Cognition 157 (2016) 289–295

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

A three-dimensional spatial characterization of the crossed-hands deficit

Elena Azañón *, Kim Mihaljevic, Matthew R. Longo

Department of Psychological Sciences, Birkbeck, University of London, London WC1E 7HX, UK

ARTICLE INFO

Article history:
Received 17 December 2015
Revised 7 September 2016
Accepted 11 September 2016

Keywords:
Crossed-hands deficit
Spatial frames of reference
Tactile spatial localization
Temporal order judgements
Three-dimensional space

ABSTRACT

To perceive the location of touch in space, we integrate information about skin-location with information about the location of that body part in space. Most research investigating this process of *tactile spatial remapping* has used the so-called *crossed-hands deficit*, in which the ability to judge the temporal order of touches on the two hands is impaired when the arms are crossed. This posture induces a conflict between skin-based and tactile external spatial representations, specifically in the left-right dimension. Thus, it is unknown whether touch is affected by posture when spatial relations other than the right-left dimension are available. Here, we tested the extent to which the crossed-hands deficit is a measure of tactile remapping, reflecting tactile encoding in three-dimensional space. Participants judged the temporal order of tactile stimuli presented to crossed and uncrossed hands. The arms were placed at different elevations (up-down dimension; Experiments 1 and 2), or at different distances from the body in the depth plane (close-far dimension; Experiment 3). The crossed-hands deficit was reduced when other sources of spatial information, orthogonal to the left-right dimension (i.e., close-far, up-down), were available. Nonetheless, the deficit persisted in all conditions, even when processing of non-conflicting information in the close-far or up-down dimensions was enough to solve the task. Together, these results demonstrate that the processing underlying the crossed-hands deficit is related to the encoding of tactile localization in three-dimensional space, rather than related uniquely to the cost of processing information in the right-left dimension. Furthermore, the persistence of the crossing effect provides evidence for automatic integration of all available information during the encoding of tactile information.

1. Introduction

Localizing touch in space is essential for spatially-coordinated action. To swat away a fly on our arm, we need to know not just where on the arm the fly landed, but also the posture of the arm in space. Thus, tactile localization (caused in this case by the insect) entails the transformation of the location of touch in a reference frame that is skin-based (a touch *on the right arm*) to one that is defined by coordinates in external space (a touch *on the right side of space*) and the subsequent integration of these two reference frames. It has been proposed that the external reference frame, in which tactile events are encoded after remapping, relies strongly on a visually-based representation of space (Begum Ali, Cowie, & Bremner, 2014; Ley, Bottari, Shenoy, Kekunnaya, & Röder, 2013; Röder, Rösler, & Spence, 2004). However, this proposal leaves open how this representation for touch in a three-dimensional space is characterized and the way the different dimensions interact.

Tactile remapping has been generally studied by manipulating limb posture, especially by crossing the arms. In this posture, a touch on the right hand (in skin-based coordinates), is located in left space, creating an incongruence between reference frames in the right-left dimension (Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001; for a review see Heed, Buchholz, Engel, & Röder, 2015). A well-known consequence of this conflicting information is the impairment in the ability to report the order of two stimuli, one applied to each hand, when hands are crossed (Heed & Azañón, 2014; Shore et al., 2002; Yamamoto & Kitazawa, 2001). In such instances, the order of two stimuli might be correctly computed, but it is inaccurately reported because of the incorrect localization of the stimuli in space (Badde, Heed, & Röder, 2016; Overvliet, Azañón, & Soto-Faraco, 2011; Roberts & Humphreys, 2008). This result has been interpreted as evidence that posture is taken into account automatically, even if this impairs task performance (Azañón, Camacho, & Soto-Faraco, 2010; Kitazawa, 2002; Yamamoto & Kitazawa, 2001). In the remapping literature, this idea has been extrapolated indirectly to all postures, to the extent that it is generally assumed that tactile remapping (or the encoding of touch in external space) is a general

* Corresponding author.
E-mail address: eazanyon@gmail.com (E. Azañón).

http://dx.doi.org/10.1016/j.cognition.2016.09.007
0010-0277/

step in tactile processing (Azañón & Soto-Faraco, 2008; Kitazawa, 2002; Overvliet et al., 2011; Röder et al., 2004).

The crossing effect has been suggested to result, amongst other models, from either an impairment of coordinate transformation (Yamamoto & Kitazawa, 2001) or a conflict in the integration of disparate spatial information (Badde, Röder, & Heed, 2015; Badde et al., 2016; Heed et al., 2015). Regardless of the interpretation of the origin of the effect, all these studies assume that the deficit indexes an automatic triggering of spatial transformations during tactile processing. And the aim of this transformation is the generation of a tactile location estimate in external space (Azañón, Stenner, Cardini, & Haggard, 2015; Heed, Backhaus, & Röder, 2012; Heed et al., 2015). Although the deficit is in the right-left dimension, the final estimate should code location in three-dimensional space and certainly not only in the right-left dimension. To our knowledge, however, no studies have shown that spatial relations in dimensions other than the left-right dimension have any effect at all on TOJ judgements. Indeed, Yamamoto and Kitazawa found that crossing the hands with one hand close to the body and another further apart did not appear to influence the deficit (Yamamoto & Kitazawa, 2001). Thus, although it is generally assumed that touch is localized with respect to all three axes of space, this has not been experimentally demonstrated.

This is a fundamental issue that needs to be addressed before assuming that the crossed-hands deficit is a valid index of tactile remapping in 3D space. Note that crossing body parts is the most popular paradigm in the tactile remapping literature, as crossing the limbs produces large effects. Very few studies have investigated remapping along other dimensions (see Azañón, Longo, Soto-Faraco, & Haggard, 2010 for a task that varied the up-down dimension, though not using TOJs), or in the left-right dimension without inducing a conflict (see for exceptions, e.g., Gillmeister & Forster, 2012; Shore, Gray, Spry, & Spence, 2005). Thus, it is not clear to what extent the crossed-hands deficit is a reflection of remapping in three-dimensional space, the result of confusion specifically in the left-right axis, or a combination of the two. It is true that, by definition, the presence of a crossed-hands deficit implies that posture has been taken into account. But the extent of the deficit and the underlying processing might not reflect the computation of a location estimate in volumetric external space, but the processing of a conflict in a particularly salient spatial dimension.

There are, in fact, some reasons for thinking that it is the presence of a conflict between reference frames in the left-right dimension, rather than tactile remapping in 3D space, what underlies the crossed-hands deficit. First, there is no comparable effect of an influence of posture when no conflict between reference frames is involved. For instance, some results show that TOJs are slightly better when uncrossed hands are placed far apart rather than close together (Roberts, Wing, Durkin, & Humphreys, 2003; Shore et al., 2005). In this situation, no conflicting information about touch is present. Thus, one could argue that this positive result indicates that touch is remapped in external space (i.e., taking posture into account) in non-conflicting situations. However, even if a default transformation takes place when the arms are uncrossed, the effects observed in these studies are small (<20 ms; as compared to hundreds of ms in the crossed-hands studies; Roberts et al., 2003; Shore et al., 2005), not always present (see Kuroki, Watanabe, Kawakami, Tachi, & Nishida, 2010) and occur only under certain stimulation protocols (Shore et al., 2005). Second, the crossed-hands deficit is based on the processing of right-left spatial information, which is known to produce larger perceptual effects than when dealing with any other spatial dimension (Corballis & Beale, 1970; Farrell, 1979; Nicoletti & Ulmita, 1984). The left-right dimension is unique in being the axis in which our bodies are bilaterally symmetric (Corballis & Beale, 1970). Thus, the left-right position of touches on the skin might be uniquely confusable, since every location has an exact contralateral homologue, especially in light of known interactions between touches on homologous fingers (e.g., Tamè, Pavani, Papadelis, Farnè, & Braun, 2015). Moreover, the left-right axis is known to rely on distinct neural mechanisms. For example, left-right confusion is among a constellations of symptoms typically reported in Gerstmann's syndrome (Benton, 1959; Roeltgen, Sevush, & Heilman, 1983), which has been linked to lesions in the left inferior parietal lobe.

In the present study, we tested the extent to which the crossed-hands deficit reflects remapping in three-dimensional space, and not uniquely on the right-left dimension. Specifically, we aimed at modulating the crossed-hands deficit by adding other sources of spatial information, orthogonal to the conflicting left-right information. Note that in all previous studies, stimuli differed along a single spatial dimension (see Yamamoto & Kitazawa, 2001, Fig. 5, for an exception). Thus, typically, one hand would be placed to the right and the other to the left of the body, and both would be aligned in all other spatial dimensions. Here, we asked blindfolded participants to make TOJs of stimuli presented to crossed and uncrossed hands that were placed at different elevations (up-down dimension), or at different distances from the body in the depth plane (close-far dimension). If the effects observed when the hands are crossed are related to the encoding of touch in three-dimensional space, then the crossed-hands deficit should reflect the encoding of touch also in the depth and vertical planes. Thus, non-conflicting spatial information in the depth and vertical planes could be used to solve the task, hence ameliorating (or eliminating) the deficit. If, on the contrary, the crossed-deficit simply reflects the by-product of a conflict in the right-left dimension, then adding extra-spatial information should be irrelevant.

2. Methods

2.1. Participants

Forty-eight healthy volunteers participated in the study, 16 in each of the three experiments (Experiment 1: M = 27.06 years; SD = 8.32; 10 female; Experiment 2: M = 25.56 years; SD = 4.70; 10 female; Experiment 3: M = 26.56 years; SD = 6.29; 14 female). Participants were right-handed as assessed by the Edinburgh Inventory (Experiment 1: M = 87.72, SD = 13.82; Experiment 2: M = 93.31, SD = 14.14; Experiment 3: M = 91.71, SD = 13.90) and reported normal tactile sensitivity. They were naïve as to the purpose of the experiment and gave written informed consent to participate. The study was conducted in accordance with the Declaration of Helsinki and was approved by the local ethical committee.

2.2. Procedure

On each trial, a touch was applied to the dorsal surface of the middle phalanx of each ring finger. Tactile stimuli consisted of a 10 ms stimulus at suprathreshold intensity delivered through 9 mm diameter solenoid tappers (rounded tip, 0.2 mm skin contact; M&E Solve, Kent, UK). Stimuli were presented at varying stimulus onset asynchronies (SOAs; ±960, ±480, ±220, ±110, ±70, ±40, ±20 ms), with a similar range to previous experiments (Azañón & Soto-Faraco, 2007; Azañón et al., 2015). Negative values indicate that the left hand was stimulated first. Participants were required to identify which stimulus was presented first by pressing a button with the corresponding hand, as accurately as possible with no time restriction. In a 2×2 factorial design, the hands of the participant could be either uncrossed or crossed over the body midline,