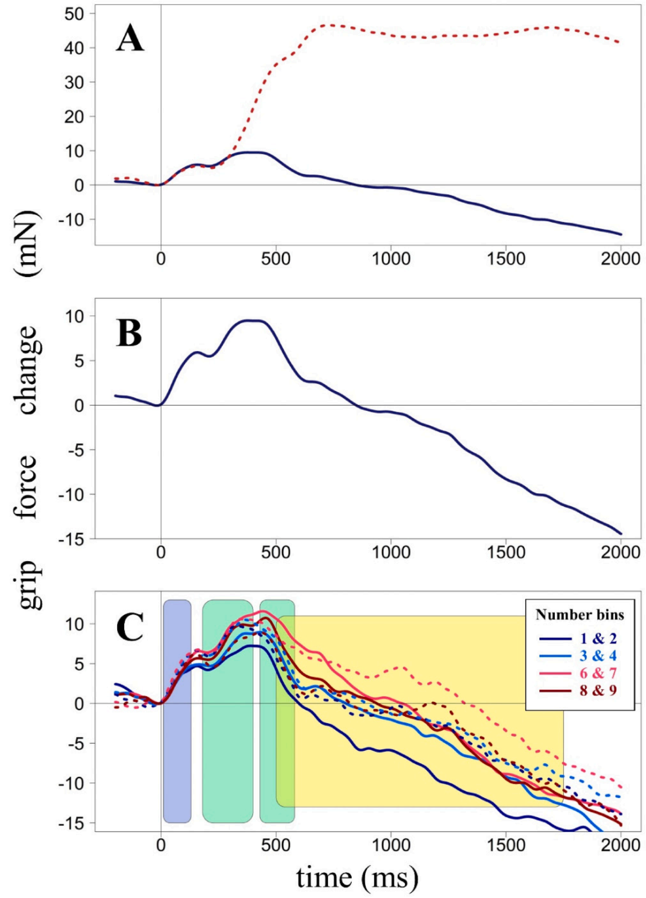


Fig. 6. Force patterns (Experiment 2)
Note. Panel A: forces in go (dotted red line) and no-go trials (solid blue line) averaged across both hands. Panel B: force in no-go trials average across both hands (note the magnified y-axis). Panel C: average force in left (dotted lines) and right hands (solid lines) in number bins of two for better visibility. See color coding of number bins in the legend. The blue rectangle represents a time window 10–130 ms (main effect of Hand). Two green rectangles represent time windows 180–400 ms and 430–580 ms (interactions between Hand and Number). The large yellow rectangle represents a time window 500–1750 ms (significant main effects of Number and Hand and the main effect of Distance-to-5 which was close to significance; see main text for details). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4.1. *10–130 ms*

Number (from 1 to 9 without 5, continuous) and Hand (left/right) were included as fixed factors. For exploratory purposes, we also included an additional variable, Distance-to-5, since magnitude comparison experiments with reaction times often demonstrate the so-called distance effect: the closer two numbers are to each other, the more difficult it is to compare them (Moyer & Landauer, 1967; van Opstal & Verguts, 2011). We coded Distance-to-5 as follows: 1 for numbers 4 and 6; 2 for numbers 3 and 7; 3 for numbers 2 and 8; 4 for numbers 1 and 9. The models included interactions between Number and Hand and between Distance-to-5 and Hand, as well as random intercepts for participants. The dependent variable was the average grip force in the 10–130 ms time window. We performed backward elimination using the drop1 function to identify the best-fitting model; effects and interactions that did not improve model fit ($p > .1$) were successively eliminated. The main effect of interest, Number, is always reported regardless of significance.

Only the effect of Hand remained significant, with lower force in the right hand ($b = -0.760$, $p = .016$). Marginal r-squared = 0.005; conditional r-squared = 0.576. Detailed results are presented in Table 4.

3.4.2. *500–1750 ms*

The same predictors and procedure were used as for the previous time window (10–130 ms), but with the averaged force in the time window 500–1750 ms as the dependent variable instead. Neither interaction was significant; thus, we removed interactions from the model. The effect of Hand was significant, with lower force in the right hand ($b = -2.548$, $p = .031$). The effect of Number was significant: increasing number magnitude led to increasing grip force ($b = 0.472$, $p = .028$). The effect of Distance-to-5 was not significant but showed a strong trend: the closer a given number was to the reference point (i.e., number 5), the larger the observed grip force ($b = -0.983$, p = .062). Removing Distance-to-5 from the model did not impact the significance of other results and only slightly reduced the percentage of explained variance. Marginal r-squared = 0.019; conditional r-squared = 0.319. Detailed results are presented in Table 5.

3.4.3. *180–400 ms*

The data were restructured, and the force of each hand was used as predictor for the force of the contralateral hand, as in Experiment 1, along with Number (from 1 to 9 without 5, continuous) and Distance-to-5 (from 1 to 4, continuous) as fixed factors. Participants were included as random intercepts. We conducted two analyses, one for each hand's force as dependent variable. The drop1 function was used to identify the best-fitting model; regression terms that did not improve model fit (p > .1) were successively eliminated. The main effect of interest, Number, is always reported regardless of significance.

When controlling for the right-hand force, we found that Number predicted the left-hand force reliably: the larger the number magnitude, the lower the left-hand force ($b = -0.371$, $p = .033$, see detailed results in Table 6). Marginal r-squared = 0.324; conditional r-squared = 0.740.

Table 4
Main effect of Hand on average grip force in the time window 10–130 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	15.54	3.942
Residual		11.56	3.399

Fixed effects	b	SE	t-value	p-value
Intercept	3.202	0.749	4.277	<0.001
Hand (right)	−0.760	0.316	−2.408	0.016

Table 5
Main effects of Hand, Number, and Distance-to-5 on average grip force in the time window 500–1750 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	71.05	8.429
Residual		160.98	12.688

Fixed effects	b	SE	t-value	p-value
Intercept	−2.841	1.672	−1.699	0.089
Hand (right)	−2.548	1.178	−2.163	0.031
Number	0.472	0.215	2.194	0.028
Distance-to-5	−0.983	0.527	−1.867	0.062

Table 6
Main effects of Number and the contralateral hand's force on average left grip force in the time window 180–400 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	81.82	9.046
Residual		51.22	7.157

Fixed effects	b	SE	t-value	p-value
Intercept	7.956	1.744	4.562	<0.001
Hand (right)	0.563	0.067	8.420	<0.001
Number	−0.371	0.173	−2.138	0.033

When controlling for the left-hand force, we found that Number predicted the right-hand force significantly: the larger the number magnitude, the higher the right-hand force (b = 0.433, p = .003, see detailed results in Table 7). Marginal r-squared = 0.256; conditional r-squared = 0.767. Fig. 7 shows regression lines (effect of Number) for each hand separately.

3.4.4. 430–580 ms

The same predictors and procedure were used as for the previous time window (180–400 ms), but with the averaged force in the time window 430–580 ms as a dependent variable instead.

When controlling for the right-hand force, we found that Number did not predict the left-hand force significantly (b = −0.312, p = .148, see detailed results in Table 8). Although non-significant, the slope was still negative: i.e., the larger the number magnitude, the lower the left-hand force. Marginal r-squared = 0.462; conditional r-squared = 0.722.

After controlling for the left-hand force, we found that Number significantly predicted the right-hand force (b = 0.599, p = .002, see detailed results in Table 9). The direction of the effect was positive: a larger number magnitude led to higher grip force. Marginal r-squared = 0.408; conditional r-squared = 0.740. Fig. 8 shows regression lines (effect of Number) for each hand separately.

Table 7
Main effects of Number and the contralateral hand's force on average right grip force in the time window 180–400 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	79.49	8.916
Residual		36.34	6.029

Fixed effects	b	SE	t-value	p-value
Intercept	7.314	1.702	4.297	<0.001
Hand (left)	0.400	0.050	8.035	<0.001
Number	0.433	0.145	2.995	0.003

3.5. Discussion

In Experiment 2, we observed significant SNAs in both hands, consistent with predictions of the Mental Number Line hypothesis: while left-hand force decreased in trials with numbers of larger magnitudes, right-hand force increased. The opposite pattern emerged for numbers of smaller magnitude. For the right hand, this effect was much stronger in Experiment 2 (b = 0.433, p = .003; time window 180–400 ms) than in Experiment 1 (b = 0.174, p = .403; time window 500–700 ms). In the left hand, the strength of the effect was comparable across Experiment 2 (b = −0.371, p = .033; time window 180–400 ms) and Experiment 1 (b = −0.464, p = .028; time window 500–700 ms). More importantly, this consistent effect of SNAs on grip force was found in Experiment 2 much earlier, already starting from 180 ms after stimulus onset and before the divergence point between go and no-go trials (300 ms). In Experiment 1, in contrast, this effect was first observed at 500 ms. The SNA-related effect in Experiment 2 continued in a further time window until 580 ms, particularly in the right hand (b = 0.599, p = .002), where it became even stronger.

Of lesser importance but still worth mentioning are two other findings. First, a significant effect of absolute number magnitude appeared in Experiment 2: increasing numbers led to larger grip force in 500–1750 ms, regardless of the hand (b = 0.472, p = .028). Second, a strong trend resembling the numerical distance effect emerged: the closer a given number was to the reference point 5, the larger the spontaneous grip force (Experiment 2, 500–1750 ms; b = −0.983, p = .062). The distance effect is a classical indicator of numerical cognition. We will discuss all these findings in more detail in General Discussion.

4. Additional analyses

In the main analyses, we used the cluster permutation method as an exploratory technique to identify time windows for further processing. We analyzed all time windows where relatively significant results emerged (i.e., the threshold was different in different experiments, mostly around p = 0.2 or 0.3). However, only when further linear mixed-effects modeling confirmed the results' significance did we claim them as a finding and interpret them.

Nevertheless, the use of the cluster permutation analysis for data exploration and the following use of a confirmatory linear mixed-effects modeling on the same data might be seen as a problematic practice (so-called circular analysis, see Kriegeskorte et al., 2009). To increase reliability of our results, we applied a more widely accepted approach: in each of the two present experiments, we split the data from 0 ms to 1000 ms into consecutive time bins of 50 ms each, i.e., 20 time bins per experiment. (Note that in the main analysis, we also focused on the first 1000 ms after stimulus onset and did not analyze effects starting after 1000 ms.) Then we applied the same linear mixed-effects models as described in the previous section to each of the resulting 20 time bins. Below, we briefly describe our results and compare them with those received in the main analysis. P-values for each relevant model term in each time bin are reported in Appendix A, and processing scripts for these additional analyses are available online (see Data Availability Statement).

4.1. Experiment 1

We ran the initial model used in Experiment 1 (i.e., with fixed terms for Number, Hand, and Number × Hand interaction) on every consecutive 50 ms time bin. The resulting p-values are shown in Table A1 (see Appendix A). We found a significant effect of Hand in the interval 50–150 ms, with lower force exhibited by the right hand. This result corresponds to the one observed in the main analysis reported above, namely the same effect of Hand in the time window 50–130 ms suggested by the cluster permutation analysis (see Table 1). We also found an interaction between Number and Hand close to significance (p-values

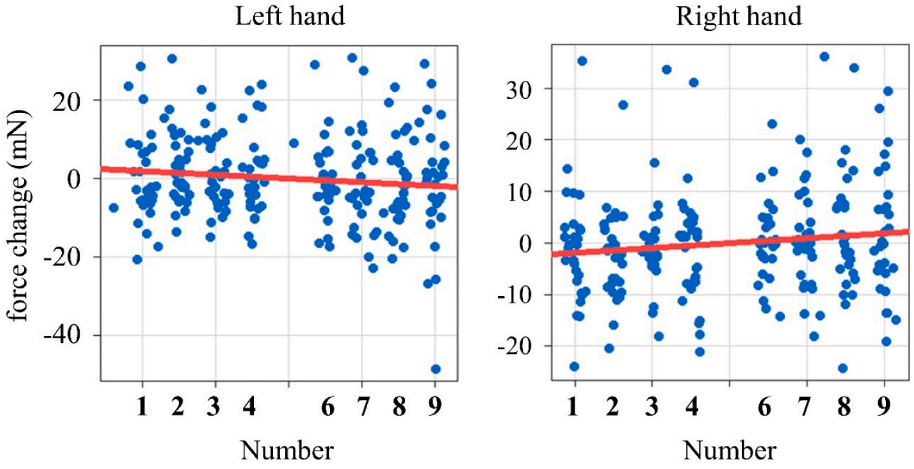


Fig. 7. Effect of Number on grip force in the left and right hands (Experiment 2, 180–400 ms).

Table 8
Main effects of Number and the contralateral hand's force on average left grip force in the time window 430–580 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	73.98	8.601
Residual		78.86	8.880

Fixed effects	b	SE	t-value	p-value
Intercept	6.906	1.700	4.062	<0.001
Hand (right)	0.658	0.056	11.778	<0.001
Number	−0.312	0.216	−1.445	0.148

Table 9
Main effects of Number and the contralateral hand's force on average right grip force in the time window 430–580 ms (Experiment 2).

Random effects	Name	Variance	SD
Participants	Intercept	83.45	9.135
Residual		65.52	8.094

Fixed effects	b	SE	t-value	p-value
Intercept	7.304	1.778	4.109	<0.001
Hand (left)	0.557	0.049	11.469	<0.001
Number	0.599	0.194	3.084	0.002

$< .2$) in the time window 550–750 ms, which generally corresponds to the time window 500–700 ms suggested by the cluster permutation. Finally, we observed a main effect of Number in the time window 600–750 ms, with larger numbers leading to overall lower force. The cluster permutation analysis did not suggest this last time window; thus, it was not examined in the main analysis.

Next, we restructured data in the same way as we did in the main analysis, i.e., we examined each force separately while including the contralateral force as a covariate. This resulted in 20 models for each hand. Again, we observed a significant effect of Number on the left force in the time window 550–750 ms, with larger numbers leading to lower left force (see *p*-values in Table A2 in Appendix A). This result corresponds to the one observed in the main analysis for the time window 500–700 ms (cf. Table 2). As in the main analysis above (cf. Table 3), no significant effect of Number on the right force was found.

4.2. Experiment 2

We followed the same approach as for Experiment 1 but included the variable Distance-to-5 in all additional analyses for Experiment 2, as it was done in the initial model in the main analysis above. All *p*-values for the main effects of Number, Hand, and Distance-to-5, as well as for the Number × Hand interaction, are provided in Table A3 in Appendix A.

We found a significant main effect of Hand in the time window 50–150 ms, with larger grip force in the left hand compared to the right hand. This result is similar to the one observed in the main analysis above, with the same effect found in the time window 10–130 ms (see Table 4). There was a significant main effect of Distance-to-5, with force decreasing as Distance-to-5 increases in the time window 500–550 ms. In our main analysis, we observed the same pattern for a larger time window 500–1750 ms. Note that we did not examine time bins after 1000 ms in this additional analysis, while the effect of Distance-to-5 remains close to significance also after 550 ms (*p*-values from 0.063 to 0.242, see Table A3 in Appendix A). It is then possible that this effect gained significance after 1000 ms, and the cluster permutation procedure merged these different time windows into one cluster.

We did not find either a main effect of Number or a main effect of Hand after 500 ms, as it was suggested by the cluster permutation procedure and confirmed by linear mixed-effects modeling (cf. Table 5). Nevertheless, *p*-values for the effect of Hand start decreasing after 800 ms in our additional analysis and reach 0.115 by the time bin 950–1000 ms (see Table A3 in Appendix A). It is then possible that there is a significant effect of Hand starting after 1000 ms, which we did not explore for the reasons explained above in the manuscript.

A significant interaction between Number and Hand was found in the time window 250–350 ms, which largely corresponds to the first time window suggested by the cluster permutation in the main analysis (180–400 ms). The second time window identified in the main analysis (430–580 ms) did not yield a significant interaction; yet, the *p*-values in the closest time window, 450–600 ms, were all below 0.2.

Finally, we restructured data in the same way as we did in the main analysis, i.e., we analyzed forces separately and included a contralateral force in each analysis as a covariate. We then run 20 models on each hand's force and reported p-values for all terms and time bins in Table A4 (see Appendix A). We found a significant main effect of Number on the left force in the time window 250–350 ms, with larger numbers leading to lower force in the left hand. This result is very similar to the one observed in the main analysis for the time window 180–400 ms (see Table 6). We did not find the same effect around the time window 430–580 ms identified in the main analysis (see Table 8). However, p-values in time bins between 450 ms and 600 ms ranged from 0.110 to 0.219.

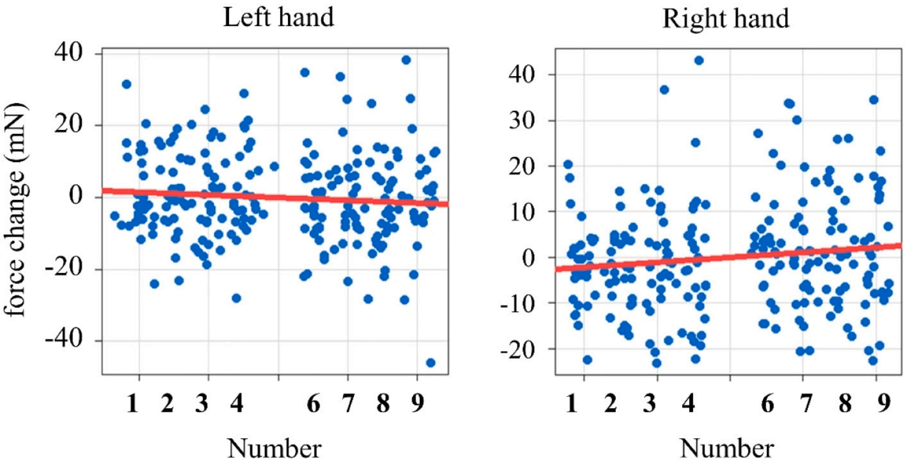


Fig. 8. Effect of Number on grip force in the left and right hands (Experiment 2, 430–580 ms).

There was a strong significant main effect of Number on right force starting at 200 ms and lasting until the end of the analyzed interval, i.e., until 1000 ms. Larger numbers led to a larger right force, as we also observed in the main analysis (cf. Tables 7 and 9). It seems that the cluster permutation analysis split this effect into two time windows (180–400 ms and 430–580 ms), probably due to the impact of the significant effect in the left hand only found at 180–400 ms but not at 430–580 ms. This strong and long-lasting effect of Number on the right force could also be responsible for the discrepancies between the two kinds of analyses described before, namely for the effects of Number and Hand found in the cluster permutation analysis for the time window 500–1750 ms, but absent in this additional analysis.

Like in our main analyses, no effect of Distance-to-5 was found in separate analyses of right or left forces.

To summarize, the results of the additional analyses largely overlap with those obtained in the main analyses. It is particularly true for the most crucial effects: interactions between Number and Hand and the main effects of Number on the right and left forces analyzed separately.

5. General discussion

5.1. Summary of results and comparison to other studies

The present study addressed the question whether and when small vs. large numbers are spontaneously associated with the left vs. the right hand, thereby creating ubiquitous spatial-numerical associations (SNAs). We extended our previous research with bimanual force recording during number processing (Miklashevsky et al., 2021) using a novel methodological approach – controlling for simultaneous force variability in both hands when estimating the effect of interest. In our previous study, we used a 1-back task, which has one crucial disadvantage: it requires participants to keep one number in their working memory while processing another number on the screen (Chen et al., 2008). This method might led to more noise in the data since both magnitudes were present simultaneously, thus revealing no SNAs.

In our current study, we manipulated experimental tasks across two experiments: a more superficial number identification task ("Is it number or letter?") was used in Experiment 1, and a semantically deeper magnitude classification task ("Is this number larger or smaller than 5?") was used in Experiment 2. Like in Miklashevsky et al. (2021), we applied a go/no-go paradigm with verbal responses in go trials. Only data from no-go trials were analyzed. Participants held two grip force sensors, one in each hand, with a constant pressure level. Our experimental task did not require lateralized voluntary motor responses. Lateralized associations and attentional shifts caused by the experimental method itself, e.g., by presenting stimuli on the left or on the right side, were also excluded through our task design. Thus, any observed changes in grip force across hands should only be related to conceptual processing. Another advantage of this method, compared to previous reaction time studies, is that it allowed us to examine the exact timing of the effects – millisecond by millisecond, as SNAs unfold. With this method, we demonstrated SNAs' sensitivity to the experimental task: superficial number processing led to later and weaker SNAs. In contrast, a deeper semantic task resulted in earlier and stronger SNAs.

In Experiment 1, we found a significant SNA effect: When controlling for the force of the contralateral hand, we observed a significant negative relationship between the number magnitude and the left grip force and a positive (yet far from significant) relationship between the number magnitude and the right grip force. This effect emerged rather late (500–700 ms after stimulus onset), long after the grip forces in go and no-go trials started diverging (300 ms). If our hypothesis about the multiphasic force pattern is correct, the divergence point signals that all steps necessary for performing the cognitive task are completed and preparation/execution of the vocal response starts. In this case, the SNA effect in Experiment 1 can reflect nothing more than post-processing associations (secondary embodiment, see Meteyard et al., 2012) but not the obligatory recruitment of previous embodied experiences as part of the retrieval of number concepts, as postulated by embodied cognition theory (Fischer, 2012). However, even if we do not see any evidence that these SNAs are related to the processing of number semantics, their activation is remarkable: neither the presentation of stimuli nor the participants' responses required lateralized activity (Shaki & Fischer, 2018), and still, the SNA effect appeared. The average reaction time in various number processing tasks is around 600 ms (see Wood et al., 2008, Table 1). If SNAs are *always* activated regardless of the task (and our Experiment 1 had minimal processing requirements), then the period 500–700 ms after stimulus onset would be the right time window for SNAs to interfere with response execution. This is exactly the time window where we found significant SNAs in Experiment 1. This part of the argument complies with the dual-route model (Gevers, Ratinckx, et al., 2006a; Gevers, Verguts, et al., 2006b) and recent experimental evidence (e.g., Pinto, Pellegrino, Marson, et al., 2019b). However, the results of our Experiment 1 suggest that the number concepts themselves can activate spatial representations even without any lateralized voluntary response. Our finding is in conflict with the claim that SNAs become only activated if the task requires participants to direct their attention to the horizontal dimension (e.g., Pinto, Pellegrino, Lasaponara, et al., 2019a, Experiment 3) and suggests that such fine-grained distinctions within the numerical domain are not necessary for SNAs to emerge.

In Experiment 2, we observed even stronger and earlier activation of SNAs, this time in both hands. Larger number magnitudes led to weaker force in the left hand and stronger force in the right hand already at 180–400 ms. This effect emerged before the divergence point (300 ms) and much earlier than the average reaction time in the previous study

(600 ms). Thus, this effect satisfies at least two of the three necessary criteria for concept embodiment as formulated by Pulvermüller (2012, p. 442): it is (1) immediate, i.e., occurs already around 100–200 ms, and (2) automatic, since no spatial information is explicitly involved in the task. The third criterion suggested by Pulvermüller, functional relevance, can only come from brain stimulation studies (such as Rusconi et al., 2013) or clinical research (e.g., Zorzi et al., 2002). The timing of the SNA effect and its sensitivity to an experimental task provide thus a not sufficient yet necessary piece of evidence of the spatial associations' functional role in number processing.

The effect of SNAs was equally strong in the left hands' grip force across both experiments, despite its variable timing; yet we observed systematic differences in the right hand. No significant effect could be seen in the right hand in Experiment 1, while in Experiment 2, the effect emerged early (180 ms) and became, with time, even more substantial (up to 580 ms). The asymmetry and timing differences might relate to the lateralization of number representations in the brain, which is currently debated (Arsalidou et al., 2018).

Interestingly, Keus et al. (2005) found electrophysiological SNA signatures at parietal electrode Pz in a parity judgment task in two time windows: 200–239 ms and 520–635 ms after stimulus presentation. The authors interpreted these signatures as mere artifacts, reflecting larger and later response-related processes. Yet, no motor response was required in our present study, but we still found SNAs at 180–400 ms and 430–580 ms in Experiment 2 using the magnitude classification task. Note that these two time windows largely overlap with those found by Keus et al. Our result suggests that the signatures identified before by Keus and colleagues might also reflect meaningful number processing rather than stem from response mapping alone.

Our study is similar to Shaki and Fischer's (2018) approach, where an implicit association paradigm was used with only one response button to eliminate lateralized responses. However, there is one key difference between the two studies: Shaki and Fischer used blocks of stimuli where numbers were combined with left- or right-pointing arrows, i.e., spatial information was explicitly included in the stimuli set. Our study did not manipulate spatial information on any explicit aspect (stimuli, primary task, or response). Closer examples would be eye-tracking studies, such as the study by Myachykov et al. (2016), who found SNAs in spontaneous ocular drift during number processing, or a recent study by Salvaggio et al. (2022), whose results demonstrate SNA-consistent covert attention shifts (measured through changes in pupil size). Similar to these two latter studies, our paradigm registers SNAs without any explicit motor response.

5.2. *Timing of effects*

Taken together, the timing and lateralization of the effects in our two experiments suggest that SNAs are highly context-dependent: in some contexts, they might be mere byproducts of number processing, activated late and without any functional relevance, like in our Experiment 1. In such cases, SNAs might be not only useless but even counterproductive for the task performance: this is a piece of irrelevant information that might slow reaction times (cf. Pressigout et al., 2019; see also Cipora et al., 2020, for a detailed discussion on this). Under different task requirements, SNAs might come much earlier and support semantic processing, serving as an “access point” for number magnitude information (like in our Experiment 2). In our Experiment 2, both the main effect of number on force (increasing force with increasing magnitude regardless of the hand, cf. size effect in RT studies, Parkman, 1971) and the distance effect (a hallmark of numerical cognition, Moyer & Landauer, 1967) appear only after SNAs, i.e., at 500–1750 ms. More generally, not only different symbolic formats “attached” to a general magnitude processing mechanism might be at play, as, for example, the triple-code model by Dehaene (1992) suggests. This central magnitude processing mechanism itself might consist of multiple subcomponents (representational “tools”). The activation of such tools depends on the current task (Cipora et al., 2020; Hartmann & Mast, 2017; Pinto et al., 2021), experimental setup (Petrizzo et al., 2021), learning history, or individual mental strategies to cope with the task (see Krause, 2014; also Sixtus, 2018, on the idea of multiple magnitude representation mechanisms; Weis et al., 2018). In line with the idea of multiple codes is the finding by Schroeder et al. (2016): even when SNAs are neutralized by using transcranial direct current stimulation, performance in processing number magnitude can remain intact, perhaps due to other representational magnitude codes still available to participants.

5.3. *Limitations and alternative explanations*

One could argue that our number identification task (Experiment 1) is not semantic-free, by analogy with the lexical decision task which also involves semantic processing to some extent (Hauk et al., 2006). Indeed, there are even more asemantic tasks, e.g., font color identification, where no SNAs (Schroeder et al., 2017) or very weak SNAs in only some groups of participants (Bull et al., 2013) were found. However, this consideration does not wave away two factors: (1) magnitude information is not necessary for performing our number identification task, and thus its activation can be called automatic in that sense; (2) even if some semantic processing is present in Experiment 1, the key difference between our two experiments is the *depth* of semantic processing, and thus any differences in results should be attributed to this parameter.

The absence of a significant effect for the right hand in Experiment 1 could be attributed to the linguistic markedness effect, for example, if all yes-responses were associated for participants with the right side and all no-responses with the left side. This effect has been found in number processing for parity status: odd numbers are associated with the left side, while even numbers are associated with the right side (Nuerk et al., 2004). However, remember that all our trials of interest were no-go trials. Participants were not required to make a no-response at all: only yes-responses were required (go-trials); otherwise, participants should refrain from any response (no-go trials). Even if we assume that participants mentally construed such an opposition (yes-response vs. no response as a “silent” no-response), this should hold for both experiments and would have led to the same pattern (no significant effect in the right hand) in Experiment 2. The opposite was the case: in Experiment 2, the effect was even stronger in the right hand, while the go/no-go paradigm remained essentially the same. Moreover, only a significant three-way interaction (markedness × number magnitude × hand) could lead to the pattern observed in Experiment 1, which would generally support our idea of automatic SNAs activation. Nevertheless, this activation should be stronger in Experiment 2 than in Experiment 1, given a deeper magnitude-related task in Experiment 2. Thus, we do not see how linguistic markedness can explain our results.

We acknowledge that other cognitive mechanisms of number processing might be reflected in grip force oscillations, such as an association between number magnitude and hand aperture. For example, Andres et al. (2004, 2008) found an association of large numbers with the power grip and small numbers with the precision grip. This association could be taken to predict an increased grip force in both hands for smaller numbers due to a narrow precision grip and decreased grip force for larger numbers resulting from a wider power grip. Yet, this was not what we observed in our study. One crucial difference between that earlier work and our study might be that an active movement was performed in studies on hand aperture and number processing, while no active movement was required in our current study.

Another possible source of predictions could be A Theory of Magnitude (ATOM), suggested by Walsh (2003, 2015). According to it, all quantitative dimensions (such as number, space, time, sound intensity, etc.) are processed by a common neurocognitive mechanism, which should lead to automatic priming across these dimensions. Suppose this would be true in our study, and grip force was controlled by the same structures responsible for processing number magnitudes. In that case, we could expect the grip force in both hands to increase for large numbers and decrease for small numbers, as ATOM does not specify lateralized predictions. Again, this is not the pattern we observed in our results.

5.4. *Statistical approach used in our study*

In our study, we used two main statistical methods: cluster permutation analysis and linear mixed-effects modeling. In the cluster permutation analysis, a random structure of the data is created by shuffling the labels of conditions. A t-statistics is then calculated, and the mass of the clusters exceeding a significance threshold is stored. This procedure repeats multiple times, which results in a distribution of cluster masses for a random data structure. The comparison between bootstrapped cluster masses and the actual cluster mass provides an estimation of the likelihood of the observed result under a random data structure (Maris & Oostenveld, 2007). We applied cluster permutation analysis as an exploratory technique that helped us identify time windows of interest, while linear mixed-effects modeling was the main confirmatory analysis. Only if we identified a significant effect or interaction by using mixed-effects models did we claim such effects or interactions as meaningful findings and interpret them.

Note that, unlike reaction times, grip force data are continuous, and deciding which time windows should be analyzed is crucial. Previous studies using force registration faced the same problem and either aggregated force in time windows predicted by the theory (e.g., Aravena et al., 2012) or split data into consecutive time bins, e.g., of 50 ms each, and analyzed them (e.g., Labrecque et al., 2016). Selecting time windows a priori based on theory might look like the best practice; however, it requires such theories to be available. Moreover, this approach will miss all effects outside predefined time windows (see Groppe et al., 2011). Since there have not been many studies on number processing using force registration, it would be challenging to predefine our time windows of interest by relying on an ad hoc theoretical approach. Cluster permutation analysis has clear advantages compared to analyzing multiple consecutive time bins: first, it accounts for dependencies across data points, i.e., it considers entire force profiles rather than means of time bins as if these time bins are independent of each other. Second, splitting data into consecutive time bins can mask significant effects which start at the end of one time bin and end at the beginning of the next time bin: Data containing such effects become averaged with larger portions of irrelevant data. The cluster permutation method is free of this limitation.

However, no method is perfect, and the cluster permutation analysis is no exception. For example, Sassenhagen and Draschkow (2019) write that cluster permutation analysis does not always precisely define the beginning and endpoint of each cluster. Specifically, they observed that high noise and small samples shift effects found in cluster permutation backward in time. Also, cluster permutation analysis can overestimate the effects' duration since the whole cluster's power may carry forward points at its margins (Sassenhagen & Draschkow, 2019). Thus, cluster permutation is good at identifying the presence of effects at costs of temporal precision (Groppe et al., 2011; Maris & Oostenveld, 2007).

We conducted a series of analyses with the data split into consecutive 50 ms time bins to cross-check our results and increase the reliability of our findings. These analyses yielded results very similar to those obtained in the main analyses, both in terms of main effects and interactions and their timing. Several differing findings across the two methods do not affect our main conclusions. Nevertheless, registering grip force as a measure of cognitive processes is a relatively recent development, and statistical analysis of force data should be further refined in future studies.

Another novelty of our approach is using the contralateral force as a covariate in analysis, as we discussed in the introduction. The opposite hand's force as a predictor was used to account for the correlation of forces due to automatic coordination between hands (Mathew et al., 2020). We believe this approach is necessary when working with lateralized stimuli or stimuli with lateralized semantics, such as numbers in the context of the Mental Number Line hypothesis. Our goal was to dissociate the effect of force increase in one hand due to our experimental manipulation from an automatic force increase in the other hand (cf. Fig. 4C) due to lower-level physiological mechanisms of hand coordination. Future studies using bimanual force registration should pay special attention to the analysis of force data and take into account bilateral hand coordination when estimating the effects.

6. Conclusions

We conducted two experiments using grip force registration during number processing. In both experiments, participants held two grip force sensors horizontally, one in each hand. No lateralized voluntary motor responses were required, but vocal responses in go trials. All stimuli of interest were presented centrally and only in no-go trials. This method excludes lateralized attentional shifts and body movements. The number semantics itself is then arguably responsible for any observed effects. In Experiment 1, we used a superficial numerical decision task ("Is it a number or a letter?") that did not require much semantic processing. In Experiment 2, we used a deeper magnitude judgment task ("Is this number larger or smaller than 5?") that activated number meaning, as indicated by the distance effect.

We observed systematic spontaneous grip force changes as a function of number magnitude in both experiments. These changes were compatible with the Mental Number Line account: smaller numbers led to increasing force in the left hand; larger numbers led to a force increase in the right hand. This pattern emerged relatively late in the numerical decision task (500–700 ms after stimulus onset) and was only significant in the left hand. In the magnitude judgment task, the effect appeared earlier (180 ms), lasted longer (until 580 ms), and was significant in both hands. It was particularly pronounced in the right hand. We hypothesize that Spatial-Numerical Associations (SNAs) are neither a byproduct of numerical processing nor a necessary part of it: their exact role is highly dependent on contextual factors, such as task in our case.

Funding statement

This work was supported by the German Research Foundation (DFG) grant FI 1915/5-2 "Motor priming from an embodied cognition perspective: A forceful dynamical test with numerical tasks" awarded to Martin H. Fischer. We also acknowledge the support of the Open Access Publishing Fund of the University of Potsdam and the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation; project number 491466077) covering publication costs. The funding agencies were not involved in study design, data collection, analysis and interpretation, writing the report, or the decision to submit the manuscript for publication.

Declaration of competing interest

None.

Data availability

The datasets generated for this study and processing scripts can be found in the Open Science Framework (OSF) at https://osf.io/tbqa3/.

Acknowledgments

We thank Christoph Scheepers for his valuable advice on using mixed effect models and Mengxiao Wang, who helped us with the data collection in Experiment 2 during her internship in the Potsdam Embodied Cognition Group.

Appendix A. Additional analyses for Experiments 1 and 2

Table A1
Summary of the results of the additional analyses for Experiment 1 (50-ms consecutive time intervals; main effects of Hand and Number and Number × Hand interaction).

Time interval	Effect of Number	Effect of Hand	Number x Hand interaction
0-50 ms	.824	.458	.439
50-100 ms	.893	**.031**	.561
100-150 ms	.732	**.011**	.502
150-200 ms	.721	.087	.610
200-250 ms	.581	.816	.467
250-300 ms	.343	.738	.474
300-350 ms	.344	.094	.367
350-400 ms	.491	.100	.753
400-450 ms	.242	.325	.558
450-500 ms	.221	.657	.279
500-550 ms	.245	.966	.244
550-600 ms	.100	.734	.141
600-650 ms	**.044**	.361	.168
650-700 ms	**.015**	.161	.115
700-750 ms	**.049**	.064	.161
750-800 ms	.092	.065	.232
800-850 ms	.132	.109	.308
850-900 ms	.140	.330	.389
900-950 ms	.065	.355	.285
950-1000 ms	.068	.324	.319

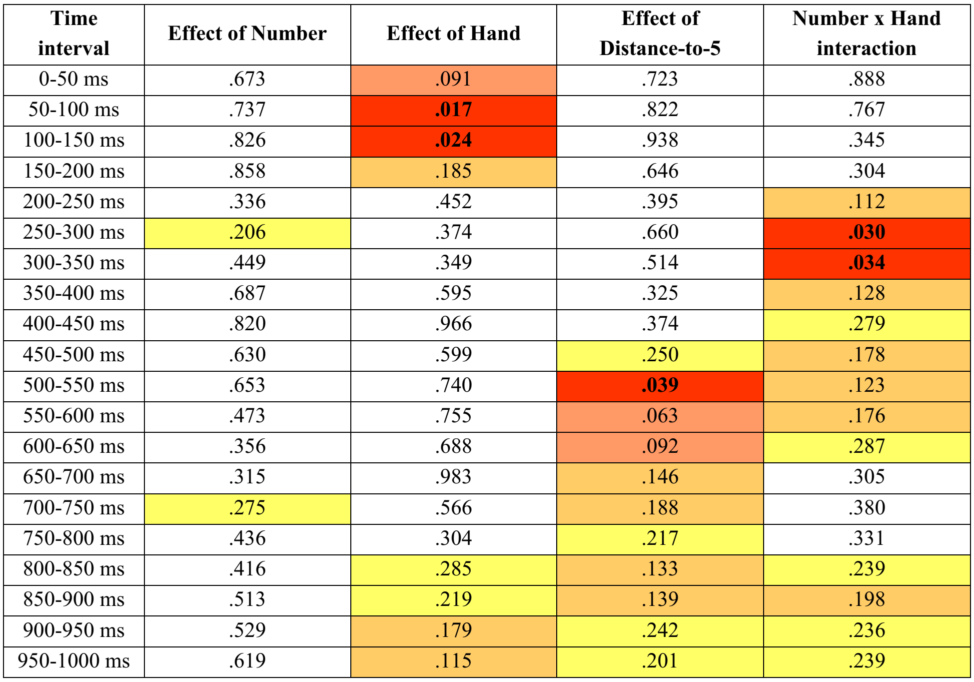
Note. Each line represents a full linear mixed-effects model (i.e., including Number, Hand, and their interaction) run on a 50-ms time interval. Only *p*-values are provided in the table (not corrected for multiple comparisons). Significant values ($p < .05$) are shown in bold. See OSF (Data Availability statement) for processing scripts.
Color coding of cells: red color denotes *p*-values under 0.05; dark-orange color denotes *p*-values between 0.1 and 0.05; light-orange color denotes *p*-values between 0.2 and 0.1; yellow color denotes *p*-values between 0.3 and 0.2.
Use the function tab_model in scripts on OSF to receive full statistics for each term in each model.

Table A2
Summary of the results of the additional analyses for Experiment 1 (50-ms consecutive time intervals; main effect of Number on each hand's force with the contralateral force as a covariate).

Time interval	Effect of Number (left hand)	Effect of Number (right hand)
0-50 ms	.852	.165
50-100 ms	.832	.283
100-150 ms	.533	.375
150-200 ms	.558	.539
200-250 ms	.396	.427
250-300 ms	.254	.607
300-350 ms	.204	.407
350-400 ms	.511	.998
400-450 ms	.261	.950
450-500 ms	.120	.337
500-550 ms	.115	.275
550-600 ms	**.036**	.247
600-650 ms	**.027**	.598
650-700 ms	**.014**	.767
700-750 ms	**.046**	.681
750-800 ms	.082	.593
800-850 ms	.124	.645
850-900 ms	.148	.792
900-950 ms	.059	.788
950-1000 ms	.062	.745

Note. Each line represents two full linear mixed-effects model (i.e., including Number and the contralateral force as a covariate) run on a 50-ms time interval. Only *p*-values are provided in the table (not corrected for multiple comparisons). Significant values ($p < .05$) are shown in bold. See OSF (Data Availability statement) for processing scripts.
Color coding of cells: red color denotes *p*-values under 0.05; dark-orange color denotes *p*-values between 0.1 and 0.05; light-orange color denotes *p*-values between 0.2 and 0.1; yellow color denotes *p*-values between 0.3 and 0.2.
Use the function tab_model in scripts on OSF to receive full statistics for each term in each model.

Table A3
Summary of the results of the additional analyses for Experiment 2 (50-ms consecutive time intervals; main effects of Hand, Number, and Distance-to-5 and Number × Hand interaction).



Time interval	Effect of Number	Effect of Hand	Effect of Distance-to-5	Number x Hand interaction
0-50 ms	.673	.091	.723	.888
50-100 ms	.737	**.017**	.822	.767
100-150 ms	.826	**.024**	.938	.345
150-200 ms	.858	.185	.646	.304
200-250 ms	.336	.452	.395	.112
250-300 ms	.206	.374	.660	**.030**
300-350 ms	.449	.349	.514	**.034**
350-400 ms	.687	.595	.325	.128
400-450 ms	.820	.966	.374	.279
450-500 ms	.630	.599	.250	.178
500-550 ms	.653	.740	**.039**	.123
550-600 ms	.473	.755	.063	.176
600-650 ms	.356	.688	.092	.287
650-700 ms	.315	.983	.146	.305
700-750 ms	.275	.566	.188	.380
750-800 ms	.436	.304	.217	.331
800-850 ms	.416	.285	.133	.239
850-900 ms	.513	.219	.139	.198
900-950 ms	.529	.179	.242	.236
950-1000 ms	.619	.115	.201	.239

Note. Each line represents a full linear mixed-effects model (i.e., including Number, Hand, Distance-to-5, and Number × Hand interaction) run on a 50-ms time interval. Only *p*-values are provided in the table (not corrected for multiple comparisons). Significant values ($p < .05$) are shown in bold. See OSF (Data Availability statement) for processing scripts.
Color coding of cells: red color denotes *p*-values under 0.05; dark-orange color denotes *p*-values between 0.1 and 0.05; light-orange color denotes *p*-values between 0.2 and 0.1; yellow color denotes *p*-values between 0.3 and 0.2.
Use the function tab_model in scripts on OSF to receive full statistics for each term in each model.

Table A4

Summary of the results of the additional analyses for Experiment 2 (50-ms consecutive time intervals; main effects of Number and Distance-to-5 on each hand's force with the contralateral force as a covariate).

Time interval	Left hand		Right hand	
	Effect of Number	Effect of Distance-to-5	Effect of Number	Effect of Distance-to-5
0-50 ms	.819	.425	.597	.218
50-100 ms	.715	.213	.841	.270
100-150 ms	.434	.926	.142	.860
150-200 ms	.361	.726	.077	.943
200-250 ms	.073	.312	**.032**	.837
250-300 ms	**.011**	.546	**.002**	.837
300-350 ms	**.020**	.607	**.001**	.940
350-400 ms	.073	.507	**.006**	.854
400-450 ms	.275	.851	**.018**	.572
450-500 ms	.231	.879	**.004**	.453
500-550 ms	.110	.777	**.001**	.240
550-600 ms	.219	.365	**.003**	.679
600-650 ms	.474	.437	**.012**	.640
650-700 ms	.515	.887	**.011**	.209
700-750 ms	.715	.946	**.023**	.270
750-800 ms	.623	.729	**.030**	.509
800-850 ms	.591	.473	**.011**	.567
850-900 ms	.533	.434	**.009**	.583
900-950 ms	.607	.482	**.014**	.702
950-1000 ms	.599	.531	**.019**	.562

Note. Each line represents two full linear mixed-effects model (i.e., including Number, Distance-to-5, and the contralateral force as a covariate) run on a 50-ms time interval. Only *p*-values for Number and Distance-to-5 are provided in the table (not corrected for multiple comparisons). Significant values ($p < .05$) are shown in bold. See OSF (Data Availability statement) for processing scripts.

Color coding of cells: red color denotes *p*-values under 0.05; dark-orange color denotes *p*-values between 0.1 and 0.05; light-orange color denotes *p*-values between 0.2 and 0.1; yellow color denotes *p*-values between 0.3 and 0.2.

Use the function tab_model in scripts on OSF to receive full statistics for each term in each model.

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