Exp Brain Res (2015) 233:1519–1528
DOI 10.1007/s00221-015-4225-9

RESEARCH ARTICLE

Beyond the SNARC effect: distance–number mapping occurs in the peripersonal space

Yi-Huan Chen · Ji-Fan Zhou · Su-Ling Yeh

Received: 8 September 2014 / Accepted: 9 February 2015 / Published online: 19 February 2015

Abstract Estimating distance of objects relative to one's body is important for interaction with the environment. Given that distance is an interval of magnitude describing space, distance and the commonly used estimations of magnitude, i.e., numbers, may share a common representation system (the ATOM theory, Walsh in Trends Cogn Sci 7(11):483–488, 2003). The current study systematically examined the association between distance and number representations on both the sagittal and transverse axes on the transverse plane in the peripersonal space. Participants in Experiment 1 judged the parity of digits by pressing one of two buttons (both were in front of participants): One was near the body and the other away from it. We found that near responses were faster when paired with smaller numbers and far responses with larger numbers. When one button was set in front and the other in back in Experiment 2, no mapping was found. In Experiment 3, when both buttons were on the right side aligned with the transverse axis, small-near and large-far mapping were found. However, no such effect was found on the left side. These results suggest that numbers are mapped onto the whole transverse plane of the peripersonal space, not only a left–right oriented number line.

Keywords SNARC effect · Peripersonal space · Number · Distance · Space · Mapping

Y.-H. Chen · J.-F. Zhou · S.-L. Yeh (✉)
Department of Psychology, National Taiwan University, Taipei 10617, Taiwan
e-mail: suling@ntu.edu.tw

J.-F. Zhou
Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, China

S.-L. Yeh
Graduate Institute of Brain and Mind Sciences, National Taiwan University, Taipei, Taiwan

S.-L. Yeh
Neurobiology and Cognitive Science Center, National Taiwan University, Taipei, Taiwan

Introduction

To interact with the environment, our brain needs to process a variety of information regarding the size and spatial location of our body and its parts. Peripersonal space, which refers to the region surrounding the body that is within the arm's reach of an individual, has an important role in our actions toward objects around us (Rizzolatti et al. 1981). There are a number of distance estimating processes involved for such action: Localizing one's own hand, localizing target object and estimating distance between hand and object (Cardinali et al. 2009; Holmes and Spence 2004). To understand these processes better, more needs to be uncovered about the representation of distance[1] relative to our body in the peripersonal space. Given that distances can be represented by different magnitudes with respect to the body, a common representation system of distances and magnitudes should be possible.

[1] In the following text, if it is not specifically indicated, "distance" refers to the distance relative to our body in the peripersonal space. It should be distinguished from the physical distance between two arbitrary objects or the mental distance between two numbers, because what we are interested in is the distance representation in the peripersonal space which serves for our limb movements, rather than the domain-general spatial representation.

It has been suggested that space and number share a common magnitude representation system. For instance, a theory of magnitude (ATOM; Walsh 2003) suggests a common magnitude system for processing the representations of time, space and quantity. That is, time, space and quantity share the information-processing resources and operating principles. This is partly due to the previous sensory or motor experiences from the invariant properties of the physical world (Fischer 2012). For instance, the time for an object to move from point A to B is proportional to the distance between these two points. Hence, these different aspects (such as time and distance) can be processed by a common representation system.

ATOM has been supported by neurophysiological and brain damage studies. Overlapping sub-regions in the parietal cortex are associated with different magnitude concepts: Intraparietal sulcus (IPS) selectively responds to numerosity (Cipolotti et al. 1991; Dehaene and Cohen 1997; Dehaene et al. 1999); ventral intraparietal (VIP) area contributes to spatial representation (Colby and Goldberg 1999). Specifically, the neural circuitry of the lateral intraparietal (LIP) area and VIP area are suggested to be the common brain regions responding to both number and space (Hubbard et al. 2005). The common representation hypothesis is also supported by studies of brain damaged patients with left neglect syndrome. When the patients were required to point out the midpoint of a number line and a physical line, the same rightward error was evident, indicating that number representation has a spatial nature (Rossetti et al. 2004; Zorzi et al. 2002).

The common representation system of number and space is also reflected by their automatic association in behavioral studies. When responding to numbers, regardless of whether the task is related to magnitude or not, the larger the number, the faster the response on the right-side relative to the response on the left side. This phenomenon is called the spatial–numerical association response code (SNARC) effect (Dehaene et al. 1993; Gevers and Lammertyn 2005). In addition to spatial location, another important spatial property—size—has been demonstrated to be associated with number: When responding to numbers by creating an aperture of their fingers, participants' grip closures were faster with smaller numbers and grip openings were faster with larger numbers (Andres et al. 2004). As well, numbers lead to an implicit left–right cuing effect on attention: Smaller numbers induce a shift of covert attention to the left visual field, and the opposite is true for larger numbers (Dodd et al. 2008; Fischer et al. 2003; Salillas et al. 2008). Lastly, the association between number and space is explicitly expressed in number-form synesthetes, a special group of people who experience a mental map of numbers when thinking of numbers (Jonas et al. 2013).

Previous studies, however, have mostly focused on left–right spatial representation, and little is known about whether near–far distance to the body is also associated with numbers. With respect to the body, space can be represented by magnitude and direction: Left and right spaces are of different directions, while near and far distances are of different magnitudes. Considering the importance of peripersonal space, a complete understanding of the common mechanism of space and number representation should also include distance representation to the body, as well as left and right spatial representation.

The current study aims to investigate the association between distance and number representations, specifically, how numbers are mapped to near or far distance with respect to the body. We conducted three experiments to investigate the distance–number mapping in different orientations on the transverse plane. Experiment 1 and 2 focused on the sagittal axis, with Experiment 1 examining the near-front and far-front space and Experiment 2 focused on the back space. Experiment 3 focused on the transverse axis on the left and right sides of the body. In these experiments, a magnitude-irrelevant binary task was performed with response keys set at different locations. If the responses at some specific locations were faster with small or large numbers, and the responses occurring at other locations were not, then the association between distance and number can be revealed from the response pattern.

Experiment 1

This experiment examined the association between distance and number representations in the front body space; specifically, whether smaller numbers mapped to near space or far space. If distance representation of body part respective to the body was processed to facilitate corresponding magnitude representation, then near responses would be made faster with smaller numbers. However, if the distance representation is relative to the screen on which target digit presented, then far responses would be faster with smaller numbers. In order to produce a large distance between the near and far response locations, the buttons at two ends of the keyboard (with distance of 17 cm) were designated as the response keys. The keyboard was rotated with 90° in the front space (Fig. 1a, top view).

Method

Participants

In the absence of previous studies that had an effect size of slope or proportion of variability for the estimation of

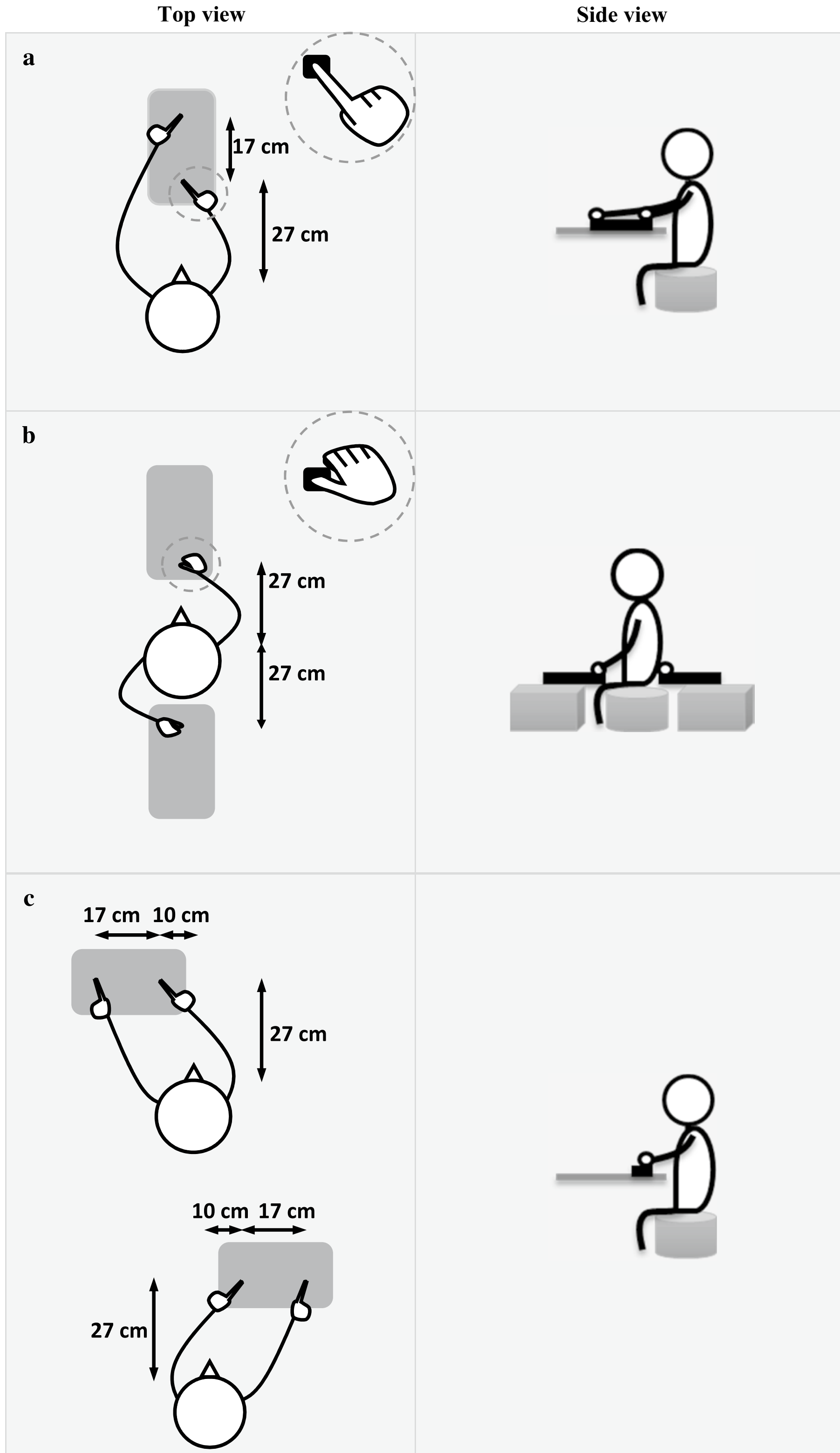

Fig. 1 Schematic drawing of the experiment setups with distances being marked (not to scale). Participants judged the parity of numbers by pressing the buttons on a standard computer keyboard. **a** In Experiment 1, a keyboard was set on the table in front of participants. Participants pressed the buttons by forefingers. **b** In Experiment 2, one keyboard was set in front of participants at the knee height, and the other keyboard was set in the back at the same height. Participants pressed the buttons by thumbs. **c** In Experiment 3, a keyboard was set on the table on the left or right side relative to participants. Participants pressed the buttons by forefingers

sample size adopted in this study, we used power analysis based on the presumable effect size and determined a range of sample size from 30 to 40. In Experiment 1, 40 adults with normal or corrected to normal vision were invited to participate in this experiment for payment. The study was approved by the institutional review board at Department of Psychology of National Taiwan University, and all participants gave informed consent.

Apparatus

The experiment was controlled by an ASUS computer, with a standard computer keyboard. Stimuli were presented on a 14-inch screen with 60-Hz refresh rate. Participants performed task individually in a dimly lit room, with a chin stand to keep the viewing distance constant at 62 cm.

Design

The speeded parity judgment task was performed in this experiment. Single Arabic numbers (.42° × .32° in visual angle) from 0 to 9 (with five repetitions each within a block) was randomly selected to appear on the screen. Four blocks were run in the formal experiment. Each block contained 50 trials; therefore, the number of total trials was 200.

The four blocks of trials were designed in a way that the assignment of parity (odd/even), response location (near/far) and hand (right/left) was counterbalanced within participants. That is, in one block, odd numbers were assigned to the near button with right-hand response, and even numbers were assigned to the far button with left-hand response. In another block, even numbers were assigned to the near button with right-hand response, and odd numbers were assigned to the far button with left-hand response. The remaining two blocks had the same assignments but with hands reversed. The order of the four blocks was randomized.

Procedure

Before the formal experiment, participants were given instructions and then completed a practice session of 10 trials, which was designed to make them familiar with the parity judgment task. Each trial began with a fixation presented at the center of screen for 500 ms, followed by a single number appearing at the center of screen until response or 2000 ms after onset. The next trial began after a 1000-ms inter-trial interval (ITI) with a blank screen. Participants were instructed to place their forefingers on the designated near key (Q key) and far key (P key) to judge the parity of numbers as quickly and correctly as possible. The near and far keys were located at a distance of 27 and 44 cm from the junction of the participant's arm and shoulder, respectively (Fig. 1a). Before conducting the formal experiment, the experimenter checked the response assignment to make sure that participants were following the instruction.

Data analysis

If accuracy of responses of a participant was lower than 70 %, the data of that participant were excluded from analysis. In addition, the data of the participant who did not strictly follow the instruction to perform the task (e.g., responded with a wrong hand) were also excluded from analysis. Before conducting the trend analysis (see below), reaction times (RTs) for error trials and RTs that exceeded three standard deviations were omitted.

A linear trend analysis of repeated measures was used to evaluate the space–number mapping. It was designed to estimate the negative or positive linear relation between independent and dependent variables. Take the left-to-right SNARC effect for example. For smaller numbers, left hand will respond faster than right hand, and thus, the difference of RT (dRT, mean RT for right-hand responses minus that for left-hand responses) should be positive; conversely, for larger numbers, the dRT should be negative. The dRT should thus become more negative as number increases, revealing a negative linear relationship. The slope of the linear relationship captures the essence of the mapping in the expected latency differences between the two responses within the range of a given magnitude. The advantage of such linear trend analysis is that it quantifies the effect size of both the slope and the proportion of variability accounted for (Pinhas et al. 2012).

To calculate the linear trend of dRTs as a function of number, first of all, the mean RTs of the correct responses were computed for each number, separately for far and near responses within each participant. Mean RTs of far responses minus near responses gave the dRT. These dRTs were then submitted to a trend analysis. The weights of the linear trend were determined by the range of target numbers which equidistantly shifted so that the sum of weights is zero. For the equally spaced number magnitude levels, weights were −4.5, −3.5, −2.5, −1.5, −.5, .5, 1.5, 2.5, 3.5, 4.5 for the target number from 0 to 9, respectively (Pinhas et al. 2012). In this study, if there is an association between distance and number, a negative or positive linear relationship between dRT and number magnitude should be observed.

Results and discussion

Mean accuracy percentage of total responses was 93 %. According to the exclusion criteria, six participants were excluded from further analysis. In the data of valid participants, RTs for error trials (3.37 % of responses) and RTs exceeding three standard deviations from mean RT (1.40 % of responses) were excluded from further analysis.

The ANOVA of RTs revealed no significant main effects of response location and parity, and a marginally significant interaction of response location and parity, $F(1, 33) = 3.61$, $p = .066$, $\eta_p^2 = .099$. The ANOVA of dRTs revealed significant main effect of number, $F(9, 297) = 3.13$, $p < .01$, $\eta_p^2 = .087$.

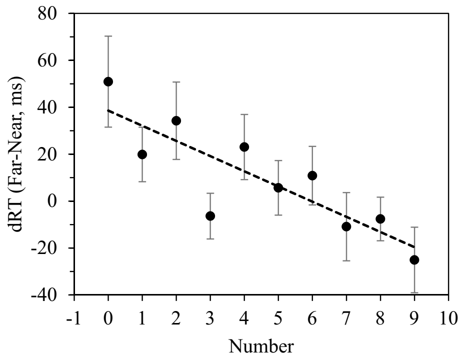

Fig. 2 Differences in mean RTs (dRTs) between near and far responses (far–near) as a function of number magnitude in Experiment 1. *Dots* indicate the observed dRTs, and the *dashed line* depicts the predicted dRTs on the basis of the linear trend analysis. *Error bars* represent standard errors from the mean differences

More importantly, the linear trend analysis lent support to a significant linear trend of the relationship between numbers and dRTs of far minus near responses, $F(1, 297) = 20.33$, $p < .001$, slope $= -6.47$, $\eta_p^2 = .064$, with medium effect size for linear trend (Cohen 1988). The result indicates that near responses are faster with smaller numbers and far responses are faster with larger numbers (Fig. 2). That is, in the front space, near–far distance is associated with number in our magnitude representation system.

Experiment 2

Based on the result of Experiment 1, this experiment went further to examine the space in the back of the body. The back of the body is important for certain goal-directing actions (Saj and Vuilleumier 2007), such as turning back to reach an object or hand toward the back space without turning one's trunk to grasp something. Since back space is much less studied than front space, how the representation of numbers is mapped there is unknown.

Considering that an arrangement of two buttons (a near and a far key) behind the back would lead to an uncomfortable posture and introduce an unwanted confounding factor of muscle strength, we compared the front and back spatial representation instead of setting both buttons in the back space. The logic is: If the back spatial representation is associated with number magnitude with the body as the origin of the distance representation system, then the front and back space with the same distance would be mapped with the same number. Thus, the responses made in front and back space should have no difference between smaller and larger numbers. Otherwise, if the origin is located to the near-front side of the body, then the front space would be mapped to smaller numbers and the back space would be mapped to larger numbers, making the responses in near-front space faster for smaller numbers than larger numbers and back responses vice versa. In contrast, if the origin were located at the near-back side of the body rather than near front, the reversed pattern would be observed. Figure 1b displays the experiment setup: One keyboard was set in the front, and the other was set behind the back. Both keyboards were rotated 90° as in Experiment 1, and the designated response buttons were both near the body. Such setting enables the comparison of the front and back responses.

Method

Participants

Forty adults with normal or corrected to normal vision were invited to participate in the experiment for payment. All participants gave informed consent.

Design and procedure

The same presentation of stimuli and design as in Experiment 1 was used, except for the following changes.

Because it is difficult to raise the hand behind the back to the height of a regular table and remain in such a posture while performing the experimental task, we lowered the height of two keyboards to participant's knee (Fig. 1b), so that participants would feel with ease to respond with front hand resting on the knee and back hand resting on the back. Another change in this experiment is that participants used their thumbs rather than forefingers to respond, because back hand responding with forefinger forces the waist to twist into an uncomfortable position.

Participants were instructed to place their thumbs on the designated front key and back key and try to judge the parity of the numbers as quickly and correctly as possible. The designated keys were designed to respond on the two numeric keypads of computer keyboard, with right hand responding with Plus key and left hand responding with Enter key. Both front and back keys were located at a distance of 27 cm from the junction of the arm and shoulder. Before each block, participants were required to complete a 10-trial practice session to familiarize with the front–back assignment.

Results and discussion

Mean accuracy percentage of total responses was 95 %. According to the same exclusion criteria as used in Experiment 1, four participants were excluded from further

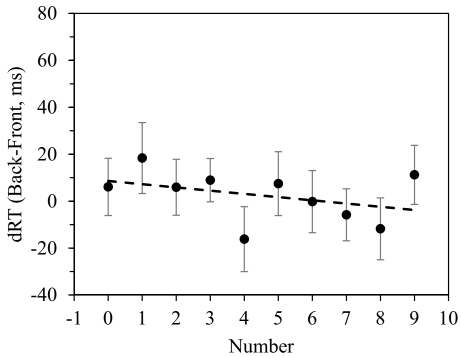

Fig. 3 Differences in mean RT (dRT) between front and back responses (back–front) as a function of number magnitude in Experiment 2. *Dots* indicate the observed dRTs, and the *dashed line* depicts the predicted dRTs on the basis of the linear trend analysis. *Error bars* represent standard errors from the mean differences

analysis. In the data of valid participants, RTs for error trials (3.45 % of responses) and RTs that exceeded three standard deviations from mean RT (1.70 % of responses) were excluded from further analysis.

The ANOVA of RTs showed no significant main effects of hand, response location and parity, suggesting that there was no difference in the difficulty for designated front and back responses. A marginal significant interaction of hand and parity was found, $F(1, 35) = 3.67$, $p = .06$, $\eta_p^2 = .095$.

Results did not support the linear trend in the relationship between numbers and dRTs of back minus front responses (Fig. 3). The ANOVA of dRTs revealed no significant main effect of number, $F(9, 306) = 1.08$, $p = .43$, $\eta_p^2 = .031$. Linear trend was not significant, $F\ (1, 315) = 1.08$, $p = .301$, slope $= -1.38$, $\eta_p^2 = .003$. The result revealed that the same distance of two responses with respect to the body made no difference for the dRTs on smaller and larger numbers, suggesting that neither the near-front space nor the near-back space is as the origin of the distance representation system. Implications of the result are discussed in the "General discussion".

Experiment 3

In this experiment, both hands of the participants were placed at the right or left side, with one hand being near body and the other far away from body. If distance–number mapping also exists on transverse axis, then regardless of left/right space, smaller numbers would be faster when paired with near response and larger numbers would be faster when paired with far response. If not, in either the right or left space, left-to-right SNARC effect would be observed.

Method

Participants

Thirty-five adults with normal or corrected to normal vision were invited to participate in this experiment for payment. All participants gave informed consent.

Design and procedure

Some participants reported that they were uncertain about parity of zero in the previous experiments, and thus, we excluded zero from target stimuli in this experiment. Accordingly, to balance the number of odd and even numbers, 5 was also not used as it is in middle of the set numbers from 1 to 9. Thus, single Arabic numbers, from 1 to 4, and from 6 to 9, were randomly selected to appear in each trial. Since the result was analyzed separately on the left and right sides, we matched the repeated frequency of numbers on each side to the frequency used in Experiment 1 and 2 (20 trials per number), making each number repeated 10 times within a block. Each block contained 80 trials, and there were two consecutive blocks for each side, making the total number of trials in the formal experiment 320 in total. Participants were randomly assigned to the blocks of sequence with left side first or right side first. The presentation order for the two blocks with either the left-side or right-side response locations was also randomized. For each side, there was one block of trials in which the odd numbers were assigned to the near button, and the other block with the reversed assignment.

Participants were instructed to place their forefingers on designated near key and far key to judge the parity of numbers as quickly and correctly as possible. Q key was designed as near key, and P key was designed as far key on the right side. The designated keys were reversed on the left side. The near key was located at a distance of 10 cm, and the far key was located at a distance of 27 cm from the body midline, respectively, on either the left or the right side. Both keys were in front at a distance of 27 cm from the junction of the arm and shoulder aligned with the sagittal axis (Fig. 1c). In all other respects, stimuli presentation and procedure were the same as in Experiment 2.

Results and discussion

Mean accuracy percentage of total responses was 95 %. According to the exclusion criteria in Experiment 1, three participants were excluded from further analysis. In the data of valid participants, RTs for error trials (3.05 % of responses) and RTs exceeding three standard deviations from mean RT (0 % of responses) were excluded from analysis.

In the left-side space, the ANOVA of RTs revealed that there was a significant main effect of hand, $F(1, 31) = 9.69$,

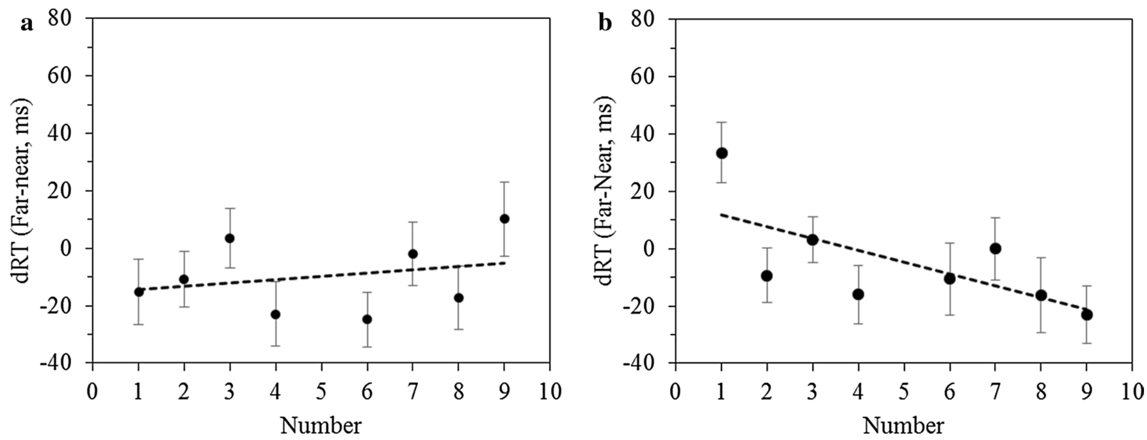

Fig. 4 Differences in mean RTs (dRTs) between near and far responses (far–near) as a function of number magnitude in Experiment 3 with responses **a** on the *left side* and **b** on the *right side*. *Dots* indicate the observed dRTs. The *dashed line* depicts the predicted dRTs on the basis of the linear trend analysis. *Error bars* represent standard errors from the mean differences

$p < .01$, $\eta_p^2 = .24$, indicating that right-hand responses were faster than left-hand responses. There was also significant main effect of parity, $F(1, 31) = 4.21$, $p < .05$, $\eta_p^2 = .12$: Responses for even numbers were faster than odd numbers. The interaction of hand and parity was not significant, $F(1, 31) = 1.59$, $p = .22$, $\eta_p^2 = .05$. In the right-side space, the ANOVA of RTs revealed that neither the main effects of hand, $F(1, 31) = .93$, $p = .34$, $\eta_p^2 = .03$ and parity, $F(1, 31) = .89$, $p = .35$, $\eta_p^2 = .03$, nor their interaction was significant, $F(1, 31) = 2.13$, $p = .16$, $\eta_p^2 = .06$.

The dRTs of far minus near responses of the left and right sides were separately analyzed. In the left-side space, the ANOVA revealed no significant main effect of number on the analysis of dRTs, $F(7, 217) = 1.28$, $p = .26$, $\eta_p^2 = .040$. Linear trend was not significant, $F(1, 217) = .63$, $p = .43$, slope $= 1.15$, $\eta_p^2 = .003$ (Fig. 4a). In the right-side space, the ANOVA of dRTs revealed significant main effect of number, $F(7, 217) = 3.05$, $p < .01$, $\eta_p^2 = .089$; Linear trend was significant, $F(1, 217) = 9.91$, $p = .002$, slope $= -4.12$, $\eta_p^2 = .044$ (Fig. 4b), and the effect size for linear trend was medium (Cohen 1988).

One may argue that the effect sizes in this experiment and the previous two experiments are rather small. However, we compared the slopes of linear trend that represent the mental number line with previous studies. The slopes of our results in the three experiments range from −4.12 to −6.47, which fall in the range of previous studies (from −4.1 to −10.1, see Dehaene et al. 1993; −5.8, see Schwarz and Keus 2004; from −2.96 to −5.23, see Müller and Schwarz 2007). Thus, the results were reliable, indicating that near responses are faster with smaller numbers and far responses are faster with larger numbers.

Therefore, the results support the hypothesis that distance–number mapping exists in the right-side space. However, this effect did not occur on the left side as neither left-to-right SNARC effect nor distance–space mapping were found. The null result could be explained by the counteracting of the left-to-right SNARC effect and the near-to-far distance–number mapping.

It may be argued that the distance–number mapping on the transverse axis is based on hand, rather than space. Effect of left/right hand may confound the SNARC effect due to unbalanced hand posture in Experiment 3: It is possible that left hand is paired with small magnitude and right hand is paired with large magnitude, rather than spatial response. We did not balance the hand posture because crossed far hands placing at the same distance of uncrossed far hands would make participants uncomfortable with the crossed hand largely stretched and easily fatigued. The distance was about 38 cm from the junction of the arm and shoulder, which was calculated as the hypotenuse of 27 cm from the trunk aligned with the sagittal axis and 27 cm from the body midline aligned with the transverse axis. Nevertheless, in a previous study when participants crossed their hands, smaller numbers were still faster with left-side responses and larger numbers were faster with right-side responses, suggesting that magnitude is paired with spatial representation, rather than responses of hands (Dehaene et al. 1993). The current significant linear trend on the right side also supports the space-based representation. Moreover, no significant main effect of hands on the analysis of RTs was found, further suggesting that the potential effect of hands did not play a role on the right side of mappings.

General discussion

The present study investigated how number representation is mapped to distance in peripersonal space. Here, a new pattern of distance–number mapping around the body was found. In three experiments, response buttons were set near or far from body at diverse orientations, and the results revealed an association between distance and number representation in peripersonal space: Smaller numbers map to near space, and larger numbers map to far space.

One exception from the overall pattern is when both responses were set in the left-side space: Neither left-to-right SNARC effect nor distance–number mapping was present. Given the well-known left-to-right SNARC effect, left-side responses should be faster with smaller numbers. A relevant study has shown that two types of space–number mappings coexist in right-to-left finger counting and left-to-right SNARC effect (Di Luca et al. 2006). In the current result, two forms of mapping (distance–number and SNARC) coexist and they both affect the responses, resulting in counteracting each other due to equivalent forces. Such interaction is not a foreseen result, since the aim of Experiment 3 was to see whether distance–number mapping on the front side would also be revealed on the transverse axis. Furthermore, this interaction probably would not occur in Experiment 1 and 2, because the Arabic numbers of SNARC effect only show on the transverse axis but not on the sagittal axis for readers of Chinese script (Hung et al. 2008).

Along the same line of reasoning, when the directions of two forms of mapping are consistent, the two mappings should add up linearly. However, the result on the right side did not seem to support such linear addition. The effect size of Experiment 3 (.036) was smaller than that of Experiment 1 (.064). Also, the slope found in Experiment 3 (-4.12) was smaller (rather than larger) compared to the slope found in Experiment 1 (-6.47), although there was no significant difference between the two slopes ($p = .34$). This may be influenced by the smaller distance of far hand in Experiment 3 (about 38 cm; the detail calculation was addressed above in the Result section of Experiment 3) than in Experiment 1 (44 cm). Alternatively, numbers may not be symmetrically represented around the body, and thus, the linear addition is not applicable on the right side. Also, these comparisons were made between different groups of participants and the magnitude of the representation–response mapping effect can differ between groups. In any case, the pattern of number representation still needs future investigations. Nevertheless, the coexistence of two mappings is not overthrown and this result argues against the view of monotonic mapping of quantities in the domain of space and magnitude (Bueti and Walsh 2009), indicating that multiple mapping representations exist in the shared mechanism between space and number representations.

The present association sheds light on the shared mechanism between space and number representations, beyond the well-known left-small and right-large association of SNARC. Our study supports the ATOM theory of shared mechanism representation. Not only specific spatial locations (e.g., the points on number line) but also distance representation is associated with number in simple responses. Furthermore, our results clarify the precise mapping relationship between distance and number. In ATOM, a common representation system for time, space and quantity is proposed without specific representation form. Theoretically, the mathematical properties of time, space and quantity differ in many ways. For instance, time is in one-dimensional scalar, space is three-dimensional, and quantity depends on what it refers to (e.g., size, number, volume, weight, etc.). Our results hint at the kind of common representation that can deal with multiple magnitudes with qualitatively distinct properties (such as different dimensions). For the one-dimensional number and three-dimensional distance, the representation system projects the numbers to the polar coordinate of distance, achieving the connection of the magnitude with different dimensions. Further studies are required to reveal more converted relations among variety of magnitudes.

It may be argued that different muscle tensions between the two designated responses could be a confounding factor in the distance–number mapping effect we found here. However, it may not have systematic influence on the effect. To extend arms, one needs to rely on the antagonism of extensor muscles and flexor muscles. We do not rely on a single muscle group to stretch or draw our arms; rather, the action was made by the cooperation of both extensor muscle and flexor muscle groups. That is, any kind of action is accompanied by not only muscle contraction but also relaxation. Thus, the effect we found cannot be merely explained by muscle tension.

Our results support the view that the origin of the distance representation system is located in the body. However, it may be argued that multiple origins could also explain the current result. For instance, the front and the back space each has an origin at their corresponding near space, such that the two response buttons are still located equally distant though with different origins. Although the multiple-origin account can also explain the current result of Experiment 2, such a representation system that owns two origins to locate a target simultaneously is difficult to implement in our cognitive system. To represent multiple origins simultaneously means having multiple reference frames at the same time, such that when one is to locate a target, the amount of calculation is more than that for a single reference frame. Moreover, it is difficult to locate the target when it meets the boundaries of different reference frames. In contrast, it is more parsimonious and straightforward to infer an in-body origin and equal distance to that origin resulted in no significant dRTs between the two responses in our Experiment 2.

Theoretically, different representations exist for spatial coordinate systems: Locations can be represented with respect to the individual in the egocentric reference frame, or locations can be represented within the framework external to the individual and independent of one's position in the allocentric reference frame (Klatzky 1998). Our findings that numbers were mapped to the distance with respect to the body and that the origin was located in the body suggest that distance may be represented in a magnitude form starting from the body and extending to the far space. The results provide a basis of understanding the origin from where the distance is estimated.

In addition to our findings, previous studies also found vertical SNARC effect on the sagittal axis, but with more adjacent spatial responses than ours (Ito and Hatta 2004). Their results suggested small-near and large-far mappings, which was contrary to their prediction based on the reading direction in Japanese (far to near or top to bottom). They pointed out that it might be caused by the repeated experiences of seeing mathematical diagrams in which larger numbers located in the upper space and smaller numbers located in the lower space. Arguably, such experience might also explain the current data. However, we think not for the following reason. The most familiar mathematical representation of number space is Cartesian coordinate, in which the number space is anisotropic. That is, the number in the positive half of the axis increases with its distance from the origin, and the number in the negative half decreases with its distance from the origin. However, our finding suggests that the distance–number mapping is isotropic: The number simply increases with the distance respective to the body, regardless of the direction. Take Experiment 2 for example. The result revealed that there was no difference of mapping between front and back space, revealing isotropic essence of the mapping relative to the body. The qualitative difference (isotropy vs. anisotropy) suggests that the mathematical experience account is unlikely to completely explain the current finding. We thus suggest that distance relative to the body is the more important factor in the number–space mapping effect we found in this study.

Moreover, based on the nature of peripersonal space, we predict that the distance–number mapping we found here would be shown on other planes as well, and eventually, it would extend to the representation of a sphere around body with near-small and far-large associations. We also predict that distance–number association would be remapped through tool use to extend to farther space; with far space taken as near space and extrapersonal space as far space. These predictions should be verified by further investigations.

In conclusion, our results show that small-large magnitude is mapped onto near–far space in the peripersonal space, beyond the classical left-to-right SNARC effect. These two number–space mappings could affect each other when they align on the transverse axis. Furthermore, our results indicate that the origin of distance–number mapping is located in the body, revealing that the coordinate system of the distance–number mapping is the egocentric reference frame.

Acknowledgments This study is supported by a grant from National Science Council of Taiwan (MOST101-2410-H-002-083-MY3). We thank Ren-Hao Li for the initial discussion of the idea, and Jye-Sheng Tan and An-Yi Chang for helpful comments on earlier versions of this manuscript.

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