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Standard body-space relationships: Fingers hold spatial information

Daniele Romano [a,b], Francesco Marini [a,c], Angelo Maravita [a,b,*]

[a] University of Milano Bicocca, Department of Psychology, piazza Ateneo Nuovo 1, 20126 Milan, Italy
[b] NeuroMi – Milan Center for Neuroscience, Milan, Italy
[c] Department of Psychology, University of Nevada, Reno, NV 89557, USA

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ABSTRACT

The representation of the body in the brain is constantly updated to allow optimal sensorimotor interactions with the external world. In addition to dynamic features, body representation holds stable features that are still largely unknown. In the present work we explored the hypothesis that body parts have preferential associations with relative spatial locations. Specifically, in three experiments, we found consistent preferential associations between the index finger and the *top* position, and between the thumb and the *bottom* position. This association was found in a tactile sensory discrimination task, which was conducted both with and without vision, as well as at the implicit conceptual association level. These findings show that body parts and spatial locations are stably associated. Therefore, not only are body segments dynamically mapped in space for perception and action, but they also hold intrinsic spatial information that contributes to somatosensory spatial processing.

1. Introduction

The idea that everyone has a mental representation of his/her own body has received wide support in the multidisciplinary field of research at the intersection of philosophy, experimental psychology, and cognitive neuroscience that focuses on how mind and body interact. This representation is thought to help localizing the bodily self and interacting with the external world (Blanke & Metzinger, 2009; de Vignemont, 2010). Different sub-components of body representations (BR) have been distinguished since its first description (e.g. Head & Holmes, 1911). On the one hand, a dynamic representation of the body oriented to action, namely the body schema (Cardinali, Frassinetti et al., 2009; Coslett, 1998; Kammers, Kootker, Hogendoorn, & Dijkerman, 2009; Maravita, Spence, & Driver, 2003), allows processing of information necessary to plan actions in space (Cardinali, Brozzoli, & Farnè, 2009; de Vignemont, 2010; Holmes & Spence, 2004; Kammers, van der Ham, & Dijkerman, 2006; Tsakiris & Fotopoulou, 2008). On the other hand, BR also includes more stable aspects about semantic and structural aspects of one's own body, whose nature is still debated (de Vignemont, 2010; Dijkerman & de Haan, 2007; Gallagher, 2005; Gandevia & Phegan, 1999; Ionta, Perruchoud, Draganski, & Blanke, 2012; Kammers, Mulder, de Vignemont, & Dijkerman, 2009; Longo, Azañón, & Haggard, 2010; Melzack & Bromage, 1973; Moseley, 2005; Tsakiris & Fotopoulou, 2008).

The characterization of different components of BR is of paramount importance because both dynamic and stable features of BR continuously affect our everyday interactions with the external world. Considering a critical aspect of behavior, i.e. the interaction between the body and external objects, there is evidence that body posture may affect the spatial processing of sensory stimuli (Azañón & Soto-Faraco, 2008; Ionta, Fourkas, Fiorio, & Aglioti, 2007; Parsons, 1987a, 1987b; Reed & Farah, 1995). Even in a simple tactile temporal order judgment task, the relative position of limbs in space can affect performance by automatically referring skin stimulations to the egocentric spatial coordinates (Yamamoto & Kitazawa, 2001a, 2001b), although the early stage of the processing is coded in a somatotopic frame of reference (Azañón & Soto-Faraco, 2008). This suggests the existence of a continuous comparison process between visual, somatosensory, and proprioceptive information, in which contingent bodily and visuospatial representations influence each other. Alternatively, spatial information might be deeply embedded in BR and invariantly modulate performance independent of ongoing postural changes. This intriguing possibility implies the existence of a standard representation of the relationship between body and space that potentially modulates all body-space interactions regardless of any potential postural change.

We sought out the existence of standard associations between spatial locations and body parts focusing on the fingers because

* Corresponding author at: University of Milano Bicocca, Department of Psychology, piazza Ateneo Nuovo 1, 20126 Milan, Italy.

E-mail addresses: daniele.romano@unimib.it (D. Romano), francesco.pd@gmail.com (F. Marini), angelo.maravita@unimib.it (A. Maravita).

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their relative spatial positions are highly flexible and not affected by strong postural or gravitational constraints about spatial elevations. Specifically, we tested the hypothesis that preferential associations existed between the thumb and the index finger and the relative spatial positions of ‘‘top” and ‘‘bottom”, respectively. Those are relative spatial positions that are often experienced with the fingers and are neutral with respect to the left/right aspect, which is known to be associated with more specific egocentric representations and cerebral dominance processes (Yamamoto & Kitazawa, 2001a, 2001b).

Across three experiments, we investigated the putative intrinsic associations between fingers and space using perceptual discrimination and cognitive tasks. In Experiments 1 and 2, we used a localization discrimination task seeking whether tactile stimuli are detected faster and more accurately when the target fingers occupy a specific relative spatial location. The rationale was that if bodily segments hold spatial information then stimuli delivered to a given body part should be processed more efficiently when that body part holds its preferred (‘‘standard”) position. Furthermore, in Experiment 2 the task was performed by blind-folded participants under the hypothesis that the contribution of stable internal spatial representations should be maximal in the absence of visual information (although task-irrelevant) about one's own body. In Experiment 3, we used the Implicit Association Test (IAT) (Greenwald, McGhee, & Schwartz, 1998; Greenwald, Nosek, & Banaji, 2003), which measures the strength of implicit associations between a stimulus category (here, fingers) and a class of attributes (here, spatial labels), in order to test the existence of conceptual associations between body parts and spatial concepts.

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

Experiment 1 was comprised of twenty-one (age = 26 ± 15 (sd) range = 21–43) participants, with normal or corrected-to-normal vision who were naïve to the purpose of the experiment. We originally set the sample size at twenty, however one participant was replaced before data inspection because he did not execute the task as requested, resulting in twenty-one participants tested. Participants were recruited among the students of the University of Milano-Bicocca and gave their written informed consent before the experiment.

The study was approved by the ethical committee of the University of Milano-Bicocca and was conducted in accordance with the Declaration of Helsinki (World Medical Organization, 1996).

2.1.2. Stimuli

The experimental apparatus consisted of a black panel (70 cm × 70 cm) with a fixation point at the center. Computerized stimuli were delivered through four tactile stimulators (custom-made electromagnetic solenoids, Heijo Electronics, Beckenham, UK; www.heijo.com), controlled by a custom-made I/O box and E-Prime software (Psychology Software Tools, Inc., Pittsburgh, PA, psychotoolbox.org). Each stimulus consisted of three 30 ms on-phases (single pulses) with two interleaved 30 ms off-phases, resulting in a 150 ms vibration

2.1.3. Task

A unimodal tactile position discrimination task was used, inspired by the one previously used to investigate cross-modal effects (Maravita, Spence, Sergent, & Driver, 2002; Marini, Chelazzi, & Maravita, 2013; Marini, Romano, & Maravita, 2016; Spence, Pavani, & Driver, 2004)

Participants sat at a table, 50 cm away from the previously mentioned black panel standing in front of them. Tactile stimulators were applied directly to the fingertips of each index finger and thumb with medical tape. Both hands were placed about 2 cm in front of the black panel and at fixed distance of about 6 cm from the fixation point, without touching each other, in such a way that the four stimulators corresponded to the vertexes of an imaginary square around the fixation point (Fig.1a). With this configuration, the distance between all adjacent stimulators was 8 cm. Moreover, one hand was placed at the ‘‘top” position and the other hand was placed at the ‘‘bottom” position (see Marini et al., 2016 for further details on this experimental manipulation). The position of each hand (right hand at the top and left at the bottom, or vice versa) was fixed for each participant and counterbalanced across participants (right hand at the top for 10 participants and left hand at top for the remaining 10 participants). On each trial, participants received a tactile stimulation at one of the four possible locations on their fingertips - finger (index/thumb), side (left/right), or hand (left/right). They were asked to discriminate as quickly as possible the elevation of the tactile stimulus (top or bottom) regardless of the stimulated finger.

Responses were delivered through two foot-pedals, one below the toe and one below the heel of the right foot. Participants raised the toe to respond ‘‘top” or the heel to respond ‘‘bottom”. A total of 120 trials (30 for each position) were delivered in a randomized sequence. Error rate and reaction time (RT) were collected.

2.1.4. Analysis

RTs were first trimmed to eliminate outliers, which were defined as trials faster than 200 ms (anticipatory responses) as well as trials exceeding 3 standard deviations above the mean (late responses), and then converted to log-values to overcome the typical asymmetry of the RT distribution (Ratcliff, 1993). Error rate scores were converted to the arcsine of the root square, a mathematical transformation that aims at aligning the distribution of the error rate data (and its residuals) with the assumptions of ANOVA (Zubin, 1935). Participants with mean Error rate exceeding 3 standard deviations above the group average were excluded from the analysis. This criterion led to the exclusion of 3 additional participants, thus the ANOVAs on RT and error rate were run on a sample of 17 participants

Statistical analyses used repeated-measure analysis of variance (ANOVA) with two factors: relative Position (top/bottom) and Finger (thumb/index) receiving the tactile stimulation. RTs and error rate were tested separately as dependent variables. We reported the effect size of significant effects calculating the partial eta-squared (η_p^2). In ANOVAs, post hoc comparisons were conducted with the HSD-Tukey test. Statistical analyses were performed using Statistica 6.0 for Windows (StatSoft Italia SRL) and SPSS 22 (IBM® SPSS® Chicago, Illinois).

We predicted faster and more accurate discrimination of tactile stimuli when fingers occupy whichever is their preferential spatial location between the upper (top) and the lower position (bottom), as reflected by an interaction of the Position and Finger factors. We did not formulate any specific prediction about which posture would be ‘‘preferential” among the two possible associations (i.e., thumb-top and index-bottom, or vice versa) because both postures can be naturally experienced in daily life and therefore both associations seemed equally plausible.

2.2. Results

2.2.1. Reaction Times (RT)

The ANOVA showed significant effects both for the main factor Position [$F(1,16) = 5.08$, $p = 0.04$, $\eta_p^2 = 0.241$; top = 634 ms (mean) ±18 (Standard Error), bottom = 602 ms ± 15] and for the interaction