A helping hand putting in order:

Visuomotor routines organize numerical and non-numerical sequences in space

Luca Rinaldi [1,2]*, Samuel Di Luca [3,4], Avishai Henik [5] and Luisa Girelli [1,2]

[1] *Department of Psychology, University of Milano-Bicocca, Milano, Italy*

[2] *NeuroMI, Milan Center for Neuroscience, Milano, Italy*

[3] *Institute of Neuroscience, Catholic University of Louvain, Belgium*

[4] *University of Luxembourg, Walferdange, Luxembourg*

[5] *Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer Sheva, Israel*

Word count:
abstract: 256 words
main text: 8932 words

* Corresponding author:

Dipartimento di Psicologia, Università degli Studi di Milano-Bicocca, Piazza dell'Ateneo Nuovo 1, Edificio U6, 20126 Milano, Italy.
Tel.: +39 6448 3865
E-mail address: l.rinaldi2@campus.unimib.it

Abstract

Theories of embodied cognition emphasize the importance of sensorimotor schemas linked to external world experience for representing conceptual knowledge. Accordingly, some researchers have proposed that the spatial representation of numerical and non-numerical sequences relies on visuomotor routines, like reading habit and finger counting. There is a growing interest in how these two routines contribute to the spatial representation of ordinal sequences, although no investigation has so far directly compared them. The present study aims to investigate how these routines contribute to represent ordinal information in space. To address this issue, bilingual participants reading either from left-to-right or right-to-left were required to map ordinal information to all fingers of their right dominant hand. Critically, we manipulated both the direction of the mapping and the language of the verbal information. More specifically, a finger-mapping compatibility task was adopted in three experiments to explore the spatial representation of numerical (digit numbers and number words) and non-numerical (days of the week, presented in Hebrew and in English) sequences. Results showed that numerical information was preferentially mapped according to participants' finger counting habits, regardless of hand posture (prone and supine), number notation and reading habit. However, for non-numerical ordinal sequences, reading and finger counting directions both contributed to determine a preferential spatial mapping. These findings indicate that abstract knowledge representation relies on multiple over-trained visuomotor routines. More generally, these results highlight the capacity of our cognitive system to flexibly represent abstract ordered information, by relying on different directional experiences (finger counting, reading direction) depending on the stimuli and task at hand.

Keywords: visuomotor routines; finger counting; reading habit; numerical information; ordinal information.

Introduction

Over the last years, the contribution of the sensorimotor system to human cognition has been widely documented by compelling empirical evidence. In the light of the so called “embodied cognition”, according to which cognitive processes are deeply shaped by the body interaction with the environment (Barsalou, 2008a, 2008b; Gibbs, 2006; Wilson, 2002), many authors have suggested an influence of the motor system not only on action control, but also on high-level cognitive functions, such as language (Glenberg & Kaschak, 2002) and mathematics (Andres, Olivier & Badets, 2008; Lakoff & Nunez, 2000). Correspondingly, although mental arithmetic was for long considered a manipulation of abstract symbols, increasing evidence has shown the influence of the sensorimotor system on the mental representation of numerical information. In particular, developmental, behavioral and neuroanatomical findings support the contribution of finger counting to numerical representation, with fingers that might represent the “missing tool” from a rough number sense to a symbolical number concept (Andres, Di Luca & Pesenti, 2008; see also Michaux, Pesenti, Badets, Di Luca & Andres, 2010).

Turning around numerical and ordinal information

Sound evidence supports the existence of a tight connection between numbers and space. In particular, the ‘SNARC’ (Spatial Numerical Association of Response Codes) effect, referring to faster responses to smaller/larger numerosities with the left/right hand in Western populations (Dehaene, Bossini & Giraux, 1993), has been taken as a proof supporting the spatial representation of numbers along a ‘Mental Number Line’ (MNL) (Dehaene, 1992; see for a review de Hevia, Vallar & Girelli, 2008). Nevertheless, ordinal sequences are more widely associated to space, since response-side effect have been reported also for non-numerical ordinal information (Gevers, Reynvoet & Fias, 2003, 2004; Gevers et al., 2010). Consequently, the SNARC effect has been partially attributed to the activation of the ordinal meaning of numbers (Gevers et al., 2003). Indeed, processing the position of a number in a sequence, rather than its relevant magnitude, is a sufficient condition to observe the well-known compatibility effect between numbers and space (see van Dijck & Fias, 2011; see for a proposal that distinguishes spatial-numerical associations in terms of cardinality and ordinality, Patro, Nuerk, Cress & Haman, 2015). Critically, while the spatial nature of the representation of any ordinal sequences is not questioned, the origin of this spatial mapping is still controversial.

On the one hand, some studies have suggested that these compatibility effects originate from reading and writing practices (Dehaene et al., 1993; Berch, Foley, Hill & Ryan, 1999), with a reduced or reversed SNARC effect in right-to-left readers (Dehaene et al., 1993; Zebian, 2005). Indeed, oculomotor routines involved in reading and writing processes would result, through repetition, in a preferential scanning direction of the external space (see Rinaldi, Di Luca, Henik & Girelli, 2014) and, in turn, of the internal representational space (Dehaene et al., 1993). Accordingly, specific cultural practices seem to be strictly necessary for a numerical mapping along a spatial continuum (Núñez, 2011; Núñez, Cooperrider & Wassmann, 2012; see for a review McCrink & Opfer, 2014; see also Nuerk et al., 2015).

On the other hand, some studies have attributed to these practices a relative rather than an absolute importance (Fischer, Mills & Shaki, 2010; Shaki & Fischer, 2012; Shaki, Fischer & Petrusic, 2009), since the directional scanning associated to reading habits can flexibly impact on the SNARC effect (Fischer, Shaki, & Cruise, 2009; Fischer et al., 2010). For instance, manipulating the position of digits within a text (i.e., placing small numbers on either the left or right side of a given page, and correspondingly for larger numbers) can influence the typical response-side compatibility effect, suggesting that the impact of reading habits is far from being persistent (Fischer et al., 2010; see also Patro, Fischer, Nuerk, & Cress, 2015). Moreover, the presence of spatial-numerical associations in preschool-age children speaks in favor of observational learning, rather than formal reading practices, as critical to shape the internal organization of mental representation (Ebersbach, Luwel, & Verschaffel, 2015; Hoffmann, Hornung, Martin & Schiltz, 2013; Opfer, Thompson & Furlong, 2010; Patro & Haman, 2012; Shaki, Fischer & Göbel, 2012). This evidence complements those on nonhumans (Drucker & Brannon, 2014; Rugani, Vallortigara, Priftis, & Regolin, 2015) and on infants

(Bulf, de Hevia & Macchi Cassia, 2015; de Hevia, Girelli, Addabbo, & Macchi Cassia, 2014), speaking in favor of an early onset of spatial-numerical associations (see for a discussion de Hevia, Girelli, & Macchi Cassia, 2012).

Only recently, however, some authors proposed that fingers might represent an embodied tool onto which numbers are mapped in space (Di Luca & Pesenti, 2011; Fischer & Brugger, 2011; but see for a more generalized concept of numerical embodied representation, Moeller, Fischer, Link, Wasner, Huber, Cress & Nuerk, 2012). In particular, associations between numbers and space can be determined by finger counting routines (Di Luca, Granà, Semenza, Seron & Pesenti, 2006) or, at least, can be modulated by them (Fischer, 2008; Fischer & Brugger, 2011; Riello & Rusconi, 2011; but see Brozzoli, Ishihara, Gobel, Salemme, Rossetti & Farné, 2008; Plaisier & Smeets, 2011). For instance, previous studies have shown that finger-number mapping is invariant whatever the hand posture, i.e., supine and prone (Di Luca et al., 2006; see also Riello & Rusconi, 2010). This ordered practice, indeed, would establish a preferential direction for mapping numerical information on the hand space (see for a discussion, Cohen, Naparstek & Henik, 2014). Accordingly, number-to-finger associations have been shown to influence number processing (Di Luca & Pesenti, 2008; Sato, Cattaneo, Rizzolatti & Gallese, 2007; Domahs, Klein, Moeller, Nuerk, Yoon & Willmes, 2011) and to modulate mental numerical representation (Di Luca et al., 2006; Di Luca, Lefèvre, & Pesenti, 2010; Fischer, 2008; Domahs, Moeller, Huber, Willmes & Nuerk, 2010). Moreover, the link between finger counting and number processing is further strengthened by neuroimaging evidence showing that activation of the primary hand motor cortex in numerical processing is partially modulated by the direction of finger counting (Tschentscher, Hauk, Fischer & Pulvermüller, 2012). On these grounds, Fischer and Brugger (2011) proposed that spatial-numerical associations might originate from finger counting routines. Whether the starting point and the directionality of finger counting is related to handedness or to cultural factors (Bender & Beller, 2011d; 2012; Lindemann, Alipour & Fischer, 2011; Knudsen, Fischer, & Aschersleben, 2014), however, is still a matter of debate (see for a discussion Previtali, Rinaldi & Girelli, 2011).

In summary, the assumption that finger counting can shape, together with reading habits, the spatial representation of ordinal sequences receives general consensus. Nevertheless, insofar no study has directly compared the influence of finger counting and reading direction. In fact, previous researches investigated the strength of finger counting routine on MNL representation (Brozzoli et al., 2008; Di Luca et al., 2006; Riello & Rusconi, 2011) without considering language direction.

Combining directions: The present study

The literature supports finger counting and reading habits as determinant cultural visuomotor routines for representing ordinal information in space. However, no study has so far investigated whether the spatial representation of numbers and, more generally, of ordinal sequences relies on finger counting (FC), on reading direction (RD) or on an interplay of both. In the present study, we directly explored the strength of the "finger-representation account" and of the "reading-representation account" in a series of three experiments, by requiring participants to map ordinal information to all fingers of the dominant hand. Moreover, to emphasize the impact of reading direction on the spatial representation of ordinal information, Israeli participants reading both from left-to-right and from right-to-left were involved.

In Experiment 1, we tested whether Spatial-Numerical Associations (SNAs) are determined by FC direction or by the standard Western left-to-right orientation of the MNL[1]. In particular, participants performed a finger-mapping task with Arabic numbers, with the direction of the finger-digit mapping systematically varied from left-to-right or from right-to-left (i.e., 1 to 5: thumb-little finger *vs* little finger-thumb). Additionally, to test the strength of FC account we further manipulated the direction of the mapping, by requiring participants to perform the task with their right hand in both pronated and supinated posture. In Experiment 2, we explored whether SNAs on the hand space are determined by FC or by RD. Specifically, we investigated whether SNAs might adapt flexibly

---

[1] A recent study by Shaki & Gevers (2011) found a regular SNARC effect with Arabic numbers in bilingual Israeli participants. On these grounds, in the present paper we refer to the MNL as flowing from left-to-right.

to situational factors, by requiring participants to map number words, presented both in English and in Hebrew, to specific fingers. Finally, we investigated the role of FC and RD in the mapping of non-numerical ordinal information, i.e., days of the week, presented in both languages. Thus, in all experiments, we explored the spatial representation of ordinal information on the hand space, i.e., on fingers.

In Experiment 1, we hypothesized that if numbers are associated to specific fingers through long-term memory representations, responses should be faster when numbers are mapped according to participants' FC routine, independently from hand posture and from the standard orientation of the MNL. Indeed, finger-numeral representations are particularly emphasized in the current task setting, which requires a fine discrimination between all fingers of the dominant hand at the response level. Similarly, in Experiment 2, number words should be preferentially mapped according to participants' FC routine regardless of language direction, due to long-term memory finger-number associations. These patterns of results would therefore suggest that finger-number associations are not sensitive to the direction of the cultural reading and writing habit, leading to the same response pattern in both prone and supine postures. Finally, since the mapping of non-numerical ordinal information has been shown to be modulated by RD, and since the present task setting particularly emphasizes FC, we expect both routines to contribute to the preferential spatial mapping. This hypothesis was tested in experiment 3.

Experiment 1

In Experiment 1, participants performed a finger-number mapping compatibility task with Arabic numbers in palm-up and in palm-down postures (Di Luca et al. 2006; *Experiment 2*). However, while Di Luca and colleagues (2006) adopted a ten-finger response setting, emphasizing both directions within and between hands, in the present study we specifically focused on numerosity 1-to-5, by requiring participants to map numbers to fingers of their right dominant hand only. In fact, a recent study by Riello and Rusconi (2011) tested the relation between MNL and FC representations by means of a unimanual classification tasks (i.e., two fingers of the same hand used to respond in different postures). Faster RTs were found only when directions of the two representations were compatible (i.e., when the right hand is pronated or the left hand is supinated, since both FC and RD run from thumb-to-little fingers and thus from left-to-right). Riello and Rusconi (2011) suggested that this pattern might have been driven by the existence of two vectors (MNL and FC) having similar force but opposite direction in the non-compatible conditions (i.e., when the right hand is supinated or the left hand is pronated). Furthermore, they attributed the difference between their own and Di Luca et al.'s results (2006) to the response setting greatly differing in terms of finger discrimination. It remains to be established whether unimanual responses might reduce the influence of FC routine (see Riello & Rusconi, 2011). Hence, in Experiment 1, we opted for a unimanual task but with all five fingers involved. Following Di Luca et al. (2006), we predicted that FC would determine the preferential spatial representation of numbers.

Method

Participants

A total of 20 right-handed participants took part in Experiment 1 for payment (*M* age = 24.7 y.o., *SD* = 1.4; 13 females). Participants were Israeli students from the Ben-Gurion University of the Negev (Israel). All of them were native-born Israelis with Hebrew as their mother language and with good English skills: they were all familiar with a left-to-right language, since they started to learn English in the fourth/fifth grade of primary school (Arabic digits are typically written from left-to-right in Hebrew). They also judged themselves as fluent in the second language and therefore we considered them altogether as bilingual or bidirectional participants. Laterality was further assessed by means of the Edinburgh Inventory (Oldfield, 1971): all participants were classified as right-handers. All the participants had a normal or corrected-to-normal visual acuity and were naïve with respect to the experimental hypotheses.

Apparatus

Data collection and stimulus presentation were controlled by a Dell OptiPlex 760 vPro computer with an Intel Core 2 duo processor E8400 3 GHz. The stimuli were presented on a Dell E198PF 19" LCD monitor. Participants were seated approximately 60 cm from the screen and answers were given by key presses on a standard QWERTY keyboard. More specifically, participants adopted a typical typing position on the keyboard to ensure a comfortable posture for the hand and arm and a good inline positioning of the fingers (keys H, J, K, L), except for the thumb, which was lowered slightly (key B). All the non-responding keys were removed from the keyboard to facilitate finger movement. For the palm-up posture condition, the keyboard was turned upside-down and was fixed on the table. The left, non-responding, hand was always placed on the ipsilateral knee, with the same posture of the hand used to execute the task.

Stimuli and Procedure

Stimuli were Arabic digits from 1 to 5, presented in black Times New Roman font (size 36) at the centre of a white background screen. Each trial started with a central cross lasting for a variable time (500, 650, 800, 950 and 1100 ms), in order to avoid automatic responses, followed by the stimulus that remained on the screen until the participant answered, and ended with a blank screen lasting for 500 ms before the next trial (see Figure 1a).

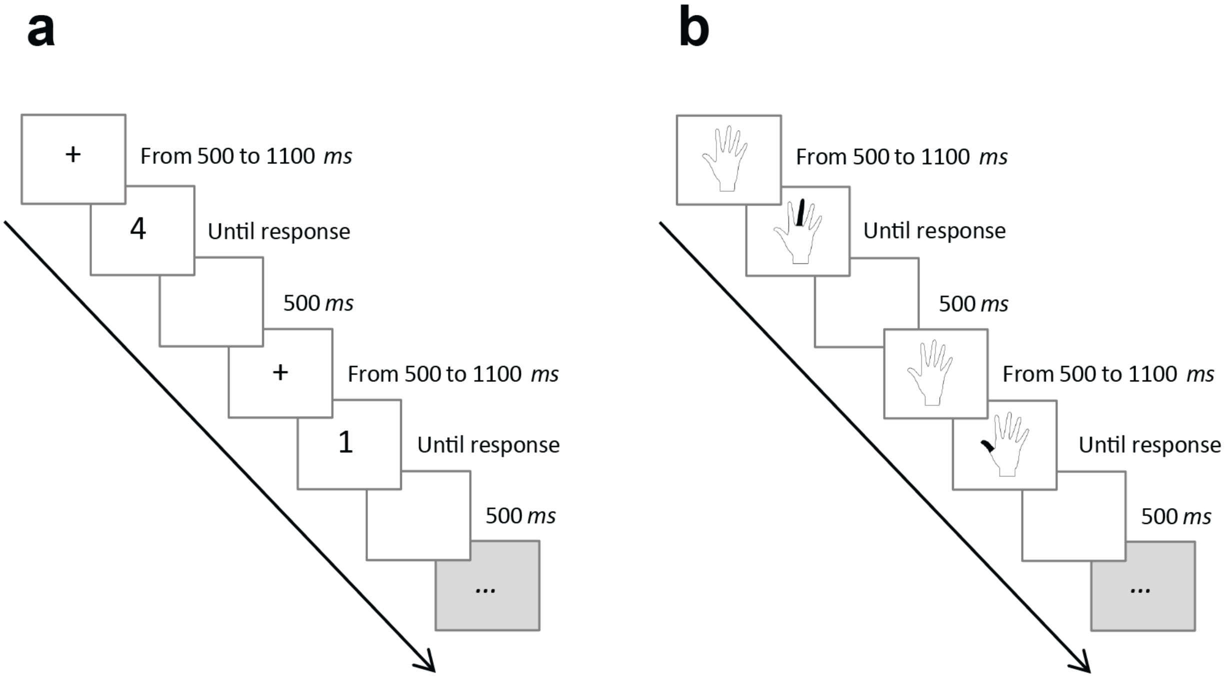

Figure 1. Procedure of Experiment 1 for (**a**) the experimental block with numbers and for (**b**) the motor baseline task. During the experimental block, each trial started with a fixation point, followed by a number that lasted on the screen until participant's answer, and ended with a blank screen. Similarly, in the motor baseline, a hand silhouette with a darkened finger appeared on the screen until participant's answer.

Each mapping was presented in a separated block, in a counterbalanced order across participants. Four mappings were obtained combining 2 variables (see Figure 2b): *a)* numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb) and *b)* hand posture (prone, supine). Thus, in the prone condition mapping A consisted in associating 1 to the thumb and 5 to the little finger, and mapping B, in associating 5 to the thumb and 1 to the little finger. Likewise, in the supine condition we had mapping C, associating 1 to the thumb and 5 to the little finger, and mapping D, associating 5 to the thumb and 1 to the little finger. Mappings resulted, therefore, as completely compatible (A) or incompatible (B) with both participants FC and MNL orientations, whereas mapping C and D were only compatible with the FC or MNL, respectively. The four mappings were assigned in a counterbalanced order across participants. A block was composed of 10 (not analyzed) practice and 50 experimental trials. The order of presentation of the stimuli was pseudorandomly determined (at least three items before the repetition of the same digit). Participants had to press, as fast as possible, the key corresponding to the displayed digit as indicated by the specific finger–digit mapping; during the training phase, a figure showing the finger-digit mapping to be adopted was placed beside the keyboard to help participants remembering each association.

Critically, Riello and Rusconi (2011) manipulated hand posture (i.e., prone and supine) across participants, in order to minimize errors due to mental rotation strategies (e.g., see Leuthard, Bächtold & Brugger, 2005). In our study, however, we reduced variability due to the individual differences, by assessing each posture in two different daily-sessions in all participants (e.g., between 24 and 72 hours).

To control for possible motor speed differences between fingers and hand postures, at the end of each session participants performed a motor baseline reaction time task. Stimuli were line drawings of a right hand in a prone or supine posture. Each trial started with a drawing of a hand lasting for a variable time (500, 650, 800, 950 and 1100 ms), in order to avoid automatic responses. It was followed by the same drawing with a finger pseudorandomly darkened, that remained on the screen until the participant answered with the corresponding finger, and then ended with a blank screen lasting for 500 ms before the next trial started (see Figure 1b). This task was composed of 10 (not analyzed) practice and 50 experimental trials.

Finally, at the end of the second session, we assessed the personal finger counting strategy as in Di Luca et al.'s study (2006). Participants were asked to place their hands palm down on their knees and, then, to show "how they count from 1 to 10 on their fingers". A spontaneous finger counting assessment allowed us to better focus on the embodied level of finger counting routine (see Wasner, Moeller, Fischer & Nuerk, 2014; see also Lucidi & Thevenot, 2014).

Finger counting assessment

Overall, 18 participants out of 20 started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand. Two subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 18 participants (*M* age = 23.9 y.o., *SD* = 1.3; 12 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check possible differences in the motor baseline task. The overall error rate was 2.6% for the prone posture and 2.3% for the supine posture. A 2x5 repeated measures analysis of variance (ANOVA) on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Results showed a main effect of finger, $F(4, 68) = 14.17$, $p < .001$, $\eta^2_p = .47$ (thumb: *M* = 430.67 ms, *SD* = 47.3; index finger: *M* = 414.3 ms, *SD* = 51.8; middle finger: *M* = 426.6 ms, *SD* = 55.6; ring finger: *M* = 448 ms, *SD* = 57; little finger: *M* = 424.5 ms, *SD* = 50.9). A main effect of hand posture was also found, $F(1, 17) = 15.48$, $p < .002$, $\eta^2_p = .49$, with faster RTs for the prone condition (prone posture: *M* = 414.3 ms, *SD* = 51; supine posture: *M* = 443.4 ms, *SD* = 51.7), while the interaction was not significant. To avoid any possible confounding motor effects, we first calculated for each participant the average RT of each finger in each posture. Then, the RT of the fastest finger was subtracted from the RT of each other finger, obtaining an index of each finger relative speed (i.e., finger Δ). The finger Δ was then subtracted from the average RT of each finger in each experimental mapping, resulting in a corrected finger RT. A further correction was applied to avoid confounding effects of hand posture. Due to the faster performance in the prone posture, for each participant the average RT of each finger in the prone posture was subtracted from its average RT in the supine posture (i.e., posture Δ). The posture Δ was then subtracted from the average RT of each finger in each experimental mapping of the supine posture, resulting in a corrected supine finger RT. Only RTs of correct responses were analyzed in the experimental sessions and we separately performed an analysis of errors.

Results

Errors

Error rates were respectively 3.2% (A), 3.3 % (B), 2.8% (C) and 3.1% (D) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A 2x2 repeated measures ANOVA analysis with numbers direction (thumb-little finger, little finger-thumb – referred to 1-5 finger-association) and hand posture (prone, supine) as within-subjects variables was carried out. Results showed no significant main effect or interaction.

Reaction Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (3.4% of the data). A 2x2 repeated measures ANOVA with numbers direction (thumb-little finger, little finger-thumb) and hand posture (prone, supine) as within-subjects variables was carried out. A significant effect of numbers direction was found, $F(1, 17) = 32.65$, $p <. 001$, $\eta^2_p = .66$, with faster RTs for the thumb-little finger mappings, i.e., mappings A and C ($M = 508.5$ ms, $SD = 125$), compared to little finger-thumb mappings, i.e., B and D ($M = 563.2$ ms, $SD = 133.7$) (see Figure 2a). All the other effects were not significant.

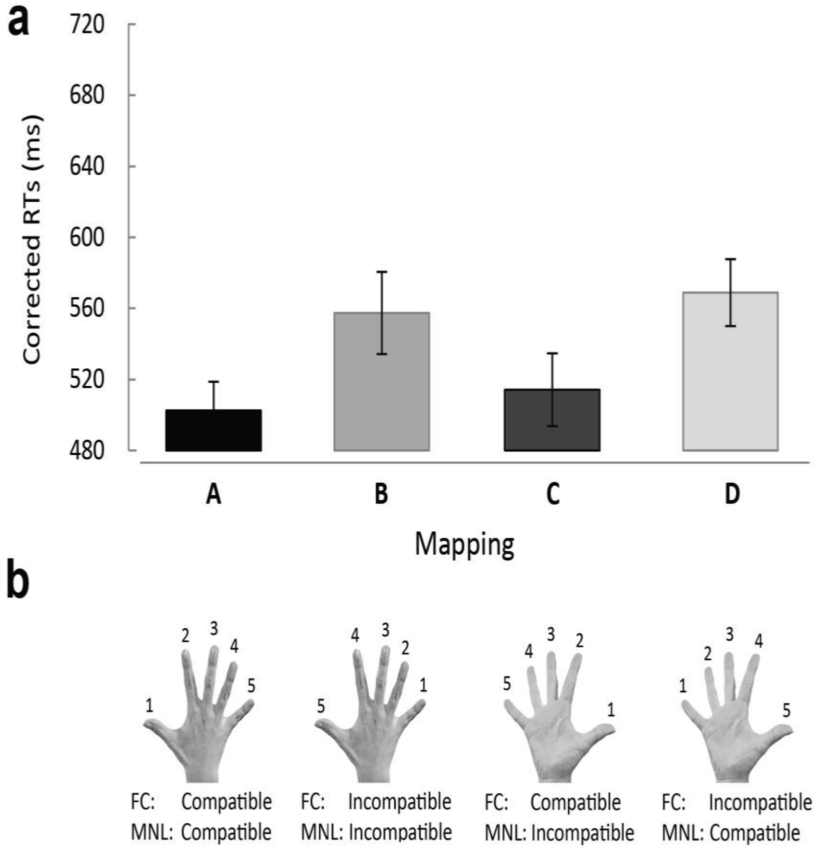

Figure 2. (**a**) Results of Experiment 1. Mean corrected response times (RTs), as a function of the finger-digits mappings. Results showed that participants responded faster with mappings compatible with FC (i.e., mappings A and C). Error bars indicate ±1 standard error of the mean. (**b**) Finger–digit mappings of Experiment 1. Mappings were obtained by combining two variables: *a)* numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb) and *b)* hand posture (prone, supine). In this way, we aimed at exploring whether Arabic digits are preferentially mapped according to FC, MNL or to a combination of both. Thus, in mapping A both FC and MNL were compatible, while in mapping B they were both incompatible. In mapping C only FC was compatible, while in mapping D only MNL was compatible.

Next, we further explored differences in terms of ordinal position of the digits to be mapped (see Figure 3 for RTs results as a function of mapping and of Arabic digits). In particular, since we were interested in investigating how numbers were classified depending on their position in the sequence, we performed a one-way ANOVA with Arabic digits as within-subjects variable (One, Two, Three, Four, Five). Results showed a main effect of Arabic digits on RTs, $F(4, 68) = 26.23$, $p <. 001$, $\eta^2_p = .61$. Post-Hoc comparisons (Scheffè) revealed that digit *One* ($M = 440.34$ ms, $SD = 81.19$) was classified significantly faster than *Two* ($M = 548.16$ ms, $SD = 93.36$; $p < .001$), *Three* ($M = 576.85$ ms, $SD = 79.95$; $p < .001$), *Four* ($M = 584.45$ ms, $SD = 104.2$; $p < .001$) and *Five* ($M = 529.27$ ms, $SD = 77.73$;

p < .01). Furthermore, digits *Two* (*p* < .01) and *Five* (*p* < .05) were classified significantly faster than *Four*.

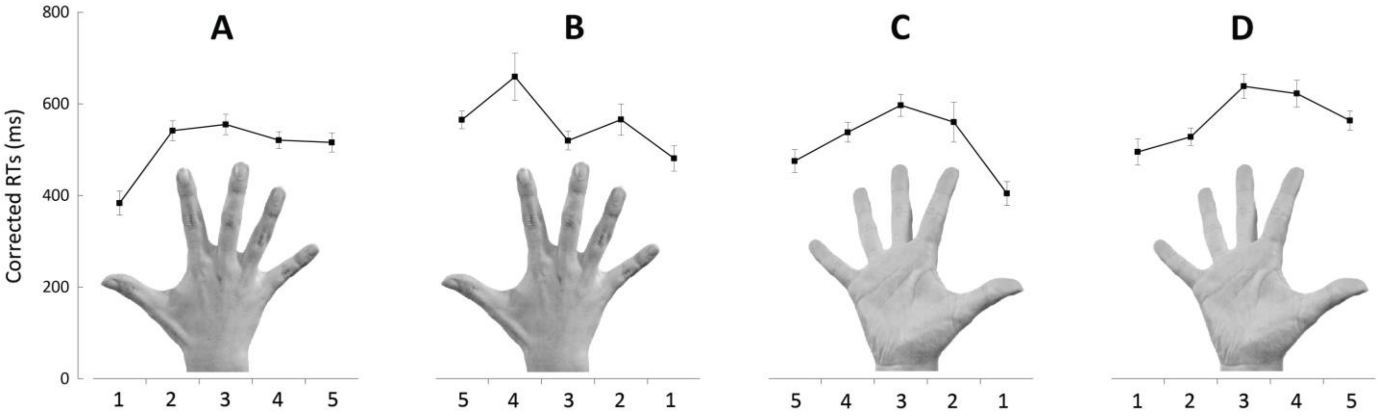

Figure 3. Mean corrected response times (RTs) in Experiment 1 as a function of each mapping and of each finger used. Results showed that participants responded faster to digit *One* than to all the other digits, while they responded slower to digit *Four*.

Discussion

The aim of Experiment 1 was to assess the strength of FC influence on SNAs, by requiring participants to identify Arabic digits from 1 to 5. In particular, according to our hypothesis, the fastest mapping was found when participants mapped numbers congruently to their finger counting strategy (i.e., mappings A and C), independently from the orientation of the MNL compatibility. Thus, our findings extended Di Luca et al.'s study (2006) to unimanual responses, based on responses given with all fingers of the hand (cf. Riello and Rusconi, 2011, in which only the index and middle fingers were used).

A previous study by Di Luca et al. (2006), indeed, found that when all 10 fingers are used to respond, the mapping reflecting the prototypical finger-counting strategy led to faster reaction times than the mapping congruent to the space-based representation, i.e., a left-to-right oriented MNL. However, Brozzoli et al. (2008) further showed that irrelevant numbers influenced a tactile detection task in a way compatible only with the MNL representation. These apparently contrasting results may be attributed to different experimental methods leading to different activation of the finger-space representation. Indeed, while in Brozzoli et al.'s study (2008) participants answered to a tactile stimulation of the hand finger with a foot response (i.e., passive hand), here a finger motor response was required (i.e., active hand). These differences might have modulated the competition between MNL and FC representations, likely resulting in higher competition when fingers representation is crucial to the selection of the response (see for a discussion, Riello & Rusconi, 2011).

Experiment 2

In Experiment 2, we addressed whether SNAs are determined by FC, by RD or by an interplay of both. Participants were now required to map both English and Hebrew number words to fingers of their right hand. In other words, Experiment 2 explored whether language direction might influence the finger-number mapping found in Experiment 1. In fact, previous research has shown that SNAs in bilingual participants rely on language manipulation (Fischer et al., 2009, 2010; Shaki & Gevers, 2011). For instance, the orientation of SNAs rapidly changes depending on whether participants are processing Russian or Hebrew number words in a classic bimanual classification task (Fischer et al., 2009). In Experiment 2, we explored any effect of language manipulation in the mapping of Hebrew and English number words on the hand space. We hypothesized that, if fingers are associated to specific numbers through long-term memory representations consolidated by visuomotor practice across the life-span, language constraints should not influence SNAs.

Method

Participants

A total of 24 right-handed participants (*M* age = 24.3 y.o., *SD* = 1.5; 12 females) took part in Experiment 2 for payment. Participants were bilingual Israeli students from the Ben-Gurion University of the Negev (Israel).

Apparatus

We used the same apparatus as in Experiment 1.

Stimuli and Procedure

Stimuli consisted of English number words (ONE, TWO, THREE, FOUR, FIVE) and Hebrew number words (חמש, ארבע, שלוש, שתים, אחת). The procedure was the same as the one adopted in Experiment 1. Eight mappings were obtained combining 3 variables: *a)* numbers direction, reflecting the prescribed mapping of number words to the fingers (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language of the stimuli (English, Hebrew). Thus, with English number words, in the prone condition mapping A consisted in associating ONE to the thumb and FIVE to the little finger, while mapping B in associating FIVE to the thumb and ONE to the little finger. Likewise, in the supine condition we had mapping C associating ONE to the thumb and FIVE to the little finger, and mapping D associating FIVE to the thumb and ONE to the little finger. Therefore, in the English condition, mappings resulted as completely compatible (A) or incompatible (B) with FC and RD, whereas mapping C and D were only compatible with the FC or RD, respectively. The same mappings were also obtained for Hebrew number words. A description of the English and Hebrew mappings is reported in Figure 4b. As in Experiment 1, hand posture was assessed in two separated daily sessions. Moreover, mappings of the same language were assessed subsequently within the same session. Hence, in Experiment 2 participants had to complete four different blocks in each session (e.g., day one: A-B-E-F; day two: C-D-G-H). The order of the eight mappings was counterbalanced across participants. To control for possible motor speed differences among fingers and hand posture, participants performed a baseline reaction time task for each pronated and supinated posture, as in Experiment 1.

Finally, at the end of the second session the personal finger counting strategy was assessed.

Finger counting assessment

Overall, 21 participants, out of 24, started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand. Three subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 21 participants (*M* age = 23.9 y.o., *SD* = 1.3; 12 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check for possible motor differences in the baseline task. A 2x5 repeated measures ANOVA on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Similar to Experiment 1 finger and hand posture were both found to be significant. Thus, as in Experiment 1, only corrected RTs were analyzed.

Results

Errors

Error rates were respectively 3.1% (A), 3.9 % (B), 4.1% (C), 2.5% (D) 5.2% (E), 4.5 % (F), 2.8% (G) and 4% (H) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A 2x2x2 repeated measures ANOVA with numbers direction (thumb-little finger, little finger-thumb – referred to 1-5 finger-association), hand posture (prone, supine) and language (Hebrew, English) as within-subjects variables was carried out. Results showed no main effect or interaction.

Reaction Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (4.6% of the data from the English mappings and 4% of the data from the Hebrew mappings). A 2x2x2 repeated measures ANOVA with numbers direction (thumb-little finger, little finger-thumb), hand posture (prone, supine) and language (Hebrew, English) as within-subjects variables was carried out. Results revealed a significant effect of language, *F*(1, 20) = 95.28, $p < .001$, $\eta^2_p = .83$, with faster RTs for Hebrew number words (*M* = 550.8 ms, *SD* = 92.2) compared to English ones (*M* = 605.7 ms, SD = 84.8). Most importantly, a significant effect of numbers direction was found, *F*(1, 20) = 39.84, $p <.001$, $\eta^2_p= .67$, with faster RTs for the mappings compatible with FC (*M* = 558.6 ms, *SD* = 82.4; i.e., mappings A, C, E, G) compared to the non-compatible ones (*M* = 597. 9 ms, *SD* = 91.9; see 3a) (see Figure 4a). Finally, a significant interaction between numbers direction and hand posture was found, *F*(1, 20) = 9.12, $p < .01$, $\eta^2_p = .31$. Post-Hoc comparisons (Scheffè) revealed that, additionally to the main effect of numbers direction, the typical finger counting mapping on the prone condition was significantly faster (*M* = 549.2 ms, *SD* = 75.5) than the typical finger counting mapping on supine posture (*M* = 567.9 ms, *SD* = 89.3; $p < .05$). No others main effects or interactions were found.

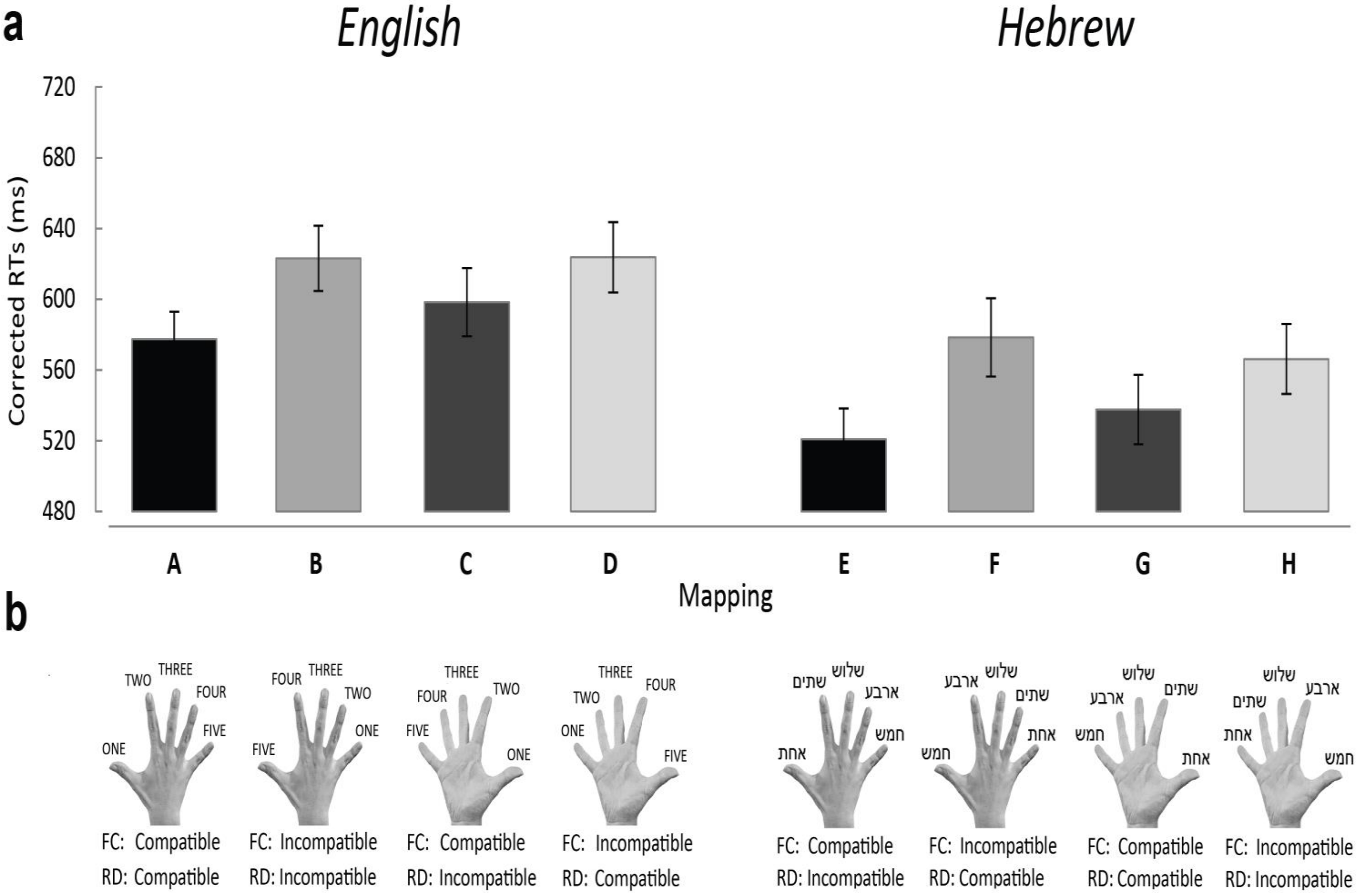

Figure 4. (**a**) Results of Experiment 2. Mean corrected response times (RTs), as a function of the finger-number words mappings both in the English (i.e., mappings A-D) and in the Hebrew conditions (i.e., mappings E-G). Results showed that participants responded faster with mappings compatible with FC, either with English number words (i.e., mappings A and C) or with Hebrew number words (i.e., mappings E and G). Error bars indicate ±1 standard error of the mean. (**b**) Finger–number words mappings of Experiment 2. Mappings were obtained by combining three variables: *a)* numbers direction, referred to 1-5 finger-association (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language of the stimuli (English, Hebrew). In this way, we aimed at explore whether number words are preferentially mapped according to FC, RD or to a combination of both.

Next, we further explored differences in terms of ordinal position of the numbers to be mapped (see Figure 5 for RTs results as a function of mapping and of number word). In particular, we performed a one-way ANOVA with number words as within-subjects variable (One, Two, Three, Four, Five).

A first ANOVA on English mappings showed a main effect of number words on RTs, $F(4, 80) = 35.54$, $p <. 001$, $\eta^2_p = .64$. Post-Hoc comparisons (Scheffè) revealed that *One* (M = 535.34 ms, SD =

64.59) was classified significantly faster than *Two* (*M* = 610.19 ms, *SD* = 66.52; *p* < .001), *Three* (*M* = 654.11 ms, *SD* = 96.85; p < .001), *Four* (*M* = 635.46 ms, *SD* = 82.28; *p* < .001) and *Five* (*M* = 593.2 ms, *SD* = 76.22; p < .001). Furthermore, *Two* was classified significantly faster than *Three* (*p* < .05) and *Four* (*p* < .01). Finally, *Five* was classified faster than *Three* (*p* < .001) and *Four* (*p* < .005).

A second ANOVA on Hebrew mappings showed a main effect of numbers on RTs, *F*(4, 80) = 32.07, *p* <. 001, η^2_p = .62. Post-Hoc comparisons (Scheffè) revealed that *One* (*M* = 503.49 ms, *SD* = 66.95) was classified significantly faster than *Two* (*M* = 585.59 ms, *SD* = 91.96; *p* < .001), *Three* (*M* = 584.62 ms, *SD* = 104.29; *p* < .001), *Four* (*M* = 574.67 ms, *SD* = 86.68; *p* < .001), but not of *Five* (*M* = 505.66 ms, *SD* = 64.4). Furthermore, *Five* was classified significantly faster than *Two* (*p* < .001), *Three* (*p* < .001) and *Four* (*p* < .001).

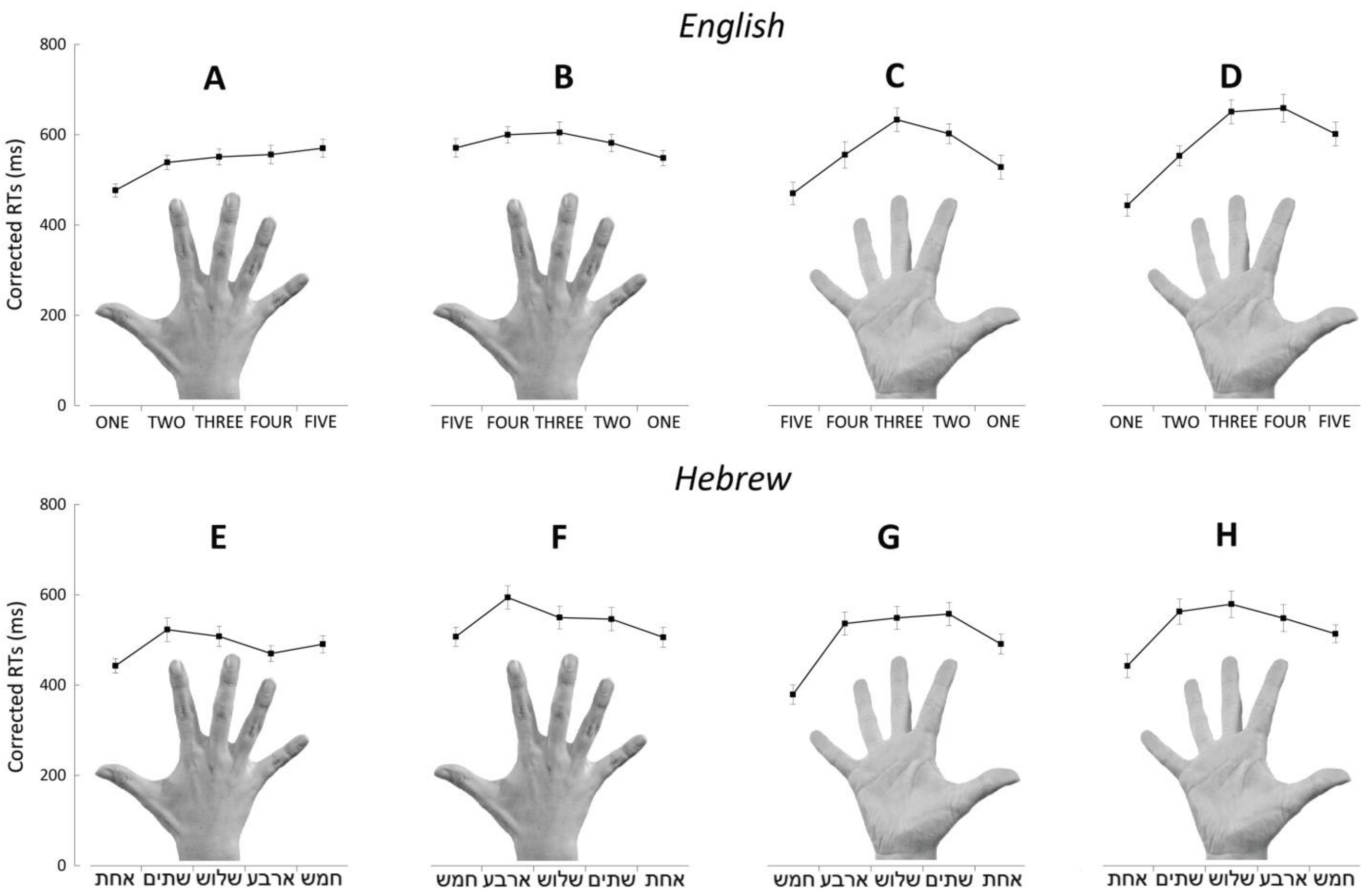

Figure 5. Mean corrected response times (RTs) in Experiment 2 as a function of each mapping and of each finger used. In the English mappings, results showed that participants responded faster to *One* than to all the other number words. On the contrary, participants responded slower to *Three* and *Four*. In the Hebrew mappings, results showed that participants responded faster to *One* and *Five*, whereas *Two*, *Three* and *Four* were classified slower.

Discussion

In Experiment 2, we explored whether language direction influences the spatial representation of numbers, by presenting number words either in English or Hebrew. Indeed, it has been previously demonstrated that the spatial representation of numbers can be influenced by either language dependent modifications (Fischer et al., 2009; Shaki & Gevers, 2011) or short-term positional changes (Fischer et al., 2010) in bimanual classification tasks. However, no study has so far investigated whether such flexibility might be observed for SNAs on the hand space. Critically, results of Experiment 2 revealed that SNAs on the hand space (i.e., fingers) are not influenced by language dependent modifications, i.e., the fastest mapping was always compatible with the typical FC strategy. These results give further support to the hypothesis of a long-term memory association between fingers and numbers (see Di Luca & Pesenti, 2011).

Experiment 3

In Experiment 3, we investigated whether the spatial mapping of non-numerical ordinal information, i.e., days of the week, presented either in Hebrew or in English, relies on FC, on RD or on a combination of both. In fact, in Experiments 1 and 2 no effect of language emerged, contrary to previous studies that adopted a bimanual task setting (e.g., Fischer et al., 2009; Shaki & Gevers, 2011). This preferential mapping can be explained by the influence of participants' previous experience with finger counting. Finger counting routine, indeed, would consolidate a systematic association between a specific finger and a specific ordinal position of the numerical sequence. To test the role of FC routine in the mapping of non-numerical information we therefore designed Experiment 3. In particular, we hypothesized that both visuomotor routines would influence the representation of non-numerical ordered sequences. Specifically, although days of the week are not systematically mapped onto fingers, we expected this information to be sensitive to both RD and FC. Thus we predicted that the fastest mapping should result when both routines are compatibly oriented.

Method

Participants

A total of 22 right-handed participants took part in Experiment 3 for payment (*M* age = 24.1 y.o., *SD* = 2.2; 14 females). Participants were Israeli students from the Ben-Gurion University of the Negev (Israel).

Apparatus

We used the same apparatus as in Experiment 1.

Stimuli and Procedure

Stimuli were English and Hebrew words of the days of the week. Since in Israel the workweek starts on Sunday and ends on Thursday, this ordinal interval was considered in Experiment 3. Therefore, each stimulus consisted of the English word of the day of the week (SUNDAY, MONDAY, TUESDAY, WEDNESDAY, THURSDAY) and of the corresponding Hebrew word (יום ראשון, יום שני, יום שלישי, יום רביעי, יום חמישי). The procedure was the same as in Experiment 1. Eight mappings were obtained combining 3 variables: *a)* days direction, referred to Sunday-Thursday finger-association (thumb-little finger, little finger-thumb), *b)* hand posture (prone, supine) and *c)* language (English, Hebrew). Thus, with English days in the prone condition, mapping A consisted in associating SUNDAY to the thumb and THURSDAY to the little finger, while mapping B in associating THURSDAY to the thumb and SUNDAY to the little finger. Likewise, in the supine condition we had mapping C associating SUNDAY to the thumb and THURSDAY to the little finger, and mapping D associating THURSDAY to the thumb and SUNDAY to the little finger. Therefore, in the English condition, mappings resulted as completely compatible (A) or incompatible (B) with FC and RD, whereas mapping C and D were compatible only with the FC or RD, respectively. The same mappings were also obtained for Hebrew days (see Figure 6b). As in Experiment 1, hand posture was assessed in two separated daily sessions. Moreover, mappings of the same language were assessed subsequently within the same session. Hence, as in Experiment 2, participants had to complete four different blocks in each session (e.g., day one: A-B-E-F; day two: C-D-G-H). The order of the eight mappings was counterbalanced across participants. To control for possible motor speed differences among fingers and hand posture, participants performed a baseline reaction time task, as in Experiment 1 and 2.

Finally, at the end of the second session the personal finger counting strategy was assessed.

Finger counting assessment

Overall, 20 participants, out of 22, started to count with the thumb of the right hand and proceeded to the little finger, following the same order (i.e., thumb-little finger) with the left hand.

Two subjects were excluded because they did not count according to a consistent anatomical finger counting strategy. Thus, a sample of 20 participants (*M* age = 24 y.o., *SD* = 2.4; 13 females) contributed to the analyses.

Motor baseline task

A preliminary analysis was carried out to check for possible motor differences in the baseline task. A 2x5 repeated measures ANOVA on the reaction times (RTs) of correct responses, with hand posture (prone, supine) and finger (thumb, index finger, middle finger, ring finger, little finger) as within-subjects variables was carried out. Similar to Experiment 1 and 2, finger and hand posture were both found to be significant, thus, only corrected RTs were analyzed.

Results

Errors

Error rates were respectively 3.4% (A), 2.9 % (B), 4.2% (C), 4.4% (D), 3% (E), 2.9 % (F), 3.5% (G) and 3.3% (H) for each mapping. Errors analysis was calculated by normalizing the percentage of errors by the arcsin of their square root (Zubin, 1935). A 2x2x2 repeated measures ANOVA with days direction (thumb-little finger, little finger-thumb – referred to Sunday-Thursday finger-association), hand posture (prone, supine) and language (English, Hebrew) as within-subjects variables was carried out. Results showed a main effect of language, $F(1, 19) = 7.45$, $p < .05$, $\eta^2_p = .28$, with more errors in English (3.7%) than in Hebrew mappings (3.1%). Additionally, a main effect of hand posture was found, $F(1, 19) = 6.75$, $p < .05$, $\eta^2_p = .26$, with more errors in the supine posture (3.9%), compared to the prone posture (3.1%). All the others main effects and interactions were not significant.

Response Times

Corrected RTs more than two standard deviations from the overall mean were excluded from the analysis (4.2% of the data for the English mappings and 3.9% for the Hebrew mappings). A 2x2x2 repeated measures ANOVA with days direction (thumb-little finger, little finger-thumb), hand posture (prone, supine) and language (English, Hebrew) as within-subjects variables was carried out. Results revealed a significant main effect of language, *F*(1, 19) = 102.19, $p < .001$, η^2_p= .84, with faster RTs for the Hebrew words (*M* = 566.9 ms, *SD* = 62.3) compared to the English ones (*M* = 662.4 ms, *SD* = 80.7). Second, a main effect of days direction was found, *F*(1, 19) = 34.94, $p < .001$, η^2_p= .65, with thumb-little finger mappings (*M* = 602.3 ms, *SD* = 82.2), i.e., those compatible with participants' finger counting strategy, faster than little finger-thumb mappings (*M* = 627 ms, *SD* = 91.6). Most importantly, the triple interaction was significant, *F*(1, 19) = 16.69, $p < .002$, η^2_p= .47. Post-Hoc comparisons (*Scheffè*) revealed that with English days of the week, mapping A (*M* = 629.6 ms, *SD* = 61.2) was significantly faster than all the others (B: *M* = 677.3 ms, *SD* = 82.3; C: *M* = 665.6 ms, *SD* = 79; D: *M* = 676.9 ms, *SD* = 100.2; all *ps* < .005), while for the Hebrew days, mapping G (*M* = 538.5 ms, *SD* = 65.3) was significantly faster than the others (E: *M* = 575.6 ms, *SD* = 61.7; F: *M* = 571.1 ms, *SD* = 60; H: *M* = 582.8 ms, *SD* = 62.2; all *ps* < .005). Note that in mappings A and G, FC and RD were both compatible (see Figure 6a). All the others main effects and interactions were not significant.

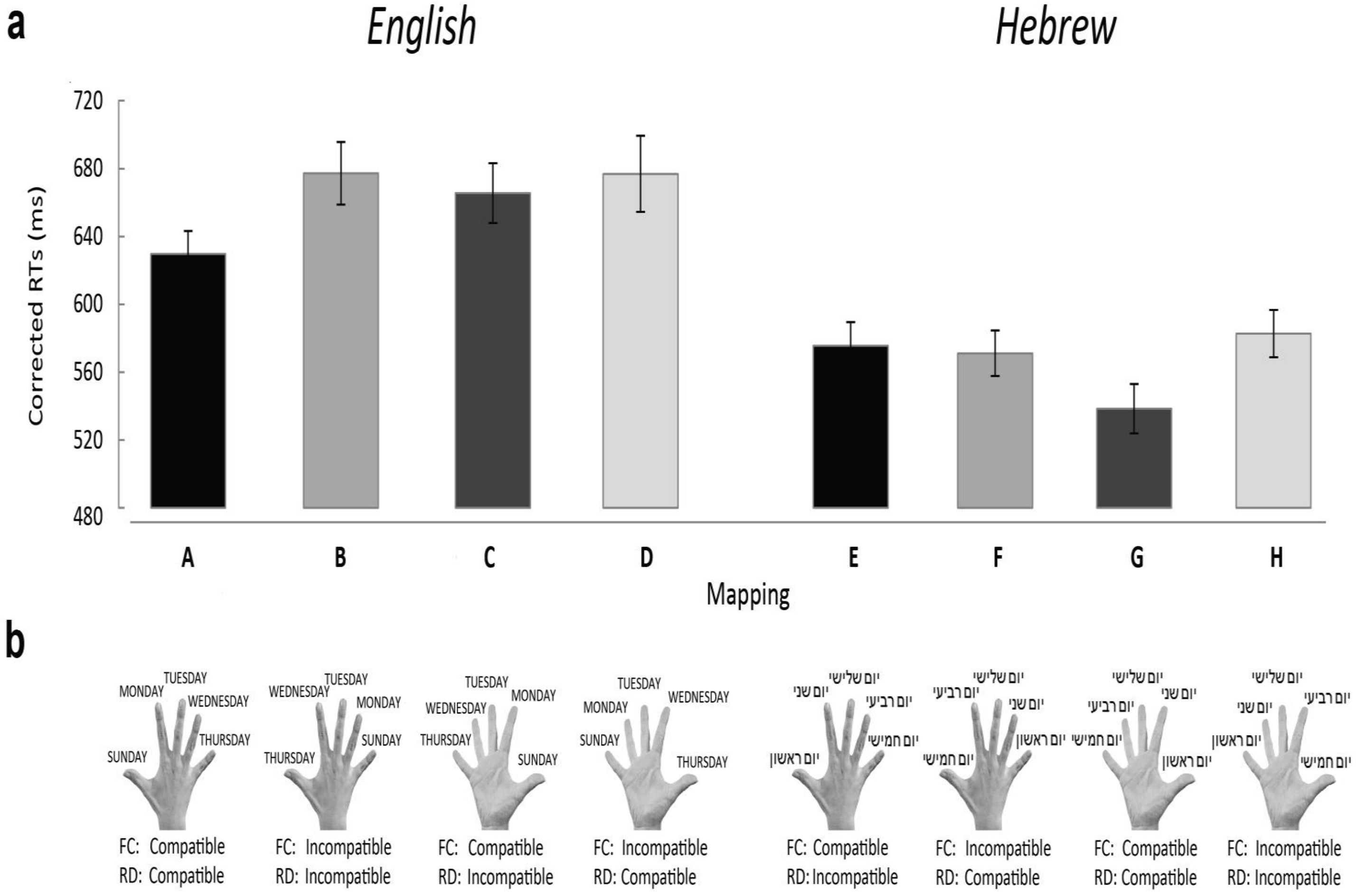

Figure 6. (**a**) Results of Experiment 3. Mean corrected response times (RTs), as a function of the finger-digits of the week mappings both in the English (i.e., mappings A-D) and in the Hebrew conditions (I.e., mappings E-G). Results showed that participants responded faster when both FC and RD were compatible (i.e., mapping A with English words and mapping G with Hebrew words). Error bars indicate ±1 standard error of the mean. (**b**) Finger–days of the week mappings of Experiment 3. Mappings were obtained by combining three variables: a) days direction, referred to Sunday-Thursday finger-association (thumb-little finger, little finger-thumb), b) hand posture (prone, supine) and c) language (English, Hebrew). In this way, we aimed at explore whether number words are preferentially mapped according to FC, RD or to a combination of both.

Next, we further explored differences in terms of ordinal position of the days to be mapped (see Figure 7 for RTs results as a function of mapping and of day). In particular, we performed a one-way ANOVA with days of the week as within-subjects variable (Sunday, Monday, Tuesday, Wednesday, Thursday).

A first ANOVA on English mappings showed a main effect of days on RTs, $F(4, 76) = 33.97$, $p < .001$, $\eta^2_p = .64$. Post-Hoc comparisons (Scheffè) revealed that *Sunday* ($M = 584.17$ ms, $SD = 56.89$) was classified significantly faster than *Tuesday* ($M = 723.57$ ms, $SD = 101.57$; $p < .001$), *Wednesday* ($M =$

661.83 ms, *SD* = 76.61; *p* < .001), *Thursday* (*M* = 733.79 ms, *SD* = 110.2; *p* < .001), but not of *Monday* (*M* = 608.41 ms, *SD* = 58.02). Furthermore, *Monday* was classified faster than *Tuesday* (*p* < .001), Wednesday (*p* < .001) and *Thursday* (*p* < .001), whereas *Tuesday* was classified slower than *Wednesday* (*p* < .005). Finally, *Wednesday* was classified faster than *Thursday* (*p* < .05).

A second ANOVA on Hebrew mappings showed a main effect of days on RTs, *F*(4, 76) = 14.62, *p* < .001, η^2_p = .44. Post-Hoc comparisons (Scheffè) revealed that *Sunday* (*M* = 528.61 ms, *SD* = 57.24) was classified significantly faster than *Monday* (*M* = 555.99 ms, *SD* = 57.92; *p* < .05), *Tuesday* (*M* = 583.93 ms, *SD* = 65.84; *p* < .001), *Wednesday* (*M* = 590.99 ms, *SD* = 64.98; *p* < .001) and *Thursday* (*M* = 575.41 ms, *SD* = 56.64; *p* < .001). Furthermore, *Monday* was classified faster than *Wednesday* (*p* < .005).

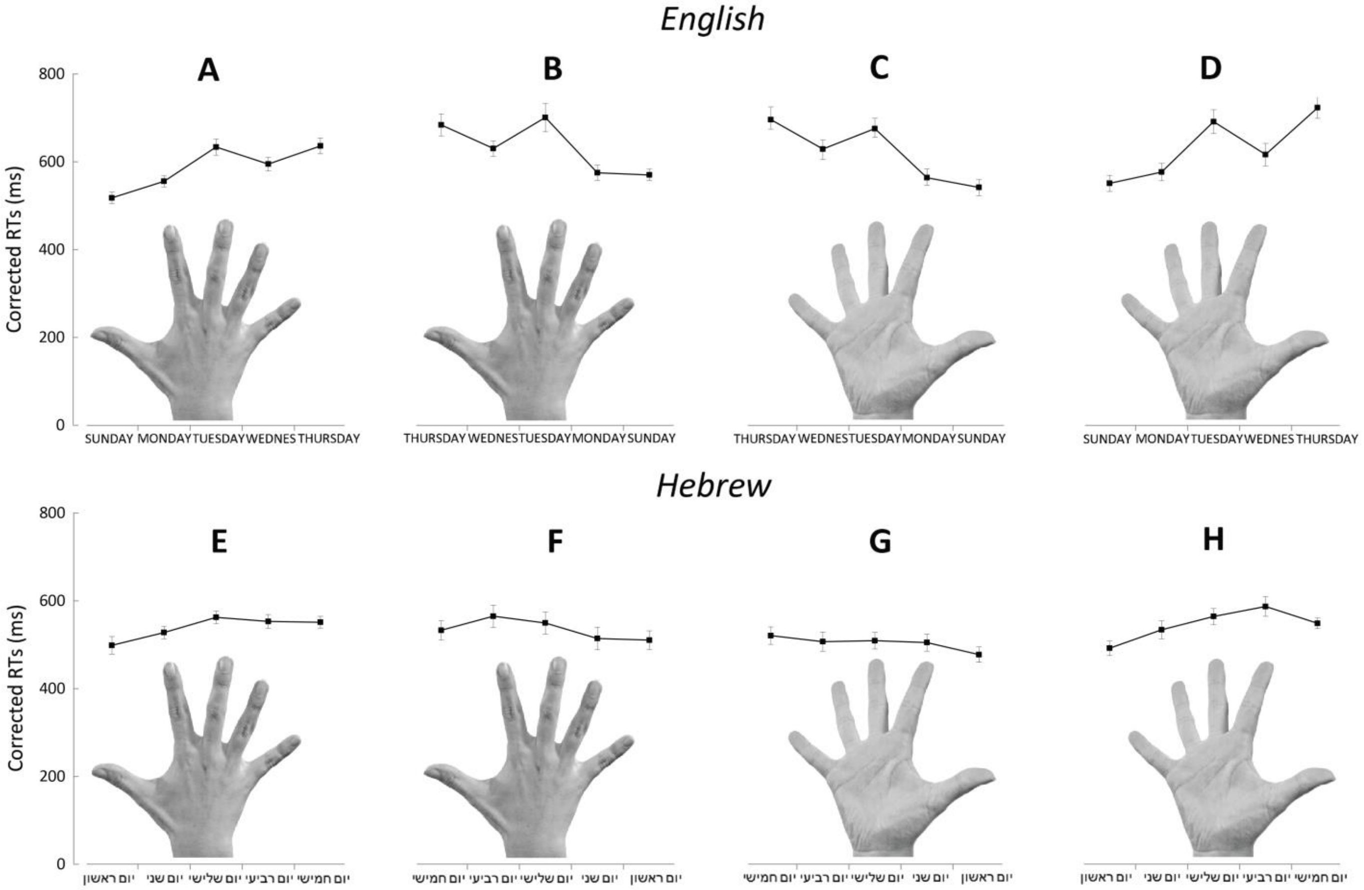

Figure 7. Mean corrected response times (RTs) in Experiment 3 as a function of each mapping and of each finger used. In the English mappings, results showed that participants responded faster to *Sunday* than to all the other days of the week, except for *Monday*. On the contrary, participants responded slower to *Thursday*. In the Hebrew mappings, results showed that participants responded faster to *Sunday* than to all the other days of the week. On the contrary, *Tuesday*, *Wednesday* and *Thursday* were classified slower.

Discussion

In Experiment 3, we explored whether the spatial mapping of non-numerical ordinal information relies *a)* on FC, *b)* on RD or *c)* on a combination of both. Results showed that the preferential mapping resulted when both FC and RD routines were compatible, thus supporting the alternative *c)*. While previous investigations with bilingual participants showed an impact of language direction on the spatial representation of ordinal information in bilingual participants (Shaki & Gevers, 2011), the present study shows that also FC contributes to shape this spatial representation. Indeed, participants responded faster in A than in all the other mappings with the English days, while they responded faster in G with the Hebrew days. Altogether, these results show that both FC and RD play a critical role in the spatial representation of non-numerical ordinal information. More specifically, these results indicate that the representation of non-numerical ordinal sequences on the hand space relies on multiple visuomotor routines.

General Discussion

Robust evidence points to directional visuomotor routines, such as finger counting and reading habit, as relevant for representing numerical information in space. However, no study has so far investigated the routine on which we rely on more. The present study addressed this issue by requiring bilingual participants, reading either from left-to-right or right-to-left, to map ordinal information to all fingers of their right dominant hand. Results of Experiments 1 and 2 show that the spatial representation of numerical information relies mainly on finger counting routine. Moreover, results of Experiment 2 indicate that this representation is not sensitive to the contextual manipulation of the numerical code (Arabic *vs* verbal numerals; Hebrew *vs* English number words), suggesting that it is stored in long-term memory as a consequence of the repeated visuomotor activity throughout the lifespan. Finally, Experiment 3 unveils that the spatial representation of non-numerical ordinal sequences, i.e., days of the week, relies on both finger counting and reading habit. This suggests that when ordinal information is not consolidated with space through a specific visuomotor routine, the representation of abstract ordered information relies on different directional experiences (finger counting, reading direction) depending on the stimuli and task at hand. Overall, the present study shows that the spatial representation of ordinal sequences on the hand space relies on directional routines and, particularly, on finger counting. These findings might have broad implications for current models of numerical representation and, more generally, for an experience-based view of cognition.

Spatial-numerical associations counts on fingers

Recent studies have shown that the spatial representation of numbers can rely on (Di Luca et al., 2006), or at least be influenced by (Fischer, 2008; Fischer & Brugger, 2011; Riello & Rusconi, 2011; but see Brozzoli et al., 2008), the direction of finger counting routine. Using a number-to-finger mapping task, in the present study we show that participants responded faster to Arabic digits and to number words when numerical information was mapped according to participants' finger counting routine. These findings are in line with evidence suggesting a strong influence of finger counting routine on SNAs on the hand space (Di Luca et al., 2006) and, more generally, they provide further evidence for a reliable contribution of FC on the spatial representation of numbers (e.g., Fischer, 2008; Riello & Rusconi, 2011). However, while Di Luca et al. (2006) reported a predominance of the finger counting mapping over the orientation of the MNL, recently Riello and Rusconi (2011) found that both FC and MNL need to be congruently oriented for generating faster mappings. These apparently contrasting findings might result from different task settings and from a different emphasis on fingers representation. Indeed, while in the study of Riello and Rusconi (2011) participants were required to classify parity numbers with two fingers only (i.e., thumb and little finger), the present study adopted a five keys response setting resulting in increased finger discriminability. The larger emphasis on the hand space, due to the use of all fingers of the hand, thus might have led to greater contribution of FC.

A current debate in the literature concerns whether the direction followed in finger counting is influenced by cultural factors, such as reading direction, or by biological factors, such as handedness (see, for a discussion, Previtali et al., 2011). Indeed, the finger counting strategy is to a certain degree culturally shared, since young children can observe and learn from their peers how to use fingers for counting (Bender & Beller, 2012). On these grounds, some authors proposed that the visuomotor scanning linked to reading and writing direction might provide a critical cue for the starting point and the overall direction of the finger counting routine (see Lindemann et al., 2011). At the same time, however, also handedness represents a sound candidate for shaping finger counting direction, with previous studies indicating a tight association between the starting hand of FC and hand dominance (see for a discussion Previtali et al., 2011). In a sample of right-handed bidirectional readers we found that more than 80% of participants started to count with the thumb of the right hand and proceeded to the little finger (with the same order followed on the left hand). Critically, this percentage replicates those reported in previous study with a Western population (Di Luca et al., 2006; Sato & Lalain, 2008), without any apparent difference due to cross-cultural variability between the two samples. Therefore, since our participants were all right handers, our findings speak in favor of a critical role of handedness in the starting point of FC and call into question whether eye scanning associated with reading direction can be an important factor in the origin of FC direction (cf. Lindemann et al., 2011). Indeed, these findings show that RD only partially interacts with FC, establishing the primacy of the latter on the hand mapping of ordinal information. The fact that the preferential mapping of numerical information was not dependent on hand posture and on language direction provides evidence for a hand-centered representation.

It is worth considering that our study involved Israeli bilingual participants who usually show less lateralized SNAs compared to monolingual readers (Shaki et al., 2010; but see for more recent studies documenting a classic left-to-right SNARC: Shaki & Gevers, 2011; see also Tzelgov & Zohar-Shai, 2014). Yet, in Experiment 1, we found that mappings compatible with the prototypical finger-counting strategy led to fastest reaction times. This finding replicates those by Di Luca et al. (2006) observed in a sample of Italian left-to-right readers. The preference for finger-counting mappings was extended in Experiment 2 to Hebrew and English number words. Thus, although SNAs in bilingual readers assessed by standard bimanual classification tasks depend on language manipulation (Fischer et al., 2009), our findings indicate that when the hand space is emphasized, numbers are better mapped according to FC rather than RD routine. Finally, in Experiment 3, the compatibility between FC and RD determined the fastest mapping for non-numerical ordered information. A recent study found a standard left-to-right SNARC effect with English letters and a reversed right-to-left SNARC effect with Hebrew letters in bilingual participants (Shaki and Gevers, 2011). Our study adds to this evidence by showing that, under specific circumstances (i.e., when participants are required to map ordered information on fingers), the representation of ordered sequences relies on the interplay between both FC and RD.

One may wonder whether such interplay was determined by participants' expertise with two differently oriented languages. Bilingual readers were indeed selected as the preferential group to investigate the representational flexibility induced by language manipulation. Nevertheless, results from Experiment 3 might be likely generalized to a monolingual sample. First, English and Hebrew days of the week were presented in different blocks, making unlikely that the results obtained were due to a rapid language switching effect. Second, if the strength of reading skills accounted for our findings, we should expect language to modulate compatibility effects. Yet, despite the overall difference in RTs, English and Hebrew words led to similar compatibility effects.

However, it is still possible that reading direction may only influence the spatial mapping of non-numerical ordered information in bilinguals, because they can read and write along opposite directions. Thus, no potential conflict between reading direction and finger counting may emerge in a group of monolingual readers. Future research is needed to address this intriguing possibility, involving ideally groups of monolingual participants reading either in a left-to-right or in a right-to-left oriented language.

A helping hand putting in order

What makes numbers specials is that they convey different meanings, among which the most salient are the cardinal meaning, referring to the numerosity of a set, and the ordinal meaning, indicating the relative position of a certain item within a set. While the former is a unique feature of numbers, the latter is shared with any ordinal sequences, such as the days of the week or the letters of the alphabet. The present study was focused on the spatial representation of ordinal information. Compelling evidence, indeed, supports a common spatial representation for both numerical and non-numerical ordinal sequences (Gevers et al., 2003; 2004; Previtali, de Hevia & Girelli, 2010; Macchi Cassia, Picozzi, Girelli & de Hevia, 2012; Rinaldi, Brugger, Bertolini, Bockisch, & Girelli, 2015), even though the origin of this spatial mapping is still debated.

In three experiments, we found that numerical information was preferentially represented in space according to finger counting routine, while both finger counting and reading direction had to be congruent for generating faster spatial associations for non-numerical ordinal information on fingers. Our findings suggest that when the task requires finer fingers discrimination at the response level, finger counting plays an active role in the mapping of ordered information. While the impact of finger counting routine on SNAs is rather unsurprising and supported by different findings, the influence of this practice on the representation of non-numerical ordinal sequences may not be taken for granted. In fact, one may question how fingers would be helpful for representing non-numerical ordinal information in space.

We propose that finger counting support to ordinal representation might be grounded on the one-to-one correspondence principle, strengthened by the systematic association between a specific finger and a specific ordinal position during counting. Experienced first with numbers, this mapping might be further easily generalized to any ordinal sequences, through repetition. Therefore, we suggest that finger counting may be considered supportive not only to arithmetic (Crollen & Noël, 2015; see also Rinaldi, Gallucci & Girelli, 2015), but also to the development of ordinal meaning. Indeed, fingers are an embodied tool available to children to keep track of information in a culturally-shaped order (Wiese, 2003), at least when visual processing is not impaired (Crollen, Noël, Seron, Mahau, Lepore & Collignon, 2014). Future studies are needed to explore this intriguing possibility.

Implications for current models of SNAs

Beyond investigating the role of directional routines in the mapping of numerical and non-numerical information in personal space, the present study contributes to a deeper understanding of both embodied and situated factors in the determination of SNAs. Indeed, current views of numerical cognition emphasize the importance of both embodied and situated knowledge (e.g., Fischer, 2012; see also Wasner, Moeller, Fischer & Nuerk, 2014). In particular, according to a recent proposal, three different aspects would account for the flexibility of SNAs (Fischer 2012; see also Fischer & Brugger, 2011). The first one, named as grounded cognition, would reflect universal properties of the physical world, such as the stable associations between numerical information (small/large) and vertical space (bottom/top) that would come from accumulating objects (Ito & Hatta, 2004; Shaki & Fischer, 2012). The second one, named as embodied cognition, would reflect the influence of sensorimotor experience on cognition, such as the effect of reading and writing direction (Shaki et al., 2009) or finger counting (Di Luca et al., 2006; Fischer, 2008) on SNAs. The third one, named as situated cognition, would lastly reflect the influence of current constrains imposed by the task at hand, such as the effects induced by language direction manipulations in bilingual readers on SNAs (Fischer et al., 2009, 2010). Hence, the influence of visuomotor practices in shaping the spatial representation of numbers has been taken as evidence for an embodiment of numerical concepts (Fischer & Brugger, 2011) although situated factors, such as task demands and the specific experimental setting adopted, might in turn influence SNAs (Fischer, 2012). In the present study, we provide novel evidence that might enrich the understanding of both embodied and situated factors on numerical representation.

In particular, Experiments 1 and 2 speak in favor of an embodiment of numerical concepts because the privileged numerical representation was hand-centered, i.e., neither hand posture or language direction counted. Since previous evidence has shown that numerical mapping in bimanual classification tasks is prone to language manipulation (Fischer et al., 2010; Shaki & Gevers, 2011) and yet to situational requirements, the present findings suggest that the mapping on the hand space is not sensitive to such manipulation, as it preferentially corresponds to the individual's prototypical finger-counting. It might be therefore possible that the more we actively use parts of our body in the response setting, the more we rely on inner and bodily representations grounded on an egocentric sensory-motor schema**.** Intrinsic features of finger counting routines would make them resistant to situational requirements. Finger counting routine is indeed practiced early in development, it is reinforced by observational exposure and by self-practice, and it is characterized by an exact one-to-one correspondence between a specific finger and a specific number.

On the contrary, in Experiment 3 a significant influence of situational factors was found. More specifically the privileged mapping of non-numerical ordinal information was determined by a combination of both reading and finger counting direction, thus resulting in an impact of hand posture. Overall, these findings highlight the more flexible representation of non-numerical ordinal sequences, showing how embodied factors interact more generally with situational requirements.

To conclude, we suggest that the need for putting in order multiple information in everyday life makes our cognitive system highly capable of representing abstract ordered information, by adjusting previous directional experience (finger counting, reading direction) to current requirements imposed by the task at hand.

Acknowledgements

L.R. was supported by a scholarship from the Israel Ministry of Foreign Affairs and by a grant from Fondazione Cariplo. A.H. was supported by the Israel Science Foundation (Grant 1799/12) in the framework of their Centers of Excellence. We thank Desiree Meloul for useful comments.

References

Andres, M., Di Luca, S., & Pesenti, M. (2008). Finger counting: the missing tool? *Behavioral and Brain Sciences*, *31*, 642–643.

Andres, M., Olivier, E., & Badets, A. (2008). Actions, words, and numbers: A motor contribution to semantic processing? *Current Directions in Psychological Science*, *17*, 313–317.

Barsalou, L. W. (2008a). Grounded cognition. *Annual Review of Psychology*, *59*, 617–645.

Barsalou, L. W. (2008b). Grounding symbolic operations in the brain's modal systems. In G. R. Semin & E. R. Smith (Eds.), *Embodied grounding: Social, cognitive, affective, and neuroscientific approaches* (pp. 9–42). New York: Cambridge University Press

Bender, A., & Beller, S. (2011d). Fingers as a tool for counting – naturally fixed or culturally flexible? *Frontiers in Psychology: Cognition*, *2*, 256.

Bender, A., & Beller, S. (2012). Nature and culture of finger counting: Diversity and representational effects of an embodied cognitive tool. *Cognition, 124,* 156–182.

Berch, D. B., Foley, E. J., Hill, R. J., & Ryan, P. M. (1999). Extracting parity and magnitude from Arabic numerals: developmental changes in number processing and mental representation. *Journal of Experimental Child Psychology*, *74*, 286–308.

Brozzoli, C., Ishihara, M., Gobel, S. M., Salemme, R., Rossetti, Y., & Farnè, A. (2008). Touch perception reveals the dominance of spatial over digital representation of numbers. *Proceedings of the National Academy of Sciences*, *105*, 5644–5648.

Bulf, H., de Hevia, M. D., & Macchi Cassia, V. (2015). Small on the left, large on the right: numbers orient visual attention onto space in preverbal infants. *Developmental Science*.

Cohen, Z. Z., Naparstek, S., & Henik, A. (2014). Tactile enumeration of small quantities using one hand. *Acta psychologica*, *150*, 26–34.

Crollen, V., & Noël, M. P. (2015). The role of fingers in the development of counting and arithmetic skills. *Acta Psychologica*, *156*, 37–44.

Crollen, V., Noël, M. P., Seron, X., Mahau, P., Lepore, F., & Collignon, O. (2014). Visual experience influences the interactions between fingers and numbers. *Cognition*, *133*, 91–96.

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1–42.Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*, 1–42.

Dehaene, S., Bossini, S., & Giraux, S. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*, 371–396.

de Hevia, M. D., Girelli, L., Addabbo, M., & Cassia, V. M. (2014). Human infants' preference for left-to-right oriented increasing numerical sequences. *PloS one*, *9*, e96412.

de Hevia, M. D., Girelli, L., & Macchi Cassia, V. (2012). Minds without language represent number through space: origins of the mental number line. *Frontiers in Psychology*, *3*, 1.

de Hevia, M. D., Vallar, G., & Girelli, L. (2008). Visualizing numbers in the mind's eye: The role of visuo-spatial processing in numerical abilities. *Neuroscience & Biobehavioral Reviews, 32*, 1361–1372.

Di Luca, S., Granà, A., Semenza, C., Seron, X., & Pesenti, M. (2006). Finger-digit compatibility in Arabic numerical processing. *Quarterly Journal of Experimental Psychology, 59*, 1648–1663.

Di Luca, S., Lefèvre, N., & Pesenti, M. (2010). Place and summation coding for canonical and non-canonical finger numeral representations. *Cognition*, *117*, 95-100.

Di Luca, S., & Pesenti, M. (2008). Masked priming effect with canonical finger numeral configurations. *Experimental Brain Research*, *185*, 27–39.

Di Luca, S., & Pesenti, M. (2011). Finger numeral representations: more than just another symbolic code. *Frontiers in Psychology: Cognition, 2*, 272.

Domahs, F., Klein, E., Moeller, K., Nuerk, H.-C., Yoon, B.-C., & Willmes, K. (2011). Multimodal semantic quantity representations: Further evidence from Korean Sign Language. *Frontiers in Psychology: Cognition*, *2*, 1.

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H. C. (2010). Embodied numerosity: implicit hand-based representations influence symbolic number processing across cultures. *Cognition, 116*, 251–266.

Drucker, C. B., & Brannon, E. M. (2014). Rhesus monkeys (Macaca mulatta) map number onto space. *Cognition*, *132*, 57–67.

Ebersbach, M., Luwel, K., & Verschaffel, L. (2015). Further evidence for a spatial-numerical association in children before formal schooling. *Experimental Psychology*, 61, 323-329.

Fischer, M. H. (2008). Finger counting habits modulate spatial-numerical associations. *Cortex, 44*, 386–392.

Fischer, M. H. (2012). A hierarchical view of grounded, embodied, and situated numerical cognition. *Cognitive Processing*, *13*, 161–164.

Fischer, M. H., & Brugger, P. (2011). When digits help digits: spatial–numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology: Cognition*, *2*, 260.

Fischer, M. H., Mills, R.A., & Shaki, S. (2010). How to cook a SNARC: Number placement in text rapidly changes spatial-numerical associations. *Brain and Cognition*, *72*, 333–336.

Fischer, M. H., Shaki, S., & Cruise, A. (2009). It takes only one word to quash the SNARC. *Experimental Psychology*, *56,* 361–366.

Gevers, W., Reynvoet, B., & Fias, W. (2003). The mental representation of ordinal sequences is spatially organized. *Cognition, 87*, 87–95.

Gevers, W., Reynvoet, B., & Fias, W. (2004). The mental representation of ordinal sequences is spatially organized: Evidence from days of the week. *Cortex, 40*, 171–172.

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number-space interactions. *Journal of Experimental Psychology: General*, *139*, 180–190.

Gibbs, R. W. (2006). *Embodiment and Cognitive Science.* Cambridge: Cambridge University Press.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*, 558–565.

Hoffmann, D., Hornung, C., Martin, R., & Schiltz, C. (2013). Developing number–space associations: SNARC effects using a color discrimination task in 5-year-olds. *Journal of Experimental Child Psychology*, *116*, 775-791.

Knudsen, B., Fischer, M. H., & Aschersleben, G. (2014). Development of spatial preferences for counting and picture naming. *Psychological research*, 1-11.

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect. *Memory & Cognition*, *32*, 662-673.

Lakoff, G. & Nunez, R. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. New York: Basic Books.

Leuthard, J., Bächtold, D., & Brugger, P. (2005). Is left always where the thumb is right? Stimulus–response compatibilities as a function of posture and location of the responding hand. *Cognitive Behavioral Neurolology, 18*, 173–178.

Lindemann, O., Alipour, A., & Fischer, M. H. (2011). Finger counting habits in middle-eastern and western individuals: an online survey. *Journal of Cross-Cultural Psychology*, *42*, 566–578.

Lucidi, A., & Thevenot, C. (2014). Do not count on me to imagine how I act: behavior contradicts questionnaire responses in the assessment of finger counting habits. *Behavior Research Methods, 46,* 1079–1087.

Macchi Cassia, V., Picozzi, M., Girelli, L., & de Hevia, M. D. (2012). Increasing magnitude counts more: asymmetrical processing of ordinality in 4-month-old infants. *Cognition*, 124, 183-193.

McCrink, K., & Opfer, J. E. (2014). Development of Spatial-Numerical Associations. *Current Directions in Psychological Science, 23*, 439–445.

Moeller, K., Fischer, U., Link, T., Wasner, M., Huber, S., Cress, U. & Nuerk, H.-C. (2012). Learning and development of embodied numerosity. *Cognitive Processing*, 13, 271–274.

Michaux, N., Pesenti, M., Badets, A., Di Luca, S., & Andres, M. (2010). Let us redeploy attention to sensorimotor experience. *Behavioral and Brain Sciences*, *33*, 283-284.

Nuerk, H. C., Patro, K., Cress, U., Schild, U., Friedrich, C. K., & Göbel, S. M. (2015). How space-number associations may be created in preliterate children: six distinct mechanisms. *Frontiers in Psychology*, *6*, 1.

Núñez, R. E. (2011). No innate number line in the human brain. *Journal of Cross-Cultural Psychology*, *42*, 651–668.

Núñez, R. E., Cooperrider, K. & Wassmann, J. (2012). Number concepts without number lines in an Indigenous group of Papa New Guinea. *PLoS ONE*, 7(4), e35662.

Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh Inventory. *Neuropsychologia*, *9*, 97–113.

Opfer, J. E., Thompson, C. A., & Furlong, E. E. (2010). Early development of spatial-numeric associations: evidence from spatial and quantitative performance of preschoolers. *Developmental Science, 13*, 761-771.

Patro, K., & Haman, M. (2012). The spatial-numerical congruity effect in preschoolers. *Journal of Experimental Child Psychology*, *111*, 534–542.

Patro, K., Nuerk, H. C., Cress, U., & Haman, M. (2014). How number-space relationships are assessed before formal schooling: a taxonomy proposal. *Frontiers in Psychology*, *5*.

Plaisier, M. A., & Smeets, J. B. J. (2011). Number magnitude to finger mapping is disembodied and topological. *Experimental Brain Research, 209*, 395–400.

Previtali, P., de Hevia, M. D., & Girelli, L. (2010). Placing order in space: the SNARC effect in serial learning. *Experimental Brain Research*, *201*, 599–605.

Previtali, P., Rinaldi, L., & Girelli, L. (2011). Nature or nurture in finger counting: a review on the determinants of the direction of number–finger mapping. *Frontiers in Psychology: Cognition, 2*, 363.

Riello, M., & Rusconi, E. (2011). Unimanual SNARC effect: hand matters. *Frontiers in Psychology: Cognition, 2*, 372.

Rinaldi, L., Brugger, P., Bockisch, C. J., Bertolini, G., & Girelli, L. (2015). Keeping an eye on serial order: Ocular movements bind space and time. *Cognition*, *142*, 291–298.

Rinaldi, L., Di Luca, S., Henik, A., & Girelli, L. (2014). Reading direction shifts visuospatial attention: An Interactive Account of attentional biases. *Acta Psychologica*, *151*, 98–105.

Rinaldi, L., Gallucci, M., & Girelli, L. (2015). Spatial-numerical consistency impacts on preschoolers' numerical representation: children can count on both peripersonal and personal space. *Cognitive Development.* http://dx.doi.org/10.1016/j.cogdev.2015.10.006

Rugani, R., Vallortigara, G., Priftis, K., & Regolin, L. (2015). Number-space mapping in the newborn chick resembles humans' mental number line. *Science*, *347*, 534–536.

Sato, M., Cattaneo, L., Rizzolatti, G., & Gallese, V. (2007). Numbers within our hands: modulation of cortico-spinal excitability of hand muscles during numerical judgment. *Journal of Cognitive Neuroscience, 19*, 684–693.

Sato, M., & Lalain, M. (2008). On the relationship between handedness and hand-digit mapping in finger counting. *Cortex*, *44*, 393–399.

Shaki, S., & Fischer, M. H. (2012). Multiple spatial mapping in numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 804–809.

Shaki, S., Fischer, M. H., & Göbel, S. M. (2012a). Direction counts: A comparative study of spatially directional counting biases in cultures with different reading directions. *Journal of Experimental Child Psychology*, *112*, 275–281.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin and Review*, *16*, 328–331.

Shaki, S., & Gevers, W. (2011). Cultural characteristics dissociate magnitude and ordinal information processing. *Journal of Cross-Cultural Psychology*, *42*, 639-650.

Tschentscher, N., Hauk, O., Fischer, M. H., & Pulvermüller, F. (2012). You can count on the motor cortex: Finger counting habits modulate motor cortex activation evoked by numbers. *NeuroImage*, *59*, 3139–3148.

Turconi, E., Campbell, J. I. D., & Seron, X. (2006). Numerical order and quantity processing in number comparison. *Cognition*, *98*, 273–285.

Turconi, E. & Seron, X. (2002) Dissociation between order and quantity meanings in a patient with Gerstmann syndrome. *Cortex, 38*, 911–914.

Tzelgov, J., & Ganor-Stern, D. (2005). Automaticity in processing ordinal information. In J. I. D. Campbell (Ed.), *Handbook of mathematical cognition* (pp. 43–54). New York: Psychology Press.

Tzelgov, J., & Zohar-Shai, B. (2014). It does exist! A SNARC effect amongst native Hebrew speakers is masked by the MARC effect. In *Cognitive Processing,* 15, S22-S22.

van Dijck, J. P., & Fias, W. (2011). A working memory account for spatial–numerical associations. *Cognition*, *119*, 114-119.

Wasner, M., Moeller, K., Fischer, M. H., & Nuerk, H. C. (2014). Aspects of situated cognition in personal numerosity: the case of finger counting. *Cognitive Processing*, *15*, 317–328.

Wiese, H. (2003). Iconic and non-iconic stages in number development: the role of language. *Trends in cognitive sciences*, *7*, 385-390.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review*, *9*, 625–636.

Zebian, S., (2005). Linkages between number concepts, spatial thinking, and directionality of writing: the SNARC effect and the reverse SNARC effect in English and Arabic monoliterates, biliterates, and illiterate Arabic speakers. *Journal of Cognition and Culture, 5*, 165–190.