Title: Influences of hand action on the processing of symbolic numbers: a special role of pointing?

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Abstract (198 words)

Embodied and grounded cognition theories suggest that cognitive processes are built upon sensorimotor systems. In the context of studies on numerical cognition, interactions between number processing and the hand actions of reaching and grasping have been documented in skilled adults, thereby supporting embodied and grounded cognition accounts. The present study made use of the neurophysiological principle of neural adaptation applied to repetitive hand actions to test the hypothesis of a functional overlap between neurocognitive mechanisms of hand action and number processing. Participants performed repetitive grasping of an object, repetitive pointing, repetitive tapping, or passive viewing. Subsequently, they performed a symbolic number comparison task. Importantly, hand action and number comparison were functionally and temporally dissociated, thereby minimizing context-based effects. Results showed that executing the action of pointing slowed down the responses in number comparison. Moreover, the typical distance effect (faster responses for numbers far from the reference as compared to close ones) was not observed for small numbers after pointing, while it was enhanced by grasping. These findings confirm the functional link between hand action and number processing, and suggest new hypotheses on the role of pointing as a meaningful gesture in the development and embodiment of numerical skills.

Keywords: numerical cognition; embodied cognition; hand action; grasping; pointing.

INTRODUCTION

The link between the mental processing of numerical information and hand action is intuitive: in everyday life, humans make use of the hands to deal with numbers. Indeed, the hands are used to visually represent numbers, to perform arithmetic calculations, to count series of items, as well as to communicate magnitude information (e.g., Andres, Di Luca, & Pesenti, 2008; Butterworth, 1999a; Hohol, Wołoszyn, Nuerk, & Cipora, 2018; Winter, Perlman, & Matlock, 2013). The use of the hands in number processing appears to be long-standing universally shared practice, since it has been observed nowadays as well as in ancient civilisations (e.g., Overmann, 2014). Interestingly, indigenous cultures world-wide represent numbers through the use of fingers, independently on the adopted numeral system, or on the richness of their language of numbers (e.g., Butterworth, 1999a); many of these cultures (e.g., Anggor and Yupno from Papua New Guinea) use also other parts of the body to count but counting starts almost always from the hand.

Many studies have investigated the role of finger use for the development of numerical skills in children. The use of the hands for counting and arithmetic is a cornerstone for the understanding and development of number concepts: for instance, finger counting can provide children with a visual representation of numbers, facilitating the link between different numerical representations (e.g., number words and Arabic numbers), and promoting the understanding of the ordinal and the cardinal number dimensions (for reviews, see: Berteletti & Booth, 2015; Crollen, Seron, & Noël, 2011). Notably, numerate adults still use hand counting to process and convey numerical information in some daily life contexts (e.g., Holol et al., 2018; Winter et al., 2013).

Both embodied and grounded theories of cognition are in line with the link between numbers and hands, suggesting that high level cognitive processes develop through sensorimotor experiences (Barsalou, 2008; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012). Grounded, embodied and situated aspects of cognition are distinct (Fischer, 2012): grounded aspects concern the fact that sensorimotor experiences and the development of cognitive skills or mental representations might be determined by universal laws (e.g., direction of gravity). Embodied aspects refer to body movements during repeated cognitive tasks (e.g., cultural habits), creating long-lasting links between sensorimotor and cognitive processes. Situated aspects concern features of a specific environmental context, which creates contingent links between sensorimotor and cognitive processes (e.g., task requirements; see also: Myachykov, Scheepers, Fischer, & Kessler, 2014). The distinction between grounded and embodied aspects of cognition somehow echoes the long-lasting debate between nature and nurture (Robinson, 2004): on the one hand, nature-determined constraints are an instance of grounded aspects, whereas introjection of cultural habits calls for the concept of embodiment.

In the context of numerical cognition, culturally-specific practices associated to the use of hands for counting and the promotion of these practices at school can be seen as *embodied* processes. Nonetheless, a number of observations suggest that mental processes related to number and hand actions are not merely determined by cultural habits, because the latter might be grounded on cognitive and neural constraints (e.g., Andres et al., 2008; Previtali, Rinaldi, & Girelli, 2011). First, several studies have shown associations between the development of fine motor skills and number knowledge (for a review, see Barrocas, Roesch, Gawrilow, & Moeller, 2020). For instance, finger gnosis (i.e., the ability to mentally represent and discriminate each finger) is predictive of number-related abilities in preschoolers (e.g., Noël, 2005), in primary school children (e.g., Penner-Wilger et al., 2007; Penner-Wilger et al., 2009), and in adults (Penner-Wilger, Waring, and Newton, 2014). Similarly, other studies have found that a variety of abilities related to

fine hand movements (e.g., drawing, precision grasping, tapping, etc.) predicts performance in number-related tasks in preschoolers (e.g., Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Suggate, Stoeger, & Fischer, 2017). Second, neuroimaging and neuropsychological studies consistently suggest the existence of common neural networks for hand action and number processes (Butterworth, 1999b). Specifically, Gerstmann's syndrome, which can occur after bilateral parietal brain damage, is characterised by the concurrent presence of acalculia, agraphia, finger gnosis, and left-right disorientation (Gerstmann, 1924; Rusconi, Pinel, Dehaene, & Kleinschmidt, 2010). Similarly, developmental syndromes affecting both number processing and finger functions have been described (developmental Gerstmann syndrome: Kinsbourne, 1968; developmental coordination disorder: Gomez et al., 2017). Consistently with neuropsychological observation, the results of neuroimaging studies show that hand-related somatosensory areas are recruited also during arithmetic tasks in children (Berteletti & Booth, 2015) and in adults (Andres, Michaux, & Pesenti, 2012), and that interfering with the activity of the angular gyrus through repetitive transcranial magnetic stimulation affect both number processes and finger knowledge (Rusconi, Walsh, & Butterworth, 2005).

Taken together, these observations support the idea that number processes are both embodied on cultural habits and grounded on neurocognitive constraints. In line with this idea, an increasing number of behavioural studies have described interactions between symbolic number processing and the hand action of reaching and grasping objects, suggesting overlapping mechanisms between the mental representation of numbers and sensorimotor processes (e.g., Grade, Badets, & Pesenti, 2017). Reaching often precedes grasping in many actions of everyday life. Nonetheless, reach to grasp actions are characterised by two distinguishable components: arm transport and hand preshaping (Jeannerod, 1999). Arm transport consists in moving the hand and arm to reach an object, thereby involving visuospatial mechanisms for processing object location and for online monitoring of the movement trajectory. Hand preshaping for grasping concerns the processes required to plan and select the correct hand configuration for grasping, and it involves object size judgments. Neuroimaging studies have reported anatomical dissociation between the two components within the frontoparietal grasp network, the neural locus of arm transport being located in more posterior parietal areas, while the neural locus of grasp preshaping being located in the anterior part of the intraparietal sulcus (e.g., Cavina-Pratesi et al., 2010, 2018).

Studies investigating the interplay between number and action have observed interactions both between symbolic number processes and hand reaching, and between symbolic number processes and hand grasping. Concerning hand reaching, previous studies have shown that processing number magnitude or number distance can influence reaching trajectories. For instance, Fischer (2003) found that leftward or rightward pointing was faster during the processing of small or large digits, respectively. Also, deviation from a standard trajectory occurs as a function of numerical distance (Song, & Nakayama, 2008), and targets consisting of larger digits biases finger trajectories more rightward as compared to smaller digits (Rugani, Betti, & Sartori, 2018). Similarly, when required to grasp and freely displace an object while performing at the same time a comparison of Arabic digits magnitude, participants systematically misplaced the object leftward while processing smaller digits as compared to larger ones (Gianelli, Ranzini, Marzocchi, Micheli, & Borghi, 2012). Finally, reach velocity while connecting with the index finger numerical stimuli on a touch screen was higher with more distant numbers than closer ones (e.g., 1-2 vs. 1-8: Girelli et al., 2016). Taken together, these interactions between number and reaching are in line with and support the well-established hypothesis of the *mental number line*, postulating that the mental representation of numbers is spatial in nature, and oriented from left to right, at least in Western societies as a possible consequence of reading and writing habits (e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005).

Concerning hand grasping, several studies have observed that number magnitude influences performance in tasks requiring grasping actions. For instance, Andres et al. (Andres, Davare, Pesenti, Olivier, & Seron, 2004) observed that, in a parity judgment task, participants were faster in initiating a closure or opening grip with smaller or larger digits, respectively. Similarly, follow-up studies found that participants are faster in initiating a precision or power grasp with smaller or larger digits respectively (Lindemann, Abolafia, Girardi, & Bekkering, 2007; Moretto, & Di Pellegrino, 2008). Lastly, Andres et al. (Andres, Ostry, Nicol, & Paus, 2008b) observed that maximal finger aperture during grasping – i.e., the Euclidean distance between index and thumb – was larger when a large digit (e.g., 8) was written on the object to be grasped compared to when the written digit was small (e.g., 2). These findings are in line with the ATOM theory (ATOM: A Theory of Magnitude) firstly proposed by Walsh (2003) and afterwards upgraded (Buetti & Walsh, 2009; Cona, Wiener, & Scarpazza, 2021; see also: Kadosh, Lammertyn, & Izard, 2008). ATOM postulates the existence of a common neurocognitive network where numerical, physical, and temporal magnitudes are commonly represented to support sensorimotor transformations. In this sense, interactions between number and grip size strongly support the ATOM theory as they can be seen as resulting from a common representation of numerical and physical dimensions during action.

Importantly, interactions between number and hand actions are bidirectional: not only numbers bias hand action, but also observing hand actions influences the processing of numbers. Specifically, several studies have shown that observing fingers depicting grip closing impacts the processing of number magnitude (Badets and Pesenti, 2010; see also Badets and Pesenti 2011), and biases random number generation (Badets, Bouquet, Ric, & Pesenti, 2012; see also Grade et al., 2017). Action-number interactions in these studies were specific for conditions where grip closing, but not grip opening, was depicted by a human hand, and not by a fake hand, demonstrating the sensorimotor nature of these effects (Badets and Pesenti, 2010; see also Badets, Bidet-Ildei, & Pesenti, 2015 for comparison between biological and non-biological movements). In a similar vein, Ranzini et al. (Ranzini, Lugli, Anelli, Borghi, & Nicoletti, 2011) observed that presenting graspable objects, as compared to ungraspable ones, enhanced the sensitivity to numerical magnitude during a subsequent number task (Experiment 1), but it reduced number magnitude sensitivity when participants were additionally required to hold an object in their hands (Experiment 2). Taken together, these bidirectional links suggest a functional relation between motor action and number processes, in agreement with embodied and grounded cognition accounts (see also: Ranzini et al., 2015; Ranzini, Lisi, & Zorzi, 2016; Felisatti et al., submitted).

In this study we sought to investigate whether the mental processing of numerical information is grounded into sensorimotor mechanisms using an experimental setting where hand action and number are processed in distinct tasks. To do this, we designed our paradigm considering neural adaptation, i.e., the progressive reduction in the neural activity of relevant brain areas following stimulus repetition, a phenomenon which has been consistently useful in neuroimaging and brain studies (Grill-Spector & Malach, 2001; Silvanto & Cattaneo, 2008). Neural adaptation paradigms have been mainly used to investigate the functioning of sensory systems (for a review see: Larsson, Solomon, & Kohn, 2016), and also to investigate the functioning of brain areas associated to cognitive or motor processing, such as number (e.g., Piazza, Pinel, Le Bihan, & Dehaene, 2007) or processes related to hand grasping (e.g., Monaco et al., 2010). In this study, participants performed repetitive grasping of an object (arm transport + grasp preshaping), repetitive pointing to the object (arm transport w/o grasp preshaping), repetitive hand tapping (motor control condition), or passively viewed at the object (motionless control condition). Subsequently, they performed the numerical task, consisting in comparing a target digit with 5 (the reference number). We were interested in the specific

effects of adaptation to arm transport and grasp preshaping on number. More precisely, we argue that number and size might be linked by a common system devoted to action for estimating both physical size (e.g., object size) and number magnitude, as predicted by ATOM, whereas number and space might be linked by a common system devoted to action for estimating both physical and numerical spatial locations and distances, as postulated in the mental number line hypothesis. In this sense ATOM and the mental number line hypothesis might highlight different aspects of the way numbers are mentally represented. The results of a recent meta-analysis of neuroimaging studies also support this view, indicating partially distinct parietal brain areas common to grasp and number processing, and to reach and number (Ranzini, Scarpazza, Radua, Cutini, Semenza, & Zorzi, under review). Interestingly, a previous study by van Dijck et al. (2015) came to a similar conclusion. In their study, participants were required to perform parity judgments while maintaining a numerical sequence in working memory. They found a compatibility between type of grip and numerical magnitude, and a compatibility between order of the item in working memory and side of response, indicating that distinct aspects of the mental representation of numbers should be functionally related to distinct motor actions.

Importantly, as compared to the above-mentioned related studies, our paradigm had two novel aspects. First, hand action and number comparison were functionally and temporally dissociated. Many experimental paradigms used to investigate bidirectionality intermix numbers and hand actions, thus requiring the participant to consider both stimuli to solve the task (e.g., to indicate the odd number within a pair when a hand closing is seen; Badets and Pesenti, 2010). Intermixed hand action and number-related processes might favour effects due to situated aspects, such as the use of implicit associative strategies: for instance, one might associate grip closing with small numbers and grip opening with large numbers, similarly to the effects of number-magnitude compatibility (Girelli, Lucangeli, & Butterworth, 2000), a point which was already addressed by previous studies (Badets & Pesenti, 2010). To avoid this concern, in our paradigm, participants performed hand action prior to number comparison, and the two tasks were unrelated and without any temporal overlap. Second, in the present study participants had to execute hand actions, instead of observing them. Previous studies have often used visual stimuli to trigger sensorimotor processes, in light of the view that observing actions recruits the same neural mechanisms involved in action execution (Buccino et al., 2001). In the context of studies on numerical cognition, interactions between observed hand action and number processing were indeed observed. However, we argue that the execution of hand actions - instead of passive hand viewing – provides a more ecological setting and a stronger test for the idea of a functional link between hand action and number processing. Importantly, the use of adaptation procedures to probe cognitive processes and the concerned neural populations (e.g., Larsson et al., 2016; Cattaneo & Silvanto, 2008) assures relatively durable changes in the neural mechanisms involved, with the consequence that biases on number processes should be safely attributed to the experimental manipulation. Some previous studies already took advantage of motor adaptation procedures to investigate the link between cognition and motor action: specifically, repeated hand motor actions have been found to affect the processing of words referring to concrete or abstract concepts (Glenberg, Sato, Cattaneo, 2008), as well as the processing of time, space and numerosity (Anobile, Arrighi, Castaldi, & Burr, 2021). Here, for the first time, we used motor adaptation to investigate the link between mechanisms involved in the representation and execution of hand action and symbolic number.

We tested two specific hypotheses:

- hypothesis 1 (HP1): functional overlap between the mechanisms of hand reaching /grasping actions and those involved in number processing predicts that the speed of number comparison should be affected by

motor adaptation: specifically, reaching and grasping repetition would affect number processing speed as compared to tapping and passive viewing. On the basis of the existing literature on the effects of fMRI adaptation (Larsson, Solomon, & Kohn, 2016), we were cautious in making clear-cut predictions about the direction of the effect, i.e., whether facilitation or interference should be observed following adaptation. Therefore, we favoured a bidirectional hypothesis;

- hypothesis 2 (HP2): based on the distinction between mechanisms for arm transport and hand preshaping (e.g., Cavina-Pratesi et al., 2010), we expected reaching (i.e., arm transport common to grasp and point actions) and grasp preshaping (specific of the grasp action) to selectively impact number processing. This idea is supported by studies highlighting interactions between number and hand grasp (e.g., Andres et al., 2008; Badets & Pesenti, 2010) and interactions between number and hand reach (e.g., Song & Nakayama, 2008; Girelli et al., 2016; see also van Dijck et al., 2015). Based on this idea, we hypothesized that adaptation to grasp preshaping (to grasp vs. other action) or to reaching (to grasp and to point vs. others) would differently impact the processing of number magnitude (small vs. large) or number distance (close vs. far numbers), effects which are usually taken as evidence of semantic processing of numbers. The hypothesis regarding the direction of these effects was bidirectional.

METHOD

Preregistration details. This study research plan was preregistered on OSF. Details on preregistration can be found [here](#). As of the date of submission of this research plan for preregistration, the data had not yet been collected, created, or realized.

Sample size and participants. We planned to test a minimum of 24 participants. We used the software program G*Power 3.1.9.4 to define this minimum sample size (planned statistical analysis: ANOVA-repeated measures; power = .99; effect size = .25; alpha error probability = .001; see the OSF registration associated to this study for further details). We planned to use Bayesian methods for data analysis, which has two major advantages. First, Bayesian methods allow to measure evidence for both the alternative and the null hypotheses. Second, as a consequence of testing of both hypotheses, these methods allow to systematically add observations until substantial evidence for one of the two hypotheses is observed. Therefore, we planned to conduct the planned analyses once data from 24 participants would be collected, and to continue data collection until we would have reached enough evidence for the alternative or the null hypothesis. The stopping rule was reached with data from 24 participants. The sample was composed by 24 Italian speakers healthy adults (mean age = 23ys, SD = 4; 16 females) with normal or correct to normal vision. Handedness was both based on self-reports and measured by use of the Edinburgh Handedness Inventory (Oldfield, 1971). All participants were right-handed (mean laterality score = 79, SD = 14; Schachter, Ransil, & Geschwind, 1987). Considering that a number of studies have disclosed the impact of hand counting direction on number processes (e.g., Göbel, Shaki, & Fischer, 2011; Hohol, Wołoszyn, Nuerk, & Cipora, 2018), we asked participants to count from 1 to 10 on their hands. The majority of participants started counting with the right-hand (right starters: N = 18). Participants were recruited through advertisements at the University of Padua and by word of mouth, and they received a reimbursement for agreeing to participate. The amount corresponding to the reimbursement was in line with the policy of the Department of General Psychology of the University of Padova. Prior to the beginning of the experimental section, each participant received and signed the informed written consent. The study conformed with the Code of Ethics of the World Medical Associations (Declaration of Helsinki), and it received the approval of the Ethical Committee for the Psychological Research of the University of Padova (Protocol number: 3174).

Materials and procedure. The experiment consisted of a within-subject design with 3 factors: Action Type (Grasp; Point; Tap; Passive view), Number Magnitude (small numbers: 1-4; large numbers: 6-9), Number Distance (close to the reference: 3-4, 6-7; far to the reference: 1-2, 8-9). The experimental session was organised in 12 blocks. At the beginning of each block participants were required to perform a washout task which consisted in stretching their arms and hands for 20 seconds in order to reset the hand motor system. This reset task was inspired by previous studies on motor adaptation (or adaptation of motor-related processes) adopting paradigms including ad-hoc washout phases (e.g., Majdandžić, Bekkering, van Schie, & Toni, 2009; Cesanek, & Domini, 2017). Then, the participant performed one condition of the motor task. The required action was indicated on the screen. Specifically the participant was required to grasp or point to an object for 16 times, to continue tapping on the table for 30 seconds, or to observe an object for 30

seconds, prior to 16 trials of number comparison. The object was a wooden cube varying in size (4 cm³ or 5 cm³) to avoid adaptation to object size across blocks. Cube size was not taken into account in the analyses. Each action within each block was repeated at self-paced timing. The end of the action was indicated by a sound. At the end of the action, the participant was instructed to place the right hand above the leg under the table, while avoiding any other type of movement. The experimenter promptly removed the object from the table and provided the participant with the microphone. Then, the number comparison task started. In number comparison, participants were presented with a number digit centrally presented on a computer screen in front of them, and they were required to judge whether the digit was larger or smaller than 5 (the set of target consisted of all digits except 5, which was used as the reference). Verbal responses were acquired with a microphone; to parcel out measurement errors due to its sensitivity, participants were trained to answer BA/BE for small/large digits (for similar procedures, see: Stoianov et al., 2008; Ranzini et al., 2015; Ranzini et al., 2016). Response mapping was counterbalanced between participants. Each participant performed a total of 192 numerical trials (4 Action Type * 8 Numbers * 6 repetitions = 192 = 12 trials per condition). All the experimental conditions were presented in a randomized order. To avoid number repetition in consecutive trials and action repetition in consecutive blocks, no full randomization was used, i.e., the list of actions and the list of digits were reset each time all the items of one list were presented once. In this way, consecutive trials with the same number, and consecutive blocks presenting the same action, were highly improbable cases. The experiment was built in EPrime (Psychology Software Tools, Pittsburgh, PA). Instructions were presented on the screen at the beginning of the session, and additionally verbally explained by the experimenter. Participants performed a short training before the experimental trials, consisting of a block of motor actions (that included all the motor actions required), and a block of number comparison trials. The timeline of the experiment, tasks and conditions, and the experimental setting are illustrated in Figure 1.¹

¹ In the same experimental session, each participant performed additional tasks, with the idea to explore interactions between different tasks and factors (i.e., digit naming, affordance judgments, and a manual task in which the participants were required to put in a box eight small objects spread on the table). Details of these additional tasks can be found in the OSF project associated to this manuscript. Interactions between different tasks and factors are outside the scope of this paper, and they will be described elsewhere.

Figure 1. **a)** Timeline of the experiment. **b)** Experimental setting during the hand motor task. The starting hand position consisted in standing the hand on the mouse with the index and thumb closed, which maintain the right mouse button pressed. The mouse was fixed on the table. After 500ms of continued pressing, the participant was presented with a beep sound indicating to begin the required motor action. The PC monitor was placed at a distance of about 65cm from the participant, and it was embedded within a structure made of black paper panels. The Eprime response box, the headphones, the cables, and the microphone on its handmade stand were hidden behind these black panels. The cube was placed at a distance of approximately 35cm from the hand starting position, centred around the participant's body midline. **c)** Experimental setting during number comparison. The experimental setting was very similar to the setting during the hand motor task, except for the following: both hands lay under the table, with the palms facing down, open and relaxed, on the participant's legs; the cube was hidden behind the black panels; the microphone was placed in front of the participant's face, close to the mouth. Target numbers were presented on the PC monitor during the number task. The participant gave verbal responses on the microphone minimizing as much as possible body movements. **d)** Illustration of the four conditions of the motor task. In the Grasp condition the participant was instructed to repeatedly grasp and lift the object, each time bringing the hand back to the starting position and pressing the right button before initiating the next grasping. In the Point condition the participant was instructed to repeatedly point the centre of the cube front face, each time bringing the hand back to the starting position and pressing the right button before initiating the next pointing. To prevent participants from counting the number of action repetitions, participants were not aware of the fact that they had to stop after 16 repetitions in the grasp and point conditions: a counting procedure was implemented in mouse pressing (during the staring position), and the participant was presented with a beep sound indicating to stop the required motor action after 16 repetitions. In the Tap condition the participant repeatedly tapped the hand on the table, bringing the hand back to the starting position only when hearing the beep sound indicating to end the action, sound which was presented after 30s. The participants tapped the hand on the table at their own pace, but in the instructions the experimenter emphasized to tap nor too slowly neither too quickly. In the Passive view condition the participant was instructed to stop pressing the right mouse button as soon as the starting beep sound was heard, and to remain with the hand in the same position close to the mouse while passively viewing the object during 30s, until the end beep sound. During the hand motor task, the other hand lay behind the table with the palm facing down, open and relaxed, on the participant's leg. **e)** Schematic illustration of the trial structure in number comparison. In each trial, a fixation cross (Calibri Light 40, 500ms) was followed by a blank screen lasting 500ms (not shown in the picture), and a target number (Calibri

Light 40) lasting on the screen until response (time limit: 5000ms), and then a variable inter-trial-interval (ITI, black empty screen) lasted a minimum of 1000ms and in any case after manual encoding of the participant's response by the experimenter.

Preregistered analyses. Our dependent variable was the response times (RTs) on correct responses in the numerical task. Trials affected by recording errors (i.e., $RTs < 120ms$ or $> 5000ms$, and recording errors detected online by the experimenter) were excluded from the analyses ($M=2\%$; range: $0\%-5\%$; $SEM=0.3\%$). Then, the participants' errors in the number task ($M=1\%$; range: $0-4\%$; $SEM=0.3\%$), as well as RTs over 3SD from a participant's mean in correct trials ($M=1\%$; range: $0\%-3\%$; $SEM=0.1\%$), were also excluded from the analyses. We analysed the mean RTs by means of a Bayesian repeated measures ANOVA with Type of Action (Grasp, Point, Tap, Passive View), Number Magnitude (small, large), Numerical Distance (close, far) as factors. Bayesian t-tests were used for planned comparisons (Cauchy prior width was set to .707, i.e., the default value set in the JASP software). We considered a Bayes Factor (BF) > 3 to be enough evidence for the alternative hypotheses (HP1 and HP2), and a BF $< 1/3$ to be enough evidence for the null hypothesis (HP0). Specifically, for testing HP1 (reach and grasp action impacts number processing), we considered evidence for the alternative hypothesis a BF > 3 for the factor Action (BF inclusion) in the ANOVA, followed by a BF > 3 for the comparison between RTs for the reach and/or grasp action conditions vs. RTs for the tapping and/or no action conditions. For testing hypothesis 2 (i.e., interaction between Action type, Number Magnitude, and/or Number Distance), we will consider evidence for the alternative hypothesis a BF > 3 for the interaction between Action and one or two numerical variables (BF inclusion), followed by a BF > 3 for the following planned comparisons: the strength of distance effect in the experimental conditions (i.e., Grasp and Point) vs. the amount of distance effect in the control conditions (Tap and Passive View); the magnitude effect in the Grasp condition vs. magnitude effect in the other conditions. We also planned to exclude data from participants not completing the task or being unable to correctly execute the hand actions, but these cases did not occur.

Exploratory analyses and robustness check. To understand in detail the effects of hand action repetition on the process of numerical magnitude and distance, we performed a fine-grained analysis of the distance effect through linear regressions. Similar methods were successfully used by previous studies (e.g., Lorch and Myers, 1990; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Zorzi, et al., 2012). Linear regressions were computed on RTs as a function of the exact number distance of stimuli (i.e., distance from 1 to 4), permitting to estimate at the individual level the distance effect more accurately, since all distances are taken into account. The linear regression slope reveals the size of the distance effect, with more negative values indicating a large distance effect. Taking into account each distance has permitted to reveal cognitive effects which would have been hidden when collapsing distances into close and far levels (e.g., Zorzi et al., 2012). Therefore, this analysis might disclose fine-grained interactions between numerical factors and motor action (this point is discussed in the Method section). The slopes in the different experimental conditions were then compared by means of Bayesian t-test. We then confirmed our findings, by showing that the same pattern of results are obtained also by analysing the data with a frequentist approach (ANOVA and t-test).

Results

Bayesian ANOVA and planned comparisons. Mean RTs and SEM for each condition are reported in Table 1, and a summary of the results from the preregistered analyses is reported in Table 2. We performed the preregistered Bayesian ANOVA on mean RTs in number comparison including Action Type (Grasp, Point, Tap, Passive View), Numerical Distance (Close, Far), and Numerical Magnitude (Small, Large) as factors. The best model included Action Type and Distance as main factors with no interactions ($BF_{10}=7.2e+9$; BF_{incl} for Action Type = 3.7, BF_{incl} for Distance = $7.5e+8$, all BF_{incl} for interactions $<.33$).

Table 1. Mean RTs and SEM for each condition.

Action Type	Number Magnitude	Number Distance	M (ms)	SEM
GRASP	Small	Close	616	19
		Far	583	18
	Large	Close	613	19
		Far	592	17
POINT	Small	Close	619	19
		Far	612	21
	Large	Close	629	23
		Far	601	17
TAP	Small	Close	609	15
		Far	579	17
	Large	Close	616	17
		Far	598	19
PASSIVE VIEW	Small	Close	619	16
		Far	588	15
	Large	Close	616	20
		Far	608	19

The effect of numerical distance (Close: $M=617$, $SEM=18$; Far: $M=595$, $SEM=18$) was coherent with previous studies showing larger RTs for numbers close to the reference as compared to numbers far from the reference in magnitude comparison tasks. Concerning aim 1, we hypothesised a main effect of action on number processing: the results showed moderate evidence for the effect of Action Type. Specifically, RTs were slowest following repetitive pointing action (Grasp: $M=601$, $SEM=18$; Point: $M=615$, $SEM=20$; Tap: $M=601$, $SEM=17$; Passive view: $M=608$, $SEM=17$; Figure 2). Concerning aim 2, we hypothesised an effect of action type on the magnitude effect or on the distance effect: the results showed evidence for the null hypothesis. Indeed, preregistered planned comparisons by means of Bayesian t-tests investigating the effects of the *transport component* (reach = Grasp + Point vs. Tap + Passive view) and of *grasp preshaping* (Grasp vs. Tap + Passive view) revealed evidence for H_0 (both $BF_{10} <.33$), suggesting that the effect of Action Type is driven by mechanisms which are different from what expected.

Table 2. Schematic summary of the results from the repeated-measures Bayesian ANOVA and resulting planned-comparisons.

Statistical analysis	Effect	BF
Repeated-measures Bayesian ANOVA	Action Type	> 3
	Numerical Magnitude	< .33
	Numerical Distance	> 3
	Action Type * Numerical Magnitude	< .33
	Action Type * Numerical Distance	< .33
	Numerical Magnitude * Numerical Distance	< .33
	Action Type * Numerical Magnitude * Numerical Distance	< .33
Planned-comparisons: Bayesian t-test		
	REACH effect: (Grasp + Point) vs. (Tap + Passive view)	< .33
	GRASP effect: Grasp vs. (Tap + Passive view)	< .33
	POINT vs. the other conditions	> 3
	GRASP vs. the other conditions	< 1
	LOOK vs. the other conditions	< 1
	TAP vs. the other conditions	< 1

Additional planned comparisons confirmed that the main effect of Action Type was driven by slower responses in number comparison after pointing as compared to the ensemble of the other conditions ($BF_{10} > 6$), while there was no evidence for differences between each other condition and the ensemble of the remaining conditions (all $BF_{10} < 1$). The effect of Action Type is illustrated in Figure 2.

Figure 2. Effects of Action Type. Preregistered planned comparisons and the related results are reported in grey (grasp vs. control conditions; reach vs. control conditions), while additional planned comparisons and the related results are reported in blue. Error bars represent within-subjects SEM, computed only for illustration purposes (Cousineau, 2005).

Fine-grained analysis of the distance effect. While indicating that the hand pointing had a specific effect on performance in number comparison, the results, however, were not completely in line with the hypotheses, because there was evidence for no effect of arm transport or grasp preshaping with respect to the control conditions. To deeper explore the effects of hand actions in number processes, we adopted a method which has been found useful in previous studies, consisting in investigating the distance effect by means of the regression analysis for repeated measures (Lorch and Myers, 1990; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Zorzi, et al., 2012). One advantage of this method is that all the distance levels can be taken into account, resulting in a more accurate estimation of the distance effect. Therefore, this measure might disclose fine-grained interactions between numerical factors and motor action (this point is discussed in the Method section). The linear regression of the mean RTs as a function of the numerical distance (distances 1-4) was computed for small and large numbers separately. In this way, the regression slope is an index of the distance effect, with a steeper negative slope corresponding to a stronger distance effect. RTs for each condition are illustrated in Figure 3a, and the corresponding slopes are illustrated in Figure 3b. Interestingly, we found that on average the distance effect for small numbers increased (i.e., it was more negative) after grasping as compared to the ensemble of the other conditions ($t(23)=-2.8$, $p=.01$, $BF_{10}>4$), while it was reduced (i.e. it was closer to 0) after pointing as compared to the ensemble of the other conditions ($t(23)=-3.1$, $p=.006$, $BF_{10}>7$). The distance effect after passive view or tap did not differ from the ensemble of the other conditions (all $p>.1$, all $BF_{10}<.33$). The same set of analyses applied to slopes for large numbers did not reveal differences among conditions (all $p>.1$, all $BF_{10}<.5$). More negative slopes for small digits after grasp action as compared to the other conditions were found in the two thirds of the participants (63%:

15/24; Figure 3c), while less negative slopes for small digits after point action as compared to the other conditions were found in the three fourths of the participants (75%: 18/24; Figure 3d).

Figure 3. Panel a. RTs as a function of number target and action type. Error bars represent within-subjects SEM, computed only for illustration purposes (Cousineau, 2005). Panel b. Regression slopes representing the size of the distance effect for small or large digits in each action type condition. Error bars represent SEM. Results from exploratory analyses are written in blue. Panel c. Individual regression slopes as a function of numerical distance in the grasp–small number condition. Negative slopes indicate performance in the direction of the classical distance effect (i.e., faster responses for digits far from the reference as compared to closer ones). Red circles indicate slopes which were more negative as compared to the other conditions. Panel d. Individual regression slopes as a function of numerical distance in the point–small number condition. Negative slopes indicate performance in the direction of the classical distance effect (i.e., faster responses for digits far from the reference as compared to closer ones). Blue triangles indicate slopes which were less negative as compared to the other conditions.

Robustness check. For completeness, and to validate our results, we also run the analyses using a frequentist approach. The results from an ANOVA with Action Type, Distance, and Magnitude as within/subjects factors confirmed the significant main effects of Action Type ($F(3,69)=3.5$, $p=.02$, $\eta_p^2=.133$) and Distance ($F(1,23)=48.4$, $p<.0001$, $\eta_p^2=.678$), and revealed a significant interaction between all factors ($F(3,69)=3.5$, $p=.02$, $\eta_p^2=.13$). The other main effects or interactions were not significant (all $p>.1$). Planned comparisons did not find effects of the *transport component* (reach = Grasp + Point vs. Tap + Passive view, $p >.1$) or of *grasp preshaping* (Grasp vs. Tap + Passive view, $p >.1$). Additional planned comparisons

confirmed that the main effect of Action Type was due to slower responses in number comparison after pointing (point vs. all other conditions: $t(23)=2.9$, $p=.008$, Cohen's $d=.6$). The comparison of each other condition against the ensemble of the remaining conditions did not reveal significant differences (all $p < .05$). Finally, the results from the exploratory analyses on the distance effect also confirmed the findings from the Bayesian approach: the distance effect for small numbers increased after grasping ($t(23)=-2.8$, $p=.01$, Cohen's $d= -.572$) and decreased after pointing ($t(23)=-3.1$, $p=.006$, Cohen's $d=.622$) as compared to the ensemble of the other conditions, while there was no significant difference for the other comparisons (all $p > .1$).

GENERAL DISCUSSION

In this study we investigated the effects of repetitive hand action on the performance in a subsequent number comparison task. The participants performed pointing, grasping, tapping or passively viewing at actions in separate blocks. Following each action phase, they were presented with a number digit on the screen, and they orally indicated whether the number was smaller or larger than five. We predicted effects of arm transport (taking place both in pointing and grasping) or grasp preshaping (present only in grasping) on the main performance in number comparison, as well as on the processing of numerical distance and/or magnitude. A series of preregistered and exploratory analyses were conducted. While arm transport and grasp preshaping do not significantly affect number processing, we found was a reduced distance effect for small numbers after pointing, while it was enhanced by grasping.

The main novel finding is that RTs in number comparison were significantly slower after repetition of pointing as compared to any other action. A unique effect of pointing is different from what we had predicted based on the combination of results from studies on human grasping and studies on number processes. Indeed, a number of studies on human grasping is based on the distinction between arm transport and grasp preshaping (Jeannerod, 1999), highlighting different cognitive and neural mechanisms associated to these two components of hand movements (Cavina-Pratesi et al., 2010). In many studies the action of pointing is often considered as representative of reaching, i.e. of arm transport (e.g., Frey, Vinton, Norlund, & Grafton, 2005; Connolly, Andersen, & Goodale, 2003; for a discussion on this topic, see: Cavina-Pratesi et al., 2018). In fact, pointing is not exactly an equivalent of reaching, since pointing can be executed both with and without arm transport. Indeed, in a more recent study (Cavina-Pratesi et al., 2018) the authors highlight a series of distinct neural activations for pointing as compared to arm transport, and they underline the communicative nature of pointing, suggesting that the uniqueness of this action might arise from a combination of visuospatial processes for object location and processes of social cognition (Leavens, 2004; see also Committeri et al., 2015).

In child development, starting from one year old, index finger pointing has an important social role, since it conveys interactions with the caregiver (Leung & Rheingold, 1981). More in general, pointing is part of gesturing during speech in many different contexts. Importantly, researchers have observed that children tend to learn maths concepts such as mathematical equivalence better when teachers encourage them to associate the correct pointing gesture to a given problem (e.g., Goldin-Meadow, Cook, & Mitchell, 2009). It appears clear that the embodiment of pointing, through its repetitive use in gesturing, should constitute a scaffold for the development of number knowledge (for related concepts, see: Allen, M., & Vallée-Tourangeau, 2016). Importantly, pointing is particularly relevant in the context of numerical cognition also because it is the action through which children learn counting arrays of visual items (e.g., Wynn, 1990). In this sense, the routine of index finger counting might elicit the understanding of ordinality (e.g., *I live on the third floor*) before the understanding of cardinality (e.g., *I see three puppies*), suggesting that the former is a prerequisite of the latter (Fluck & Henderson, 1996).

Many studies have underlined that numerical order is processed by mechanisms that are at least partially separated from the ones involved in the process of number magnitude (for a review see: Lyons, Vogel, & Ansari, 2016). One example comes from studies observing the distance effect during comparison of non-numerical ordered sequences (e.g., Leth-Steensen & Marley, 2000). Furthermore, it has been observed that judging order or magnitude of pairs of digits can differently interact with the numerical distance (Turconi and Seron, 2006). This suggests that, depending on the task, different processes – possibly serial search and

magnitude comparison – are preferentially recruited (see also Gevers, Reynvoet, & Fias, 2003). In addition, other studies indicated that order can be automatically activated during number magnitude comparison (Sasanguie, Lyons, De Smedt, Reynvoet, 2017), albeit the distance effects in magnitude and order tasks are not correlated (Goffin & Ansari, 2016). Finally, some studies have argued that the automatic processing of number order may explain biases in magnitude tasks, biases typically attributed to the unique effect of magnitude (e.g., van Dijck & Fias, 2011; Antoine, Ranzini, Gebuis, van Dijck, & Gevers, 2017; see also: van Dijck, Fias, & Andres, 2015). In view of these studies, we propose that pointing might trigger mechanisms implied in the process of order information due to its link to actions of ordering and counting, consequently impacting number comparison.

We could not find a link between number magnitude and grasping, and between number distance and reaching, as originally predicted (hypothesis 2). Nonetheless, the exploratory analyses highlighted differential fine-grained effects of grasping and pointing on numerical distance. Specifically, statistical analyses indicated that, for small numbers only, the distance effect is exacerbated by immediate repetition of grasping action, while, in contrast, it disappears when number comparison is preceded by repetitive pointing. This effect was unpredicted and require future study in order to be replicated and interpreted. We advance here one possible interpretation which should be tested in future studies: considering that the origin of the distance effect is rooted in number semantics (see Ansari, 2008, for a review), these results might reflect shared mechanisms between grasp and number cardinality, on the one hand, and between point and ordinality, on the other hand (for a similar dissociation see van Dijck et al., 2015). Interestingly, the grasping and pointing influenced distance effect only for small numbers (<5), while for larger number (>5) the distance effect was not modulated by the type of the prior action. In line with this finding, previous studies had already noticed that some behavioural effects ascribed to the functional relation between grasping and number magnitude suggest a specific link between precision grip and small numbers (e.g., Badets & Pesenti, 2010; Badets & Pesenti, 2011; Badets et al., 2012; Ranzini et al., 2011). These observations might suggest that the mental representation of small numbers might be particularly sensitive to embodiment, possibly because, in everyday life, precision grip is mostly performed by one hand, as well as it is mainly possible to count small quantities when using one hand (Ranzini et al., 2011). That said, future studies are needed to confirm and clarify the exact mechanisms relating grasping and pointing to number magnitude and distance.

CONCLUSION

The present study clearly confirms bidirectionality in the interactions between motor action and number (e.g., Ranzini et al., 2011; Ranzini et al., 2015; Blini et al. 2019; Felisatti et al., submitted; Ranzini et al. 2016; Rossetti et al. 2014; see also Anobile et al., 2021), in line with embodied and grounded cognition accounts (e.g., Fischer, 2012). More than this, this study gives new insights for future lines of research, suggesting taking into account the meaning of each hand action when studying number-action interactions. Indeed, we suggest that the effects of pointing in number comparison might stem from the functional role of pointing in number processing. In this sense, pointing – as well as it was shown for grasping (e.g., Badets & Pesenti, 2010) - might have a *special status* in number processing, possibly due to its repetitive use in counting and in conveying spatial information during child development. Finally, we have described here the effectiveness of a promising method to study number-action interactions, which is based on the neurophysiological principles of neural adaptation (Cattaneo & Silvanto, 2008) thus permitting to advance

convincing claims on the functional link between motor action and number processes (see also Anobile et al., 2021; Glenberg et al., 2008).

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