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RESEARCH REPORT

Finger posing primes number comprehension

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Abstract Canonical finger postures, as used in counting, activate number knowledge, but the exact mechanism for this priming effect is unclear. Here we dissociated effects of visual versus motor priming of number concepts. In Experiment 1, participants were exposed either to pictures of canonical finger postures (visual priming) or actively produced the same finger postures (motor priming) and then used foot responses to rapidly classify auditory numbers (targets) as smaller or larger than 5. Classification times revealed that manually adopted but not visually perceived postures primed magnitude classifications. Experiment 2 obtained motor priming of number processing through finger postures also with vocal responses. Priming only occurred through canonical and not through non-canonical finger postures. Together, these results provide clear evidence for motor priming of number knowledge. Relative contributions of vision and action for embodied numerical cognition and the importance of canonicity of postures are discussed.

Keywords Embodied cognition · Finger counting · Numerical cognition · Priming

Introduction

Cognitive scientists are revising their long-standing belief that cognitive processes are independent from bodily states. Evidence is rapidly accumulating that body and mind are indeed interacting in various ways (for recent reviews, see, e.g. Coello and Fischer 2016). A strong version of the "embodied cognition" stance claims that features of the body shape cognition permanently, in that both sensory and motor activations which were present during knowledge acquisition remain associated with that knowledge and become mandatory parts of all knowledge retrieval. The present study examines this claim.

One domain of embodied cognition that has recently gained much attention is numerical cognition (Lindemann and Fischer 2015). Numbers, traditionally seen as a paradigmatic case of symbols with modal cognitive representations, are no longer thought of as abstract conceptual entities: they were learned and internalized through the use of fingers, thus featuring systematic sensory and motor associations with the body (Fuson et al. 1982; Butterworth 1999; Fischer and Brugger 2011; Knudsen et al. 2015). Not only children employ finger postures to represent numbers; adults use them to convey quantities to others, e.g. when verbal communication is difficult (Pika et al. 2009) or when the verbal system is occupied (Lucidi and Thevenot 2014). Even blind adults rely on finger postures during number processing when their vision was intact during number learning (Crollen et al. 2014).

The mechanisms of embodied number knowledge are currently not well understood. In the case of finger counting, multi-modal (visual, motor and proprioceptive) associations between fingers and numbers may develop through repeated co-occurrence (e.g. Fuson et al. 1982; Fuson 1988; Butterworth 1999) and this is reflected in shared

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cortical regions for both finger discrimination and number processing (Andres et al. 2012; Rusconi et al. 2005; Sato et al. 2007; Tschentscher et al. 2012). For example, Tschentscher et al. (2012) found that visually presented numbers 1 through 5 evoked activity in the observer's hand motor cortex, selectively for the hemisphere contralateral to the hand on which this person would begin to count.

Behavioural studies confirm the close coupling between specific numbers and fingers. Di Luca et al. (2006) required participants to classify the numbers 1 through 10 by pressing buttons with all ten fingers according to different finger-number mappings. The mapping conforming to the participants' finger counting habits produced the fastest responses. In a masked priming study, Di Luca and Pesenti (2008, Experiment 2) presented pictures of finger configurations subliminally, followed by Arabic digits that were classified as smaller or larger than five. In congruent trials, finger configuration and target digit were both either larger or smaller than five and this led to faster digit classification than incongruent trials. Importantly, this congruency effect only consistently emerged for canonical finger configurations (i.e. those actually used for counting), consistent with an embodied number representation. Badets et al. (2010) found a comparable facilitating finger-number priming effect in arithmetic with supraliminal presentations of finger configurations: participants solved addition problems faster when the correct outcomes were presented after each response as canonical finger configurations than when they were presented as rod configurations.

So far, finger postures have only been introduced as visual stimuli. This raises the important question of whether their effect on number processing reflects visual recognition of familiar stimuli or a covert motor simulation[1] (Jeannerod 2006) of the observed posture. Finger postures—which are readily imitated even by neonates (Nagy et al. 2014)—are automatically simulated by adults: Brass et al. (2000) showed that merely seeing a rising finger interfered with the observer's own downward finger movement, thus indicating spontaneous visuo-motor priming. Glover and Dixon (2013, Experiment 2) reported evidence that motor priming also takes place through imagined movements alone without the need for visual perception altogether. The authors studied perseveration effects for grasp mode (vertical or horizontal grasp). They found that posture selection relied on motor codes rather than visual perception (Experiment 1) and that even motor imagery led to perseveration of grasp mode (Experiment 2), indicating that visual perception and also proprioception do not augment the priming induced by motor codes alone. This study, however, does not inform about the effects of pure visual perception or proprioception.

Both motor and proprioceptive information is influential for conceptual number processing. It is often assumed that numbers are mentally represented as positioned on a mental number line with larger numbers to the right of smaller numbers (in Western cultures; e.g. Dehaene 1992). Motor and proprioceptive information has been shown to shift attention along this mental number line: for example, in a random number generation task, participants produced more small numbers when turning their head to the left than when turning it to the right (Loetscher et al. 2008); the proprioceptive experience of leaning to the left induced smaller numerical estimates (Eerland et al. 2011); tapping movements in left or right peripersonal space resulted in, respectively, stronger or weaker underestimations of the midpoint between two three-digit numbers (Cattaneo et al. 2011). Apart from these spatial associations, several studies recently demonstrated an association between motor-related and numerical magnitudes as, for instance, illustrated by the link between grasping actions and number processing (Andres et al. 2004; Lindemann et al. 2007; Ranzini et al. 2011). It has, for example, been shown that grip openings were initiated faster in response to large numbers while grip closures were initiated faster in response to small numbers (Andres et al. 2004). Also power grip actions were initiated faster when preceded by large numbers while precision grip actions were initiated faster when preceded by small numbers (Lindemann et al. 2007). Similarly, Ranzini et al. (2011) showed that visual presentation of graspable objects (i.e. objects associated with grasping movements) as well as the actual, task-irrelevant action of holding an object amplified a numerical magnitude effect (i.e. faster responses to small than large numbers).

Finger counting has even tighter links to mental number representations than the above-mentioned movements and grips, as finger counting is a compound of visual, motor and proprioceptive experiences of the hands with displaying numbers. In accordance with the embodied cognition stance, we expect that finger postures exert priming effects on number processing largely via motor and proprioceptive rather than visual mechanisms.

In order to test this hypothesis, the present study examined visual and motor contributions to the finger priming effect in number processing. Experiment 1 compared the influence of both visual and motor codes on magnitude classification relative to a fixed reference value using a go/no-go number classification task, while Experiment 2 further investigated number priming through motor codes in a magnitude comparison task. We will henceforth label the combination of initial activation of motor codes

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[1] We understand motor simulation with Jeannerod (2006, p. 129) "as the off-line rehearsal of neural networks involved in specific operations such as (…) acting. In other words, [motor] simulation is what makes it possible to (…) activate motor mechanisms without executing an action".

through manual adoption of finger postures and ongoing proprioceptive feedback[2] as “motor priming”, while conditions with exclusively visual presentation of finger postures will be labelled as “visual priming”.

Experiment 1

When comparing the impact of visual and motor priming from the hands on number processing, one possible outcome could be that visual priming is more effective than motor priming because of spontaneous motor simulation in the visual priming condition. Thus, the visual prime would effectively be rendered a visuo-motor prime (cf. Brass et al. 2000), providing both visual and motor inputs to the same number concept. If, on the other hand, motor simulation does not possess priming capabilities, but visual perception and active movements do, then both visual and motor priming might emerge similarly strongly. However, if it is mainly (covert) motor simulations induced by pictures of canonical finger configurations that produces their priming effect, then actively adopting those same postures should arguably induce much stronger activation of related number concepts, even when the postures are not visually available. The fact that the perception of numbers activates the motor area of the hand that is responsible for the respective numbers during finger counting (Tschentscher et al. 2012) suggests a tight motoric link between fingers and numbers. In the light of this reasoning, as well as Glover and Dixon’s (2013) findings, we expected the motor condition to elicit stronger priming effects than the visual condition.

Method

The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki. It consisted of a magnitude classification task in which participants indicated via foot pedals whether an auditorily presented number was smaller or larger than five. Before each block of ten number comparisons, a single finger posture was introduced as a prime stimulus. This posture was either shown throughout the trials and visually processed (visual priming), or it had to be adopted out of view by the participant (motor priming). No-go trials ensured participants’ attention towards the visual stimuli. Instructions were given purely visually and not, for instance, by manipulating the participant’s fingers; this was done to avoid tactile stimulation of the fingers, which is also known to trigger numerical concepts (Krause et al. 2013). The implied counting direction was manipulated to ensure equally distributed spatial attention to the left and right sides of the display (in the visual priming condition) and of one’s own body (in the motor priming condition). Also, no-go trials were introduced to ensure the same amount of attention to the display in both priming conditions. Experimental software, raw data and analysis scripts for both experiments are available via the Open Science Framework platform at https://osf.io/rwgh6.

Participants

Thirty-one undergraduate students at Potsdam University (20 females, 11 males) took part in Experiment 1. All reported to be right-handed, were native German speakers and received course credit for participation. One participant had to be excluded from analyses due to technical problems during data collection.

Apparatus and experimental set-up

Participants were seated at a table with a computer monitor (60-cm screen diagonal; 60 Hz refresh rate) mounted on top of a custom-made rack with a height of 102 cm (see left panel of Fig. 1 for illustration). They were instructed to place their hands on a surface underneath the rack. Participants’ lower arms and hands were shielded from view with a dark cloth that was attached to the rack. The experimenter was positioned behind the set-up and monitored participants’ hand postures throughout the experiment.

Auditory stimuli were presented via headphones. Responses were given with the left or right foot on two custom-made pedals connected via USB, positioned under the table. Stimulus presentation and response recording were controlled by a custom-made program based on the free Python library *Expyriment* (Krause and Lindemann 2014).

Stimuli

Target stimuli for the magnitude classification task consisted of eight spoken German number words (1–9 except 5) with a duration of 500 ms each. A 440 Hz tone (500-ms duration) served as error feedback for incorrect and slow responses. Visual prime stimuli were colour photographs of pairs of hands on a black background (see Fig. 1). Depending on the postures, the hands subtended visual angles of 10°–16° vertically and 13°–19° horizontally; they wore no rings or wrist bands/watches. Palms were always oriented towards the participant. The stimulus set comprised all 18 canonical finger counting postures representing the numbers from 1 to 9. That is, each number was

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[2] Desmurget et al. (2000) estimated proprioceptive information from the unseen hand to remain cognitively available for at least 15 s.

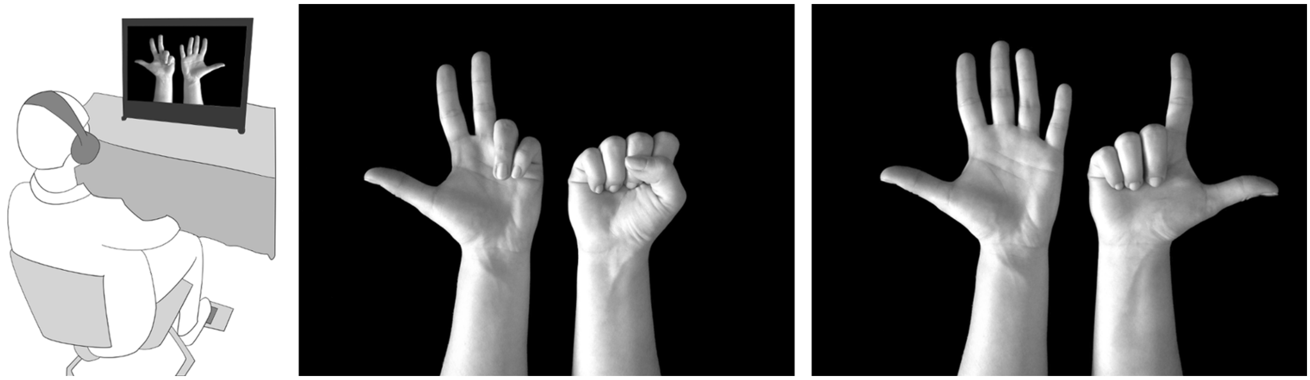

Fig. 1 Experiment set-up and sample stimuli. The *left panel* shows the set-up with a visual finger prime “8” with a right full hand. The participant classified auditorily presented numbers with two foot pedals. The experimenter (not visible) sat behind the rack to monitor the participant’s finger postures. The *central* and *right panels* show further example stimuli with a left starting hand

represented by two finger postures resulting from different counting directions, i.e. either left to right (with 1 associated with the left thumb extended) or right to left (with 1 associated with the right thumb extended; see Fig. 1).

Motor prime stimuli were manual postures. They were instructed via the same photographs as in the visual condition, only with the hands coloured green. During data collection, they were replaced by two rectangular grey blocks, matching the average size of the finger counting postures. In no-go trials, the hands (in the visual condition) or the rectangles (in the motor condition) turned red.

Procedure

A practice phase familiarized participants with all finger postures. Green-coloured pictures of all 18 hand postures were presented once in randomized order, and participants were instructed to imitate the postures. The experimenter monitored responses and corrected participants as necessary. Each participant also performed a short training of the auditory magnitude classification task alone to learn the foot pedal responses.

During data collection, each mini-block of ten trials started with the visual presentation of a green finger posture. In the *motor priming* condition, the participant adopted this posture and pressed a foot pedal when ready. A double beep tone was then played to indicate the start of the next ten auditory magnitude classification trials, and the screen showed two grey rectangles during data collection. In the *visual priming* condition, participants placed both hands palm down flat on the table and pressed the foot pedal when ready. Again, a double beep tone sounded and the green instruction stimulus (which was not to be imitated) changed its colour to natural and remained visible as visual prime throughout the following ten trials.

The remaining procedure was identical across the two priming conditions: an auditory number word was presented and participants indicated whether the number was smaller or larger than 5 by pressing the left or right foot pedal according to the instructed response mapping. Responses had to be given within 1500 ms. Importantly, in both conditions no-go trials were quasi-randomly inserted (see “Design” section) to ensure that participants attended and processed the visual stimuli: the colour of the displayed hands or rectangles turned red with the onset of the auditory target and participants had to refrain from making foot responses. An error tone followed incorrect or too slow responses. Reaction times (RTs) were defined as the durations from target number onset until a pedal was depressed. After a random inter-trial interval (350–750 ms), the next trial started. After ten trials, a new finger posture was instructed (in the motor condition) or shown for the next ten trials (in the visual condition). The experimenter verified the required finger posture through visual inspection and marked trials with incorrectly performed postures.

Design

The stimulus–response mapping (i.e. left vs. right foot pedal for small vs. large numbers) changed in the middle of the experiment for each participant. The order of the stimulus–response mappings was randomized across participants (24 participants whose data were analysed started with the mapping right pedal for small numbers). Within each of the two response mappings, there were two blocks with different priming conditions: visual and motor priming; their order was balanced across participants (16 participants whose data were analysed started with the motor condition and 14 with the visual condition).

Each of the four resulting experimental blocks comprised 80 trials. Each mini-block of ten trials consisted of all eight target numbers (go trials) plus two additional, randomly chosen target numbers (no-go trials). All target

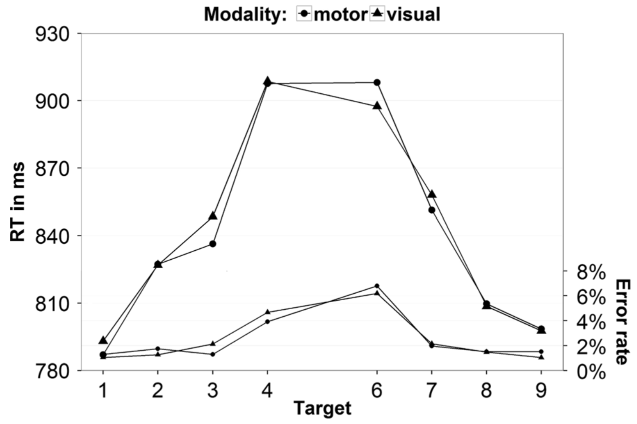

Fig. 2 RTs for trials with correct responses (*large symbols*) and error rates (*small symbols*) per auditory target number (*x* axis), separately for each prime modality

numbers were presented with each of the eight finger postures for numbers 2, 3, 7 and 8 in both counting directions. Thus, there was a total of 320 trials: 2 response panel mappings × 2 finger prime modalities × 4 finger postures × 2 counting directions × 10 numbers (8 target numbers [1–4, 6–9; go trials] + 2 random target numbers [no-go trials]). The first trial within a mini-block of ten trials never consisted of a no-go trial; apart from this, the trial order in each mini-block was randomized. Additionally, each of the four blocks began with ten randomly chosen warm-up trials that were not further analysed. The entire experiment lasted approximately 30 min.

Results

For RT analyses, only go trials were used. We excluded all trials with incorrectly adopted finger postures (1.15%), slow responses (RTs > 1500 ms; 1.85%) and erroneous responses (2.45%). Errors were too infrequent to be further analysed. Average RTs and error rates are depicted in Fig. 2.

Signatures of number processing

We first examined typical signatures of numerical processing such as the SNARC effect[3] and the distance effect (Hinrichs et al. 1981). Afterwards, we addressed our specific question about visual vs. motor contributions to the priming of number concepts by finger postures. Effect sizes for *t*-tests were computed as Cohen's d_z (cf. Rosenthal 1991). Standard deviations (SDs) for (differences of) RTs are given in ms.

SNARC effect

We conducted a 2 (prime modality: visual vs. motor) × 2 (response side: left vs. right) × 2 (target magnitude: small numbers 1–4 vs. large numbers 6–9) repeated-measures analysis of variance (ANOVA) on the RTs. Results showed a main effect of response side, $F(1, 29) = 6.03$, $p = .020$, $\eta_p^2 = .17$, indicating that responses given with the right foot pedal (839 ms, SD = 88) were faster than those given with the left foot pedal (851 ms, SD = 83). Importantly, over both prime modalities a reliable interaction between response side and target magnitude emerged, $F(1, 29) = 38.41$, $p < .001$, $\eta_p^2 = .57$, signalling the presence of a SNARC effect: small target numbers were classified faster with the left foot pedal (826 ms, SD = 86) than with the right foot pedal (863 ms, SD = 92), $t(29) = 4.42$, $p < .001$, $d_z = .81$, and vice versa for large target numbers (left: 875 ms, SD = 87; right: 815 ms, SD = 92), $t(29) = 6.36$, $p < .001$, $d_z = 1.16$. Moreover, there were no main effects or interactions of the factor prime modality, all *ps* > .1.

Distance effect

The distance effect refers to slower classification of numbers closer to the reference value in magnitude classification tasks (e.g. Hinrichs et al. 1981). We conducted a 2 (prime modality: visual vs. motor) × 4 (distances of auditory targets from the reference number 5) repeated-measures ANOVA on RTs. As expected (see Fig. 2), responses were faster for larger distances (distance 1: 910 ms, SD = 95, distance 2: 853 ms, SD = 91, distance 3: 819 ms, SD = 85, distance 4: 798 ms, SD = 89), $F(3,87) = 170.05$, $p < .001$, $\eta_p^2 = .85$. Paired *t*-tests confirmed that every increase in numerical distance led to a significant reduction in decision latencies: distance 1 against 2: $t(29) = 14.93$, $p < .001$, $d_z = 2.73$; 2 against 3: $t(29) = 6.43$, $p < .001$, $d_z = 1.17$; 3 against 4: $t(29) = 4.18$, $p < .001$, $d_z = .76$). Again, an interaction with or main effect of the factor prime modality did not reach significance, both *Fs* < 1.

Category priming

Following Di Luca and Pesenti (2008), trials where prime and target were both smaller or both larger than 5 were defined as congruent with respect to response category, all others trials as incongruent. A 2 (magnitude category congruency: congruent vs. incongruent) × 2 (prime modality: motor vs. visual) repeated-measures ANOVA on RTs showed no reliable main effect of magnitude category congruency, $F(1, 29) = 2.66$, $p = .114$, or prime modality, $F(1, 29) < 1$, $p = .948$, but a significant interaction

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[3] The SNARC effect (spatial-numerical association of response codes; Dehaene et al. 1993) refers to a pervasive association of smaller numbers with left space and larger numbers with right space in Western cultures (for recent review, see Fischer and Shaki 2014).

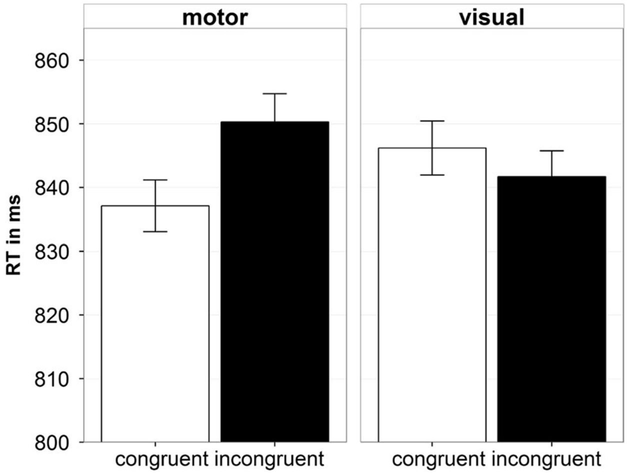

Fig. 3 Mean RTs in ms for congruent (*white*) and incongruent (*black*) conditions for magnitude category congruency in the motor (*left panel*) visual (*right panel*) priming modality. *Error bars* represent within-subject standard errors as suggested by Cousineau (2005)

between these two factors, $F(1, 29) = 4.83$, $p = .036$, $\eta_p^2 = .14$. Paired t-tests showed that for the motor condition, responses in congruent trials were significantly faster (837 ms, $SD = 90$) than those in incongruent trials (850 ms, $SD = 79$), $t(29) = 2.25$, $p = .032$, $d_z = .41$. In the visual condition, there was no significant difference between congruent (846 ms, $SD = 87$) and incongruent trials (842 ms, $SD = 90$), $t(29) = 1.25$, $p = .221$ (see Fig. 3). A post hoc power analyses revealed that based on our sample size of 30 subjects, an alpha level of .05 and an intended power of 80%, the design allowed us to detect main effects and interactions of small to medium size, $\eta_p^2 = .04$.

Motor and visual primes were either adopted or presented for the rather long period of ten trials. Therefore, we also analysed the priming properties over time: we computed "priming slopes" of each condition, that is, the RT effect (i.e. RT difference in ms of incongruent minus congruent condition per subject, trial and modality) for each modality was regressed over the trial number (1 to 10). The resulting estimated regression equations were for the motor priming condition $y = 8.69 + 1.01 * \text{trial number}$ and for the visual priming condition $y = -4.54 - .11 * \text{trial number}$. The individual slope coefficients were tested against zero (cf. Lorch and Myers 1990). Neither in the motor nor in the visual condition, this one-sample t-test became significant; both $t(29) < 1$.

Discussion

Experiment 1 studied performance in a magnitude classification task with finger posture primes and found evidence for faster number processing following congruent compared to incongruent motor primes. Importantly, our novel comparison between visual and motor priming conditions shed light on the relative contributions of visual and manual codes to this previously reported finger-based priming of number concepts. We showed that response selection was facilitated by actively adopting, but not by passively seeing, canonical finger counting postures matching the magnitude category of subsequently presented Arabic digits.

The lack of a persistent priming effect in the visual condition challenges the hypothesis that visually perceived body postures induce an effective motor simulation by the observer; it shows instead that active posturing provides additional and specific information, such as proprioceptive input, to the conceptual system beyond what is available through mere simulation. The presence of this proprioceptive information possibly explains the conflict between the visual priming effect reported by Di Luca and Pesenti (2008) and the lack of visual priming effects in the present study. Di Luca and Pesenti considered their effect to be visual in nature, but we note that their participants actively moved their fingers to classify the numbers, thus including tactile and proprioceptive input from the hands in their task. In our visual priming condition, participants' hands rested passively on a surface and the experimenter monitored compliance with this instruction. This might even have created a conflict, because when simulating own body movements, proprioceptive information is integrated (e.g. Lorey et al. 2009) and we instructed participants to hold their hands flat, that is, essentially in the posture corresponding to the number 10.

Even though the present study failed to find any effects of the visual presentation of hand postures, it cannot be excluded that visual priming might have affected the processing of numbers. Indeed, it is plausible to assume that the perception of a hand causes motor resonance (Brass et al. 2000; Schütz-Bosbach and Prinz 2007) and therefore also induces priming of the number concept to a certain extent. However, crucially, the effect in the motor condition was significantly stronger than in the visual condition, revealing the dominance of priming through proprioception over priming through visual perception of postures. Likewise, the short visual presentation of the postures in the beginning of each mini-block of the motor condition might have caused a visual priming of the number concepts. Yet, the stronger priming in the motor condition illustrates the key role of proprioceptive information for the impact on number processing.

Having established a contribution from motor priming on number processing, the question arises of how robust motor priming of number concepts is across tasks, modalities and response requirements. For example, previous work has shown that pictures of both canonical and non-canonical finger postures can prime magnitude concepts, but that canonical finger postures do so more pervasively (cf. Di Luca and Pesenti 2008). On the other hand, an embodied view of numerical cognition that assumes active motor experience to be the source of embodiment would predict that non-canonical finger postures (with regard to numerical meanings) should not activate number concepts at all. We therefore report below a replication of our main finding in a design that examined also non-canonical postures and that required visual magnitude comparison instead of auditory magnitude classification.

The second experiment furthermore allowed us to address a concern regarding a possible account of our finding through posture naming. Specifically, we wished to ascertain that it was not merely verbal transcoding of the adopted finger postures into number names which activated the specific number concepts. Thus, we reasoned that verbalizing the target numbers would suppress possible subvocal verbalization strategies for the finger postures.

Experiment 2

Experiment 2 aimed to replicate the motor priming effect with a substantially different methodology. First, we changed the task from auditory magnitude classification, which is relative to a fixed standard, to visual magnitude comparison, which requires the comparison of two new numbers in each trial (cf. Moyer and Landauer 1967). Secondly, we tried to eliminate strategic verbal recoding by disguising the focus of the study on finger counting by mixing canonical and non-canonical postures and by avoiding all references to finger counting. Furthermore, we also replaced foot responses with verbal responses to interfere with verbal recoding. Verbally responding has the additional advantage of being non-lateralized, thus enabling us to test whether motor priming requires lateralized responses, perhaps because the finger stimuli involve lateralized effectors. The embodied cognition stance predicts that only adopting canonical postures should prime number concepts.

Method

Participants

Twenty-seven participants (19 females, 8 males) took part in Experiment 2 for either course credit or payment. Two participants were subsequently excluded from analyses: one reported during debriefing that the verbal responses were meaningful in her native language (from Polish approx. "these" and "this"), which might influence RTs and confound effects due to finger postures, and the other because post-experiment testing indicated that "canonical" postures of the experiment were not actually canonical for her. All reported to be right-handed and had normal or corrected-to-normal vision. They were German native speakers and naïve as to the purpose of the experiment.

Apparatus and experimental set-up

Participants sat in front of a monitor (viewing distance of about 60 cm, 43-cm screen diagonal, 60 Hz refresh rate) with both hands resting on a table in front of them. The left hand made a loose fist throughout the experiment, and the right hand was out of sight behind a board, about 5 cm in front of a 54 mm wide × 33 mm tall circular button ("PowerMate"; Griffin Technology, Nashville, USA). Verbal response latencies were recorded with a headset microphone connected to a voice key device ("SV-1 Voice Key"; Cedrus Corporation, San Pedro, USA). For errors, tones sounded from speakers that were positioned behind the monitor. The experiment was again controlled using the *Expyriment* software (Krause and Lindemann 2014).

Stimuli

Motor primes consisted of three canonical and three non-canonical finger postures with 2, 3 or 4 extended fingers (see Fig. 4). Arabic numerals between 1 and 5 (text size = 36 pixels, sans serif font type) were displayed in light grey at the centre of a black display; they comprised about 1° of the participant's visual field.

Procedure

Participants were not told about the meaning of the finger postures, and no reference was made to finger counting at any time. They were asked to take off rings to avoid any additional stimulation on their fingers.

At the beginning of each mini-block, the participant adopted the finger posture that the experimenter manually demonstrated. Each trial was started by the participant pressing the button with the right hand and then immediately re-adopting the finger posture, resulting in a motor prime that was produced out of view at the edge of the table. Next, a fixation cross was shown for a random period of time between 1000 and 1500 ms until the reference number (2, 3, or 4) appeared for 400 ms. After a 300-ms blank screen, the target number appeared, being either smaller or larger than the reference number by one. It remained visible until a response was given.

Participants decided as fast and accurately as possible if the target was larger or smaller than the reference number by uttering the syllable "tah" or "toh". Those (for German speakers meaningless) syllables were chosen because they

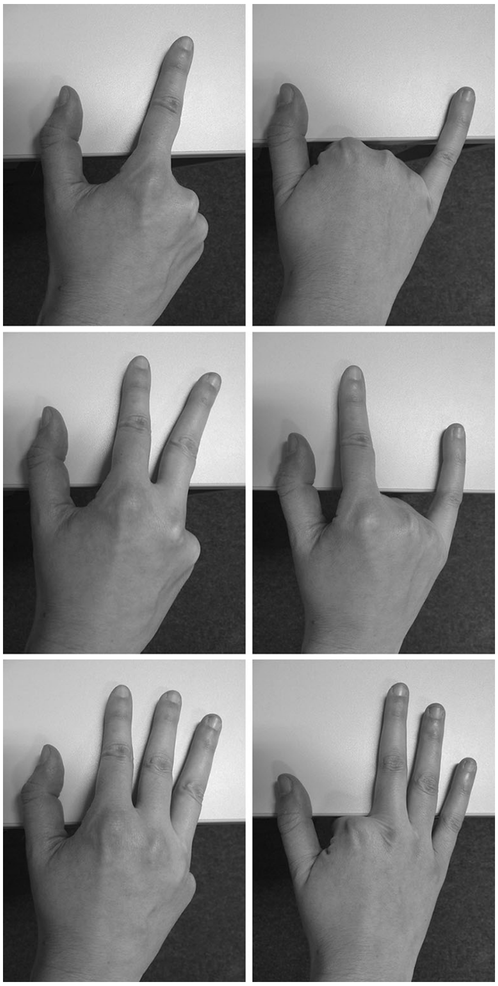

Fig. 4 Canonical finger postures (*left*) and non-canonical finger postures (*right*) with 2, 3 or 4 extended fingers

have the same length, they were easily distinguishable for the experimenter who entered the responses, and they start with the same plosive consonant to ensure the most precise detections of the voice onset with the voice key device. RT was defined as the time from onset of the target number until the beginning of the verbal response. The experimenter entered the response identity or the occurrence of recording problems (microphone malfunction, coughing, etc.) via the keyboard. Trials with incorrect responses and false RTs due to recording problems were repeated at the end of the mini-block.

After the experiment, participants stated their assumptions about the objectives of the study and reported their handedness, using two (translated) questions from Annett (1970): "Show me how you would butter bread" and "Show me how you would deal out playing cards". Finally each participant's manner of finger counting was recorded by asking "Show me how you would count from one to ten with your hands" and observing the response.

Design

Each trial comprised a sequence of two visual numbers: a reference number (2, 3 or 4) and the following target number (1 through 5), the latter being smaller or larger than the former by exactly 1. Target numbers 1 and 5 did not have a corresponding finger posture and thus only served as fillers, so that participants could not reliably predict the correct response for reference numbers 2 and 4. In total, the experiment contained 288 trials: 6 number combinations × 6 finger postures (3 canonical, 3 non-canonical) × 8 repetitions. The experiment was structured into mini-blocks of 12 trials, presenting every one of the six possible reference–target combinations twice, in a random order. Using 24 mini-blocks, each combination appeared 48 times. The experiment was preceded by at least three mini-blocks (or more if required) with only non-canonical finger postures 2, 3 and 4 in a random order. This training ensured that participants could execute the non-canonical postures effortlessly.

Results

The data of two subjects had to be excluded (see "Participants" section). Only one of the remaining 25 participants guessed the true objective of the experiment; when referring to hand postures, three participants mentioned the (number of outstretched) fingers, and the others either had no assumptions or at most assumed that the postures were supposed to generally disturb the comparison task.

Training trials and trials with erroneous RTs due to false microphone activation were deleted before further analyses. The error rate amounted to only 1.71%, so no error analyses were conducted. In contrast to Experiment 1, Experiment 2 had no pre-programmed RT limit. Therefore, RTs exceeding the mean ± 2 SDs per participant were excluded from analyses; this excluded a further 4.13% of the data. Also, only trials with target numbers 2, 3 and 4 were analysed because 1 and 5 had no corresponding finger postures (see "Design" section). Table 1 shows mean RTs for each finger posture, target number and posture condition.

A repeated-measures ANOVA on RTs with the factors target (2 vs. 3 vs. 4), posture (2 vs. 3 vs. 4) and canonicity (canonical vs. non-canonical) revealed no significant main or interaction effects, all $ps > .29$, except for a marginally significant main effect of canonicity, $F(1, 24) = 4.14$, $p = .053$, $\eta_p^2 = .15$, due to 14-ms faster responses with canonical compared to non-canonical postures.

Congruency effect

Congruency is here defined as a match of target number with the number of extended fingers of the right hand;

Table 1 Mean RTs (standard errors in parentheses) by canonicity, finger posture and target number

Posture	Canonical			Non-canonical		
	Target 2	Target 3	Target 4	Target 2	Target 3	Target 4
2	735 (44)	766 (45)	751 (39)	767 (50)	764 (42)	772 (48)
3	756 (53)	779 (47)	771 (41)	762 (52)	779 (47)	774 (41)
4	763 (51)	770 (46)	739 (37)	774 (50)	789 (47)	772 (45)

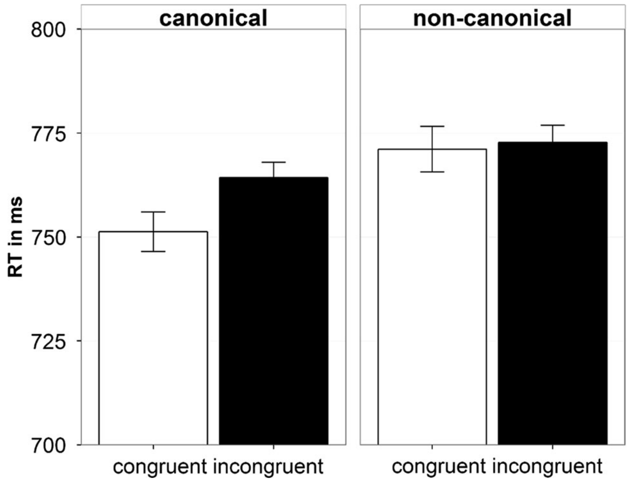

Fig. 5 Mean RTs in ms for congruent (*white*) and incongruent (*black*) conditions with canonical finger postures (*left panel*) and non-canonical finger postures (*right panel*). *Error bars* represent within-subject standard errors as suggested by Cousineau (2005)

incongruent trials involve finger postures and targets that do not represent the same number. We hypothesized that canonical finger postures would elicit a congruency effect (faster RTs for congruent than incongruent trials), whereas non-canonical finger postures should not. This was indeed the case: with canonical postures, RTs were significantly faster for congruent (751 ms, SD = 161) than incongruent trials (764 ms, SD = 179), $t(24) = 2.39$, $p = .025$, $d_z = .48$. RTs of trials with non-canonical postures were not significantly influenced by congruency (congruent: 771 ms, SD = 184; incongruent: 773 ms, SD = 182), $t(24) < 1$ (see Fig. 5). A post hoc power analyses revealed that based on our sample size of 25 subjects, an alpha level of .05 and an intended power of 80%, the design allowed us to detect medium to large effects of $d_z = .58$.

Again, we also analysed the priming properties over time: the RT effect (i.e. RT difference in ms of incongruent minus congruent condition per subject, trial and canonicity) for canonical and non-canonical postures was regressed over the trial number (1–12). The individual slope coefficients were tested against zero (Lorch and Myers 1990). Neither for canonical nor non-canonical postures, this one-sample *t*-test became significant; both $t(24) < 1$.

Starting hand

Participants adopted all postures with their dominant hand, which was not necessarily identical with their starting hand in finger counting. Out of the 25 participants, six started counting with the left hand, 18 with the right hand, and one was uncertain, but all of them counted from the thumb of the starting hand to the pinkie of the other hand, except for one who used the right hand twice from thumb to pinkie when counting to ten. We excluded the latter participant from a repeated-measures ANOVA with the within-subject factors canonicity (canonical vs. non-canonical posture) and congruency (congruent vs. incongruent condition), and the between-subject factor starting hand (left vs. right). Except for a main effect of canonicity, $F(1, 22) = 9.44$, $p = .006$, $\eta_p^2 = .30$, no significant effects emerged, all $p > .1$.

Discussion

Experiment 2 replicated, in a novel task and with verbal responses, the main finding of Experiment 1 that adopting canonical finger counting postures primes numerical concepts, thereby leading to faster responses in congruent conditions. It also confirmed the prediction of embodied numerical cognition that non-canonical finger postures do not possess this priming capability. The result was obtained with non-lateralized verbal responses, thus ruling out the need for lateralized responses to match lateralized finger stimuli as an important ingredient for motor priming of number concepts. The verbal responses engaged the participants' verbal apparatus and thus arguably prevented, to some extent, transcoding of finger postures into number names. Together with the participants' absence of insight into the purpose of the experiment, this evidence goes some way towards excluding a strategic verbalization account of the priming effect.

Contrary to expectation, the habitual starting hand in individual finger counting did not play a role in motor priming of number concepts. However, this null effect might be due to the relatively small number of left starters in our sample. Moreover, recent work by Wasner et al. (2015) showed that, depending on situated factors, either hand can be used to initiate finger counting, thus challenging the notion of a habitual starting hand.

General discussion

The present study investigated the priming mechanism underlying the association between numbers and fingers in adults. In Experiment 1, participants classified auditorily presented target numbers according to their magnitude as larger or smaller than five while either seeing or manually adopting finger counting postures. The objective of this manipulation was to compare the effectiveness of visual and motor priming of number processing through finger postures. We obtained several novel and theoretically important results: decision latencies for classifying auditorily presented target numbers in the magnitude classification task were faster when their magnitude category matched the current finger counting posture. Importantly, however, this priming effect was only present when participants manually adopted category–congruent postures and not when they merely viewed pictures of the same postures. This finding clarifies that the highly overlearned associations between finger postures and numerical concepts of adult subjects are not primarily based on visual representations of the hand, but instead highlight the importance of motor codes and proprioceptive feedback from manual behaviour for these embodied representations. This involvement of motor codes is in accordance with number processing theories (e.g. Fischer and Brugger 2011) which postulate that the development of numerical concepts is shaped by the acquisition of bidirectional associations between number words or symbols and motor experiences as it is, for instance, the case, when fingers are used to support counting in early childhood (Butterworth 1999; Knudsen et al. 2015; Lindemann and Fischer 2015). Importantly, the small error rates, the presence of a SNARC effect and the numerical distance effect, which were all equally present in the visual and motor priming conditions, indicated that participants processed the target numbers semantically.

Experiment 2 replicated the finding that adopting canonical finger counting postures yields faster response latencies in semantically congruent compared to incongruent conditions. Participants decided whether a visually presented target number was larger or smaller than a previously presented reference number while adopting canonical or non-canonical finger postures. Importantly, the numerical meaning of the finger counting postures was obscured by the non-canonical filler postures and almost no participant realized their true connection to the task. The requirement to respond verbally furthermore discouraged verbal recoding of finger postures and thus addressed the concern that any priming effect in the first experiment was due to strategic verbalization. Overall, the study highlights the importance of proprioceptive information in manual action for the retrieval of number knowledge that was previously learned through finger movements.

What might be a plausible mechanism for motor priming of number concepts? Our results of Experiment 1 suggest categorical response priming: participants responded faster when the category of the target number (small/large) matched the category of the manually adopted finger posture in a given mini-block. This finding is in line with a wide range of previous studies on numerical size priming through task-irrelevant primes, even when they are presented in different notations than the target stimuli (e.g. Dehaene et al. 1998; Di Luca and Pesenti 2008; Naccache and Dehaene 2001). The literature on response priming indicates that effects of dichotomous semantic stimulus categories—even when presented subliminally—are driven by a pre-activation of motor codes associated with a task-irrelevant stimulus feature or prime, due to an instructed response mapping of a similar but task-relevant stimulus feature (e.g. Reynvoet et al. 2005; for a review on response priming see Kiesel et al. 2007). The response time effects in the present study hence indicate that finger postures are automatically associated with numerical concepts so that they pre-activate the response that is related to those numerical concepts.

On the other hand, attentional shifts along the mental number line, induced by producing small or large numbers, could explain the results pattern: focussing on the “small” or “large side” of the number line would facilitate responses to numbers from that side. Previous studies found that attentional shifts on the mental number line influence numerical estimations (e.g. Cattaneo et al. 2011), so it is conceivable that category congruency is mediated by a spatial dimension.

The present study furthermore provides evidence for the notion that a particular finger counting posture is coupled with a specific numerical concept by demonstrating priming effects of specific numbers that are not caused by the compatibility between dichotomous categories of stimuli and responses (Experiment 2). We interpret this finding as evidence for the notion that an adopted finger posture is not only associated with a broad relational dichotomy of *small* or *large*, but that on top of that, sensorimotor representations of specific counting postures are linked to equally specific concepts of cardinality. Non-canonical finger postures with the same amount of outstretched fingers did not elicit this priming effect, thus highlighting the importance of the specific posture for a specific numerical concept.

It remains an open question whether visual- and motor-based priming is based on essentially the same or different cognitive mechanisms. Observers automatically mirror perceived actions of others by activating their own motor representation (e.g. Brass et al. 2000). This mechanism has been labelled as 'motor resonance' and has been proposed as the basis of action understanding (for a review see Fischer and Zwaan 2008). In the context of research on motor resonance in action observation, the present data suggest that motor representations are involved in the retrieval of numerical meanings of finger postures. These motor activations are triggered by action observation and are presumably the crucial ingredient for the emergence of apparently visual priming effects in previous studies using finger posture primes (e.g. Badets et al. 2010; Di Luca and Pesenti 2008). We therefore want to stress that the absence of the visual priming effect in the present study should not necessarily be taken as evidence against the existence of visual priming of number processing by hand postures in general. Moreover, it is plausible to assume that visual processing of finger postures results in motor resonance or motor simulation (Brass et al. 2000; Jeannerod 2006; Schütz-Bosbach and Prinz 2007), which might in turn have induced additional activation of the associated number concept. However, crucially, the present study reveals that the priming effects due to proprioception are stronger.

In conclusion, our findings of finger posture priming of number concepts are consistent with the embodied view of number cognition, according to which sensory and motor activations are a crucial part of knowledge representations and their retrieval. Our experience of actively performing counting postures while acquiring number knowledge in childhood is probably a crucial source of this association. The present results highlight the importance of the manual (i.e. motor and proprioceptive) codes activated by finger counting experiences for establishing such life-long links between fingers and numbers.

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