Article

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Stimulus intensity modulates perceived tactile distance

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Abstract

Several features of tactile stimuli modulate the perceived distance between touches. In particular, distances are perceived as farther apart when the time interval between them is longer, than when it is shorter. Such effects have been interpreted as a form of 'psychological relativity', analogous to Einstein's conception of a four-dimensional space–time. We investigated whether similar effects occur for stimulus features other than time, specifically stimulus intensity. We hypothesised that perceived distance would be increased when the two stimuli differed in intensity, since they would then be farther apart in a multi-dimensional feature space. Participants made verbal estimates of the perceived distance between two touches on their left hand. Intensity was manipulated such that both stimuli could be intense, both could be light, or one could be intense and the other light. We found no evidence for change in perceived tactile distance when stimuli intensity mis-matched. In contrast, there were clear effects of average stimulus intensity on perceived distance. Intense stimuli were judged as farther apart than light stimuli, and mixed stimuli were intermediate. These results are consistent with theories of general magnitude representation, which argue that multiple dimensions of magnitude are dependent on a shared underlying representation of domain-general magnitude.

Keywords

somatosensory, spatial cognition, body perception, haptics/touch

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Public Significance Statement

The ability to perceive how far apart two touches on the skin are is a basic perceptual ability. For more than a century, it has been known that the timing between touches can affect perceived distance. It is unknown whether this relation is specific to space and time, or whether differences in other stimulus features, such as intensity, also influence perceived distance. We show that the fact that two touches differ in intensity does not affect the perceived distance between them. However, the average intensity of the two stimuli does have an effect, with distances felt as farther apart for more intense stimuli.

In his classic studies, Weber (1834) discovered that as he moved the two points of a compass across his skin, the perceived distance between them was bigger when he touched a region of high tactile sensitivity compared to a region of lower sensitivity. Subsequent research showed a systematic relation between skin sensitivity and perceived tactile distance (Cholewiak, 1999; Miller et al., 2016; Taylor-Clarke et al., 2004). Similar illusions occur comparing stimuli in different orientations on individual skin surfaces (Green, 1982; Longo & Haggard, 2011; Tamè et al., 2021), with distances oriented across body width perceived larger than those along body length. This shows what is called an *anisotropy*, meaning that the stimulus is felt as bigger when in one orientation than another. Such anisotropies in tactile distance have striking correspondence to anisotropies in tactile acuity (Cody et al., 2008) and the geometry of tactile receptive fields of somatosensory neurons (Brooks et al., 1961). Similarly, adaptation aftereffects for tactile distance show sensitivity to several features linking them to relatively low-level features of the somatosensory system, such as orientation-specificity, region-specificity, and lack of transfer contralaterally or between the palm and dorsum (Calzolari et al., 2017). These links between perceived tactile distance and established features of primary somatosensory maps suggest that tactile distance perception arises from basic features of early somatosensory processing.

At the same time, other evidence has linked tactile distance perception to higher-level, and more cognitive aspects of body representation. For example, perceptual illusions which alter perceived body size have been found to produce corresponding changes in perceived tactile distance (Taylor-Clarke et al., 2004). Similarly, tool use also changes patterns of tactile distance perception on the hand and arm (Miller et al., 2014). Finally, tactile distance perception is altered in anorexia nervosa (Keizer et al., 2011), a condition strongly linked to altered body image (Keizer & Engel, 2022). One recent study showed that patients with anorexia show increases in judged tactile distance when a delay is introduced between the stimulus and response (Engel et al., 2022), suggesting that higher-level cognitive influences may shape responses. Thus, tactile distance perception is shaped both by bottom-up factors related to the basic organisation of the somatosensory system, and by higher-level cognitive factors relating to body image.

A further interesting connection between tactile distance perception and higher-level cognitive process comes from a recent study (Hidaka et al., 2020) which reported an anisotropy in tactile time perception analogous to the anisotropy in tactile distance perception found in many studies (Longo & Haggard, 2011). The perceived duration that elapsed between two taps on the hand dorsum was larger when the two touches were oriented with the medio-lateral hand axis than when aligned with the proximo-distal hand axis. Similarly, simultaneously presented pairs of touch are perceived as closer together than sequentially presented pairs (Cholewiak, 1999; Green, 1982; Sadibolova et al., 2018). Such findings fit with a larger literature showing numerous linkages between tactile information about space and time (Goldreich, 2007), including effects such as the cutaneous rabbit (Geldard & Sherrick, 1972) and tau/kappa effects (Helson, 1930; Suto, 1952).

One approach to effects of temporal information on tactile distance perception is to suppose that rather than reflecting only the distance between two judged locations on the skin, tactile distance perception involves calculating distance in some higher-dimensional feature space. For example, consider the finding of Sadibolova et al. (2018) that perceived tactile distance is bigger for sequential than for simultaneous pairs of touches (Figure 1A). Simultaneous touches differ only in spatial location. Sequential touches, in contrast, differ both in location *and* in time (or temporal 'location'). Perceived distance

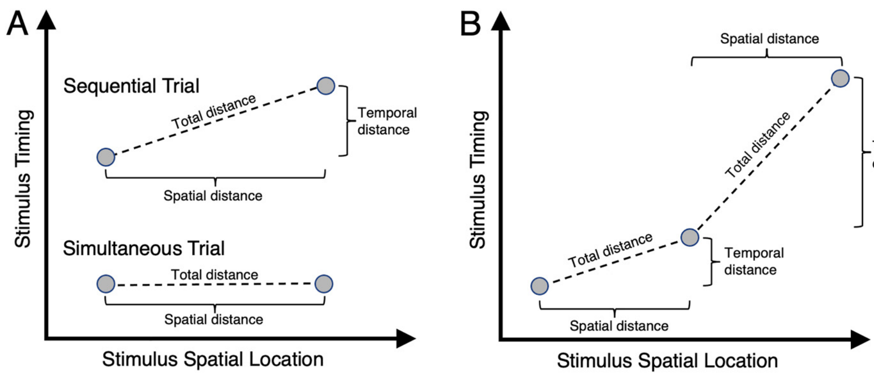

Figure 1. Helson's concept of 'psychological relativity', applied to two experimental paradigms. *Panel A*: In Sadibolova et al. (2018), the perceived distance between two touches was bigger for sequential than simultaneous touches. According to psychological relativity, this reflects the fact that sequential trials have an additional temporal component to the total distance. *Panel B*: In the tau effect (Helson, 1930; Helson & King, 1931) three touches are presented sequentially at equal spatial intervals, but unequal temporal intervals. The perceived distance between the two touches that are farther apart in time is perceived as larger. This can be explained as reflecting the fact that while the spatial distances are the same, the temporal distances differ, leading to differences in overall distance in psychological space–time.

might reflect both these components of 'distance' within a psychological space–time. Similarly, in the tau effect (Helson, 1930; Helson & King, 1931), when three evenly spaced touches are applied across the skin with the duration between the first and second less than that between the second and third, the perceived distance between the final two touches is bigger than between the first two touches (Figure 1B). While the difference in spatial location between the pairs of touches is equal, the temporal difference is bigger for the latter pair. Helson called this *psychological relativity*, drawing an explicit link between perceived distance in an integrated psychological representation of space and time with Einstein's (1920) physical conception of four-dimensional space–time (Figure 1).

Helson's ideas about the effects on tactile distance of space and time are related to more general ideas about the role of distances in 'psychological space' in determining perceived similarity and generalisation across concepts (Shepard, 1987). The distance between touches may be larger when stimuli differ in *any* stimulus dimension in addition to location. For example, touches that differ in texture or intensity may feel farther apart than touches identical except for location.

The present experiment investigated this possibility. Participants judged the distance between two touches on their hand. On some trials the touches were low intensity (*light* stimuli), on other trials high intensity (*intense* stimuli), and finally on some trials one stimulus was weak and one intense (*mixed* stimuli). If perceived tactile distance is based on distance in a multi-dimensional stimulus space, perceived distance should increase on mixed trials, since the two stimuli differ in a dimension in addition to location. In contrast, on a general magnitude interpretation, perceived tactile distance should scale with stimulus intensity, and thus be larger for intense than for light trials, and intermediate for mixed trials.

Method

Participants

Twelve volunteers (11 women; *M*: 30.6 years) participated. All were right-handed by the Edinburgh Inventory (*M*: 81.6, range: 15.8–100). Participants gave written informed consent. Procedures were approved by the Department of Psychological Sciences ethics committee at Birkbeck.

In Sadibolova et al. (2018), the comparison of sequential versus simultaneous touches shows a large effect size (Cohen's $d_z = 1.509$, calculated by converting the reported F-statistic to a t-statistic). A power analysis using G*Power 3.1 using alpha of 0.05, and power of 0.95 showed that eight participants are needed. Our sample size is 50% larger than this, and thus is well-powered to detect a comparable effect of stimulus intensity.

Procedures

The stimuli were von Frey hairs (2 and 180 g), similar to those we used previously (Longo & Golubova, 2017). von Frey hairs allow control of the pressure applied by each stimulus. Stimuli were applied manually to the left hand dorsum for approximately 1 s.

On each trial, two locations were stimulated sequentially (~1 s inter-stimulus interval). Ten locations were marked in a line across the medio-lateral hand axis, separated by 5 mm (numbered 1–10 from left to right). Across trials, there were five distances between touches: 2 cm (locations 1–5, 3–7, 4–8, 6–10), 2.5 cm (locations 1–6, 2–7, 4–9, 5–10), 3 cm (locations 1–7, 2–8, 3–9, 4–10), 3.5 cm (locations 1–8, 2–9, 3–10), and 4 cm (locations 1–9, 2–10). For each pair, the order of stimulation was counterbalanced across trials. Participants were blindfolded and not permitted to see the marked locations. They were also not told which specific distances would be applied or even how many there would be.

Participants verbally estimated the distance between each pair of touches (in cm). Responses were unspeeded, but participants were instructed to respond as precisely as possible. If participants felt only one touch, they were asked to respond with 0 cm, which occurred on a total of 14 trials (0.005%). These trials were included in analyses.

There were three experimental conditions. In *light* trials, the weak stimulus was used for both locations. In *intense* trials, the strong stimulus was used for both locations. Finally, in *mixed* trials, one of each intensity was used. For mixed trials, the order of the weak and intense stimulus was counterbalanced across trials.

Within each condition, there were 80 trials, 16 of each of the 5 distances. The 240 trials were presented in random order. There were 4 blocks, separated by a short break.

Raw data are available as Supplemental materials.

Analysis

We conducted three analyses on the data. The first used a repeated-measures analysis of variance (ANOVA) to investigate the effects of actual distance (2, 2.5, 3, 3.5 and 4 cm) and intensity (light, mixed and intense) on judged distance. Where Mauchley's test indicated violation of the sphericity assumption, the Greenhouse-Geisser correction was applied.

The second analysis re-expressed judged distance relative to actual distance to quantify overestimation as a percentage of actual distance. This allowed us to collapse across the five actual distances. We then conducted a one-way repeated measures ANOVA comparing the three intensities. The three intensities were compared to each other using post-hoc paired *t*-tests using Holm-Bonferroni correction for multiple comparison.

Finally, we investigated the effects of intensity on a trial-by-trial basis using linear mixed-effects models. For each trial, we coded whether the two stimuli matched or mismatched in intensity as a dichotomous variable. We also coded the average stimulus intensity (in milliNewtons). Mixed-effects models were calculated using the lme4 R toolbox (Bates et al., 2015). Judged size was modelled using actual distance and average intensity as random effect and mismatch as a fixed effect, including by-participant random intercepts and slopes for actual distance and average intensity. Significance was assessed using model comparison.

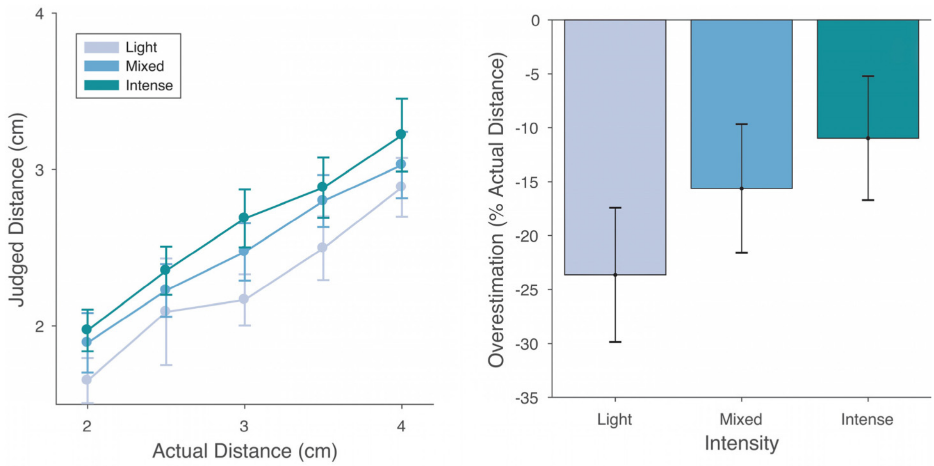

Figure 2. *Left panel*: Judged distance as a function of actual distance. Judged distance increased monotonically with actual distance, but was influenced by stimulus intensity. *Right panel*: Data re-expressed as overestimation of actual distance and averaged across stimulus size. Intense stimuli were judged as farther apart than light stimuli. Mixed stimuli were intermediate between the two. Error bars are one standard error.

Results

The left panel of Figure 2 shows mean judgments of distance as a function of actual distance. There was a main effect of actual distance, $F(4, 44) = 40.45$, $p < .0001$, $\eta_p^2 = .786$, with judgments increasing monotonically with actual distance. There was also a significant main effect of intensity, $F(2, 22) = 20.70$, $p < .0001$, $\eta_p^2 = .653$, with a large effect size. There was no significant interaction, $F(2.22, 24.42) = 0.37$, $p = .718$, $\eta_p^2 = .032$.

To assess the relation between actual and judged size, we expressed each response as an overestimation as a percentage of actual stimulus distance. This allowed us to collapse across actual distance, greatly simplifying the results (Figure 2, right panel). Across conditions, there was a tendency to underestimate stimulus size (16.74% underestimation), $t(11) = -2.87$, $p = .0152$, $d = 0.827$. To compare the different intensities, we conducted a one-way ANOVA, which revealed a main effect of intensity, $F(2, 22) = 17.13$, $p < .0001$, $\eta_p^2 = .609$, with a large effect size. Judgments in the mixed condition were intermediate between the other two conditions. Post-hoc comparisons with Holm-Bonferroni correction for multiple comparisons revealed that perceived distance was larger in the intense condition than in the light, $t(11) = 5.12$, $p < .001$, $d_z = 1.479$, or mixed, $t(11) = 2.27$, $p = .0443$, $d_z = 0.656$, condition, and larger in the mixed than the light condition, $t(11) = 3.98$, $p = .002$, $d_z = 1.148$.

Finally, we investigated the effects of stimulus mismatch and average intensity using linear mixed-effects models. There were clear effects of actual stimulus size, $\chi^2(1) = 24.34$, $p < .0001$, and average intensity, $\chi^2(1) = 16.28$, $p < .0001$. In contrast, however, there was no effect at all of mismatch, $\chi^2(1) = 0.68$, $p = .411$.

Discussion

We investigated the effect of stimulus intensity on tactile distance perception. Two touches were judged as farther apart when they were both intense compared to when they were both light. Mixed pairs, with one intense and one light stimulus, were intermediate. These results suggest that perceived tactile distance scales with the average intensity of two stimuli. In contrast, perceived tactile distance was not affected by the mismatch in intensity between the two stimuli.

These results are inconsistent with the idea that perceived tactile distance reflects distance in a higher-dimensional feature space, incorporating not only spatial information but other stimulus features. This idea is related to Helson's (1930; Helson & King, 1931) hypothesis of 'psychological relativity', in which perception is related to distance in an integrated representation of space–time. Though Helson framed this idea specifically in the context of space and time, we hypothesised that analogous logic would apply to other features of stimuli, specifically to stimulus intensity. This linkage would have been consistent with wider ideas on the link between psychological 'distance' and similarity in multi-featural mental spaces (Shepard, 1987). This hypothesis, however, was not supported by the data. Whether or not two touches differed in intensity had no effect on the perceived distance between them.

Our results have similarities with those of Flach and Haggard (2006), who compared 'spatial' and 'spatio-temporal' models of timing effects on tactile localisation in the cutaneous rabbit illusion. In this illusion, a series of rapid touches first at one skin location and then at a second location is experienced as a sequence of taps 'hopping' between the two locations. Flach and Haggard argued that timing effects result from decay within a unimodal tactile map, and not from an integrated representation of space and time. They suggest that timing effects on perceived tactile distance in the tau effect may result from distortion of an initially purely tactile spatial representation of distance by later processing stages. Our results are consistent with a similar model of the effects of intensity. Differences in intensity between two stimuli do not appear to be interpreted as an additional component of 'distance' between them. Rather, judgments reflect a combination of the actual spatial relation between the stimuli, which presumably reflects readout from early tactile maps such as in primary somatosensory cortex, and the average intensity of stimuli, which may reflect distortion from later processing stages, as suggested by Flach and Haggard in the cutaneous rabbit.

The effect of stimulus intensity on perceived tactile distance fits with a larger literature showing that task-irrelevant features of magnitude that can be interpreted as 'more than' and 'less than' affect perception of other magnitudes (Lourenco & Longo, 2011; Walsh, 2003). For example, there is clear evidence for cross-dimensional interactions between magnitude dimensions such as size and numerosity (Tzelgov et al., 1992), size and duration (Cohen et al., 1954; Xuan et al., 2007), duration and numerosity (Dormal et al., 2006), and number and luminosity (Cohen Kadosh et al., 2008). The present finding that the distance between touches is felt as larger for more intense stimuli fits with these other studies.

Our results add to a growing list of variables that alter perceived tactile distance. These include body part (Weber, 1834), with distances felt as larger on sensitive than on less sensitive skin surfaces; orientation (Fiori & Longo, 2018; Longo & Haggard, 2011), with distances across body width felt as larger than those along body length or height; the timing between touches (Helson & King, 1931); vision of the body (Longo & Sadibolova, 2013); the presence of joints (de Vignemont et al., 2008; Le Cornu Knight et al., 2014, 2020), tool use (Canzoneri et al., 2013; Miller et al., 2014); and illusions of body size (Taylor-Clarke et al., 2004). Our results show that average stimulus intensity also influences perceived tactile distance.

Author contribution(s)

Matthew R. Longo: Conceptualization; Formal analysis; Formal analysis; Methodology; Supervision; Visualization; Writing – original draft.
Sonia Medina: Conceptualization; Investigation; Writing – review & editing.

Declaration of Conflicting Interests

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Supplemental Material

Supplemental material for this article is available online.

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