Chapter 5

Measuring Tactile Distance Perception

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Abstract

Illusions of tactile distance have been studied since the start of scientific research on the sense of touch in the nineteenth century. In the past 15 years, these illusions have become increasingly popular among researchers due to their connections with basic aspects of somatosensory neurophysiology, higher-level aspects of mental body representation, and relation to clinical disorders. This chapter will discuss methods for measuring tactile distance perception, focusing on two broad classes of methods. One type of method involves making estimates of the distance between a single pair of touches applied to the skin. The other method involves making a judgment about the relative distance between two such pairs. These methods can be applied to a range of experimental designs, body parts, and experimental conditions.

Key words Touch, Distance perception, Size perception, Anisotropy

1 Introduction

Ernst Weber's studies in the nineteenth century were among the first systematic investigations of the sense of touch [1]. Among many seminal observations, Weber observed an intriguing tactile illusion which now bears his name (Weber's illusion). As he moved the two points of a compass across his skin, it felt to him like the distance between them increased as he moved them from a region of relatively low tactile sensitivity to a region of higher sensitivity. Several subsequent studies have confirmed this general pattern that touches feel farther apart on skin surfaces with high than with low tactile spatial acuity [2–4]. Analogous illusions have also been reported for stimuli in different orientations on single skin surfaces, with distances generally being perceived as farther apart when oriented across the width of the body [5–7]. Such anisotropies have been reported extensively on the hand [6], but also on other body parts including the forearm [5], thigh [5], shin [8], foot [9], and face [10]. The only place where this effect does not seem to

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appear is on the torso, with no apparent anisotropy on the belly [11], and two recent studies finding a reversed effect on the lower back [12, 13].

Longo and Haggard [6] related both Weber's illusion and tactile distance anisotropies to the geometry of the receptive fields (RFs) of neurons in the somatosensory cortex. RFs are smaller on highly sensitive skin surfaces compared to less sensitive skin surfaces [14], and are also generally oval-shaped with the long axis of the RF running parallel to the long axis of the limbs. This is found in the somatosensory cortex [15], the spinal cord [16], and even in individual peripheral afferent fibers [17]. Correspondingly, several studies have reported that tactile spatial acuity [1, 18] and the precision of tactile localization [19, 20] are higher across the width of the limbs than along their length. Consistently, adaptation aftereffects for perceived tactile distance have been reported [21], which show selectivity for a range of characteristics (e.g., orientation, location, skin surface) suggesting that they arise from relatively early stages of somatosensory processing.

At the same time, tactile distance perception also appears linked to higher-level aspects of body perception, being modulated by body size illusions [3, 22, 23] (*see* also Chapter 13, this volume), tool-use [24–26], and categorical segmentation of the body into discrete parts [27–29]. Similarly, the baseline distortions in tactile distance perception in which distances across body-part width are overestimated are similar to perceptual distortions of body size measured using a variety of other tasks [30–32]. Finally, several recent studies have found abnormalities of tactile distance perception in clinical disorders, such as anorexia nervosa [33] and obesity [34], low-back pain [35], as well as after surgical elongation of the arm [36].

2 Materials

A range of stimuli have been used to measure perceived tactile distance, including wooden, metal, or plastic sticks [3, 5, 6, 28, 29, 37–40], calipers [8, 27, 33, 34, 41, 42], von Frey hairs [7, 43], solenoid tappers [22], electric shocks [44], vibrotactile stimuli [2, 12], air puffs [45], and a laser which selectively stimulates nociceptive afferents [43]. While no research to my knowledge has directly compared these stimuli, it is worth noting that broadly comparable results (e.g., Weber's illusion) are apparent across a range of stimulus types. For example, anisotropies of similar magnitude have been found on the hand dorsum measured with sticks [6], von Frey hairs [7], and air puffs [45]. Similarly, comparable anisotropy in the opposite direction has recently been found on the lower back using both vibrotactile stimuli [12] and sticks [13]. Intriguingly, however, one study that compared tactile (von

Frey hairs) with nociceptive (infrared laser) distance perception found that participants were unable to make meaningful distance judgments of nociceptive stimuli at all [43].

Many studies have used simple verbal responses, either of judged size [2, 5, 7, 37, 43, 46] or of which of two stimuli is perceived as bigger [3, 6, 21, 22, 47], or manual entry of numbers [44], which do not require any specialized measurement equipment. Other approaches, however, do require other equipment. For example, Tamè and colleagues [45] used a visual comparison procedure in which participants manually adjusted the length of a line presented on a monitor to match the perceived distance between two touches. The script was controlled by a custom MATLAB script using the Psychophysics toolbox [48].

Some other studies [8, 33, 34, 41, 49] have used kinesthetic judgments in which participants use two fingertips to match the perceived distance between two touches. While this can be done using paper-and-pencil and a ruler [34, 49], most studies have used a more automated procedure in which distances are measured using a touchscreen tablet computer [8, 33, 41].

3 Methods

Methods for measuring tactile distance perception fall into two broad families, those involving estimating the distance between a single pair of touches (size estimation methods) and those involving comparing the relative distance between two different pairs (two-interval forced-choice, 2IFC methods, *see* Chapter 1, this volume for discussion of different experimental designs).

3.1 Size Estimation Methods

The first set of methods involves size estimation of a single tactile distance, which can involve four procedures:

3.1.1 In Magnitude Estimation

In which participants give a verbal estimate of distance using an arbitrary magnitude scale [2, 5]. Green [5], for example, asked participants to respond with “a number that reflected the apparent distance between the two stimuli” (pg. 316), while explicitly avoiding mapping these numbers onto known metric units such as inches or centimeters.

3.1.2 In Absolute Estimation

In which participants give verbal [7, 11, 27, 43, 46, 50] or written [44] estimates of the distance between two touches using an absolute metric scale (e.g., cm or inches). It is important to note that absolute over- or under-estimation of tactile distance using this method could be due to misrepresentation of the measuring unit, rather than an actual tactile distortion. Thus, in my view, inferences using this method should be restricted to comparisons of different experimental conditions, not to veridical size. One approach to addressing this issue would be to have a visual ruler present showing the actual size of a cm. Even in this case, however, interpreting absolute values is potentially problematic.

3.1.3 In Visual Comparison

In which participants compare a tactile distance with a visual comparison stimulus [45]. In the recent study by Tamè and colleagues [45], the stimuli were presented on a computer monitor, but they could also conceivably be printed on sheets of paper or even be physical 3-D objects. Compared to absolute estimation, this provides a more valid measure of over- or under-estimation of a single stimulus, though it is important to keep in mind that deviations from veridical judgments could just as well reflect misperception of visual as of tactile stimuli. For example, different estimates will likely be obtained if the visual comparison stimulus is oriented vertically versus Horizontally, due to the well-known visual horizontal-vertical illusion [51].

3.1.4 In Kinesthetic Estimation

In which participants use the distance between their thumb and index fingertips to match the perceived distance between two touches [8, 33, 34, 41, 49]. In these studies, the kinesthetic judgments have been made with a hand that was not being stimulated. As with absolute estimation and visual comparison, deviations from veridical judgments could reflect biases in kinesthetic perception, just as much as tactile distance perception.

3.2 Size Estimation Analysis

Whichever of these estimation methods is used, different analysis approaches can be employed:

3.2.1 Linear Regression

Some studies have used linear regression to assess how perceived tactile distance relates to actual tactile distance [5, 43]. Different skin surfaces, or different orientations on a single surface, can be compared either in terms of slope or *y*-intercept.

3.2.2 ANOVA

Other studies using similar designs have used analysis of variance (ANOVA) approaches to analyze data [2, 11, 46]. For example, the top row of Fig. 1 shows data on the hand and belly [11]. Because these skin surfaces have very different two-point discrimination thresholds [52, 53], different actual tactile distances needed to be used (Fig. 1, top left panel), leading to deviation from a purely factorial design. Re-expressing perceived distance as overestimation as a proportion of actual distance (Fig. 1, top right panel) can facilitate analysis and allow comparison of skin surfaces which require different absolute distances due to differences in 2-PDT (*see* **Note 4.1**). The results show a clear anisotropy on the hand, but not on the belly, as well as relative overestimation on the (relatively sensitive) hand compared to the (relatively insensitive) belly (i.e., Weber's illusion).

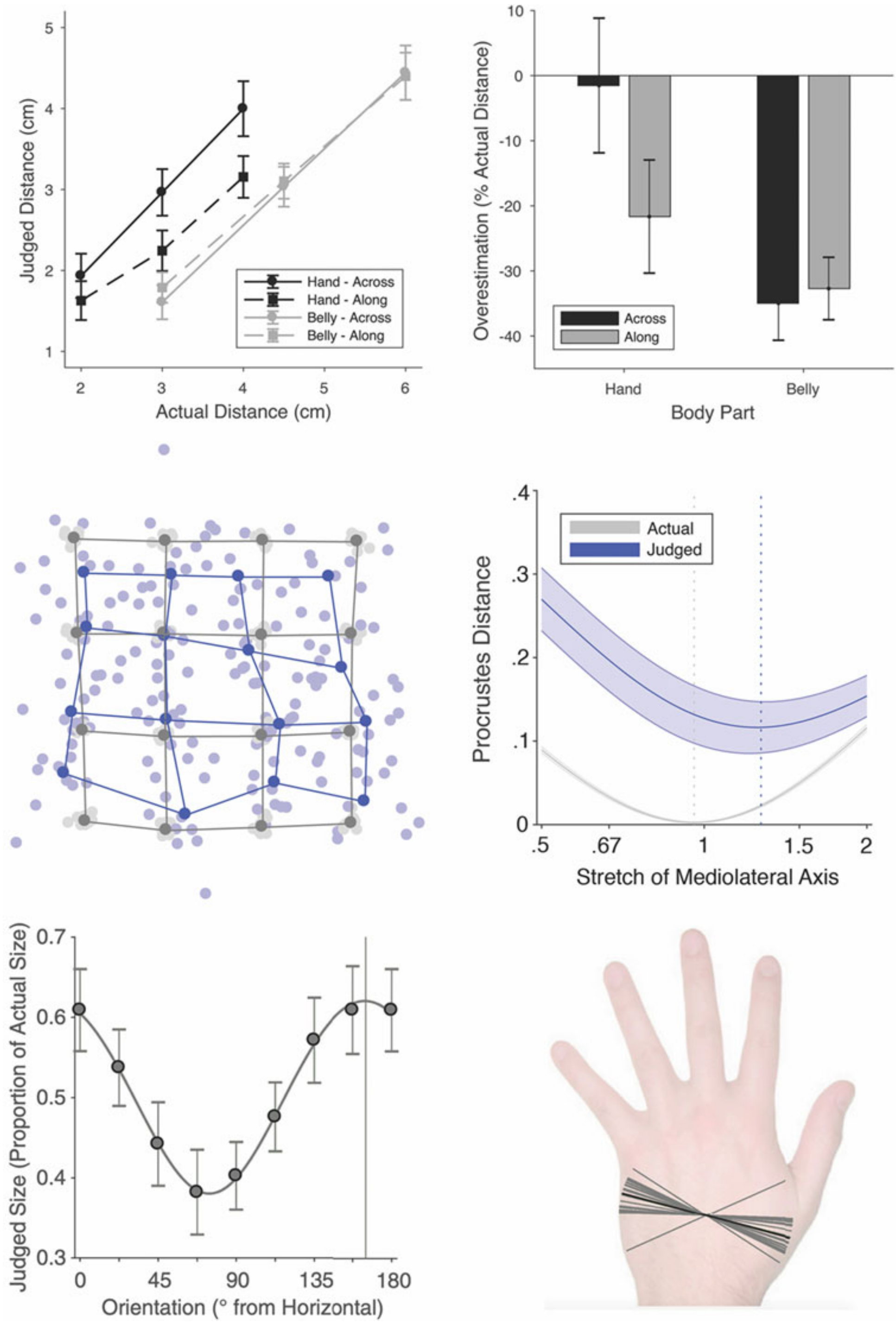

Fig. 1 Methods for analyzing results from size estimation procedures. Top row: Results ($N = 37$) showing tactile distance anisotropy on the hand and belly [11]. Results were analyzed using ANOVA assessing judged size as a function of actual size and orientation (top left), and assessing overestimation as a percentage of actual size (top right; error bars show SEM). Middle row: Use of multidimensional scaling (MDS) to reconstruct

3.2.3 Multidimensional Scaling

Two recent studies [7, 45] have used multidimensional scaling (MDS) to reconstruct perceptual maps of tactile space. MDS is a statistical procedure, akin to principal components analysis, positioning items in a multi-dimensional space based on a matrix of the pairwise distances or dissimilarities between items, such that the pairwise distances between points match the distance matrix as closely as possible [54, 55]. Applied to tactile distance perception, a fixed set of locations on the skin is stimulated and across trials tactile distance estimates are obtained from each pair of locations, producing a full perceptual distance matrix. MDS applied to this distance matrix produces coordinates in 2-D (or other dimensionality, if so desired) space. The middle panel of Fig. 1 shows results from the study of Longo and Golubova [7] which used MDS to reconstruct the tactile space of the hand dorsum (Fig. 1, middle left panel). Overall distortion in these maps was quantified by finding the deformation applied to an idealized square grid that minimized the dissimilarity (quantified as the Procrustes distance) with each perceptual map (Fig. 1, middle right panel). Tamè and colleagues [45] also applied the same logic to representational dissimilarity matrices measured using fMRI to compare perceptual and neural maps of tactile space.

3.2.4 Computational Models

Finally, a recent study by Fiori and Longo [37] presented stimuli at a range of orientations and used a simple computational model to quantify the magnitude and orientation of "stretch" of tactile space. The basic idea is that if anisotropy on a skin surface reflects a geometrically simple stretch of tactile space, perceived distance as a function orientation should show a sinusoidal function across a range of orientations (Fig. 1, bottom row). This approach uses least-squares regression to fit a three-parameter model to individual participant data, allowing the magnitude and orientation of stretch to be quantified. For example, the bottom right panel of Fig. 1 shows the orientation of maximal stretch for each of the 25 participants on the hand dorsum.

3.3 Forced-Choice Methods

Whereas the size estimation methods described so far involve making judgments about single stimuli, another set of methods ask participants to compare the relative size of two pairs of touches, presented either on two different skin surfaces or in two

Fig. 1 (continued) perceptual maps of the tactile space of the hand dorsum [7] (middle left; $N = 12$). Overall distortion in these maps was quantified by identifying the deformation of a square grid that minimized the dissimilarity (i.e., Procrustes distance; middle right; shaded area shows SEM). Bottom row: The model used by Fiori and Longo [37] to assess whether tactile distance illusions reflect a geometrically simple stretch of tactile space (bottom left; $N = 25$; error bars show SEM). This approach allows the orientation of maximal anisotropy to be estimated in a data-driven way for each participant (bottom right)

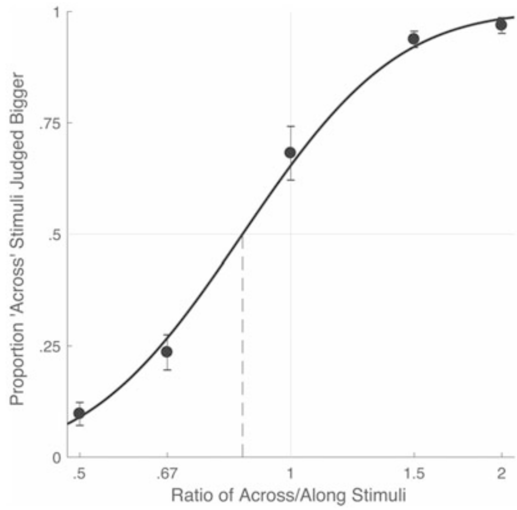

Fig. 2 An example of a psychometric function fit to 2IFC data ($N = 18$; error bars show SEM; dotted vertical line shows the point of subjective equality; from [50])

orientations on a single skin surface. In all cases, this has involved sequential, rather than simultaneous, presentation of the pairs of stimuli.

Some studies have simply quantified the percentage of trials on which one type of stimuli is judged as larger [3, 22]. Most studies, however, have adopted some form of the method of constant stimuli, using psychometric functions to quantify biases in the perceived tactile distance [6, 10, 21, 25, 28, 29, 38, 39, 47].

Figure 2 shows a typical example, taken from the "together" condition in Experiment 1 of [50]. On each trial, two tactile distances were applied sequentially, one oriented with the mediolateral ("across") hand axis the other with the proximo-distal ("along") axis, and the participant judges which one feels larger (i.e., by saying "first" or "second"). Across trials, five different pairs of distances were used, varying the relative size of the stimuli in the two orientations, according to the method of constant stimuli. The proportion of trials on which the across stimuli were judged as larger was calculated as a function of the ratio of the across and the along stimuli. The psychometric function was modeled using a cumulative Gaussian curve fit using maximum likelihood estimation using the Palamedes MATLAB toolbox [56]. The mean of this curve indicates the point of subjective equality (PSE), that is the ratio between the across and the along stimuli where the participant is equally likely to say that each orientation is bigger. The results shown in Fig. 2 indicate a typical anisotropy on the hand dorsum, as the PSE corresponds to a ratio between the across and the along stimuli less than 1, meaning that the along stimulus needs to be bigger than the across stimulus for them to be judged as being the same size.

4 Notes

4.1 The Two-point Discrimination Task

As noted above (*see* Subheading 3.2.2), one issue that frequently comes up in designing studies of tactile distance perception is the relation between the actual distances applied and the two-point discrimination threshold (2PDT) on that skin surface. While the 2PDT has been criticized as a measure of tactile acuity [57] (*see* Chapter 1, this volume), in this context what is relevant is whether or not the participant experiences one point or two. If the participant only feels a single point, it is not sensible to ask them to judge how far apart the stimuli felt. In many studies, participants are asked to assume that if they feel just one point to assume that it was a small distance [6], and in others to consider the spatial extent of that single point [5]. In some studies using verbal responses, they are explicitly told that they can give a response of "0 cm" [37]. This, however, does not necessarily solve the problem, and such trials (whether or not they are included in the analysis) can potentially distort the pattern of results.

To address this issue, researchers can consult studies that have measured 2PDT across the body [52, 53]. Ideally the smallest tactile distance applied should be larger than the average 2PDT on that skin surface, although since the numbers reported in those papers are averages, even this does not guarantee that participants will feel two touches on all trials. Another point is that while large-scale studies of 2PDT [52, 53] have assessed the perception of stimuli in a single orientation, it has been known since Weber's work that 2PDT varies with the orientation of stimuli [1]. Thus, stimuli which are felt as two distinct touches in one orientation will not necessarily be felt the same way in another orientation on that same surface. On some body parts, this can leave a relatively narrow range of usable stimuli that are both large enough to be felt as two points and small enough to actually fit on the skin for all participants. On the palm and dorsum of the hand and on the arms, for example, we have found that a range of 2–4 cm is appropriate, with stimuli less than 2 cm commonly felt as a single point and stimuli more than 4 cm not fitting on some participants' bodies.

4.2 Testing Different Parts of the Body

Another consequence of varying 2PDT across the body is that the stimuli appropriate for testing one body part may not be appropriate for other body parts. For example, as shown in the top left panel of Fig. 1, a recent study comparing anisotropy of tactile distance on the hand and belly [11] used different sets of stimuli on each body part for exactly this reason. While it would obviously be preferable to use identical stimuli on each skin surface, the combination of different sensitivity and different size of skin regions makes this impossible. Analogous problems arise in many types of psychophysical studies, for example comparing different parts of the retina in vision, or different frequencies in audition. One approach to dealing with this violation of a fully factorial experimental design is to re-express each judgment in terms of overestimation of actual distance as a percentage of actual distance, as shown in the top right panel of Fig. 1.

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