
SHORT REPORT

Proximal-distal, not medial-lateral, movement across an edge increases discrimination of edge sharpness

Christopher Kent¹, Andy L Skinner², Carys Weeds¹, Christopher P Benton¹

¹Bristol Tactile Action and Perception Lab, School of Experimental Psychology, University of Bristol, 12A Priory Road, Bristol BS8 1TU, UK; ²MRC Integrative Epidemiology Unit, University of Bristol; e-mail: c.kent@bristol.ac.uk

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Abstract. Edges are fundamental properties of our environment and the objects we interact with. There is a lack of research on the haptic perception of edges, especially the sharpness of an edge. Skinner et al. [2013 *PLoS ONE*, **8**(9): e73283] found that haptic discriminability of sharpness was clearly superior when using a relatively unrestrained, free exploration strategy compared with a static single touch strategy. In the free exploration condition two distinct movement patterns were frequently used by participants: a proximal-distal movement of the fingerpad across the test edge and a medial-lateral movement of the fingerpad along the test edge. Here, using the same stimuli and two-alternative forced-choice method of constant stimuli as Skinner et al. (2013), we demonstrate that a proximal-distal movement results in substantially lower sharpness discrimination thresholds than a medial-lateral movement. The underlying neurophysiology and implications for the design of haptic displays are considered.

Keywords: haptic, discrimination, edges, sharpness, perception, tactile

1 Introduction

Despite the importance of edge perception to haptic object recognition, there is little direct research on how humans are able to discriminate the different features of an edge (eg Park, Doxon, Provancher, Johnson, & Tan, 2012). In particular, the sharpness of an edge, defined as the angle at which two faces meet, as distinct from the curvature of an object (see Kappers, 2011, for a review of curvature), has been underexplored. In one study directly investigating edge sharpness, Skinner et al. (2013) showed that perception of edge sharpness was affected by exploration strategy. Specifically, Skinner et al. found that the discrimination threshold for the sharpness of an edge (using only the index finger) decreased when participants were allowed to explore the edge using a relatively free exploration strategy with the index finger compared with when participants were allowed only a single static touch of the edge. This finding is consistent with previous studies demonstrating improved discriminability for more active exploration strategies of angle (eg Gibson, 1962; Levy, Bourgeon, & Chapman, 2007; Wijntjes & Kappers, 2007; note that active exploration does not always lead to improved performance—for example, movement benefits discriminability for fine textured surfaces, but not coarse textured surfaces; Hollins & Bensmaïa, 2007). The authors offered several explanations for the improved discriminability under the free exploration condition based on the experimenter's observations. There were two prominent movement patterns employed in the free exploration strategy which may have led to improved discriminability: firstly, a proximal-distal movement of the glabrous skin of the fingertip (fingerpad) across the edge in a slow fore and aft movement (see figure 1a); and, secondly, a medial-lateral movement of the fingerpad along the edge (see figure 1b). The experiment reported here was designed to test whether one strategy leads to better discriminability than the other.

Although a complete review of the broad literature on the neural coding of haptic and tactile perception is beyond the scope of this paper (see eg Goodwin & Wheat, 2004,

2008, and Johansson & Flanagan, 2009, for reviews), it is useful to consider the types of mechanoreceptors that the movement patterns might be maximally activating to provide insight into the possible reasons to expect differences in discriminability between movement patterns. There are four types of low-threshold cutaneous mechanoreceptors in the human fingerpad characterized principally by the rate at which they adapt to stimulation: slowly adapting type 1 (SA1) that end in Merkel cells (sensitive to static shapes, edges, and rough textures); slowly adapting type 2 (SA2) that end in Ruffini corpuscles (sensitive to skin stretch); fast-adapting type 1 (FA1) that end in Meissner cells (sensitive to coarse texture, ie low-frequency changes in surface height, light touch, and low-frequency vibration); and fast-adapting type 2 (FA2) that end in Pacinian corpuscles (sensitive to fine texture, ie high-frequency changes in surface height).

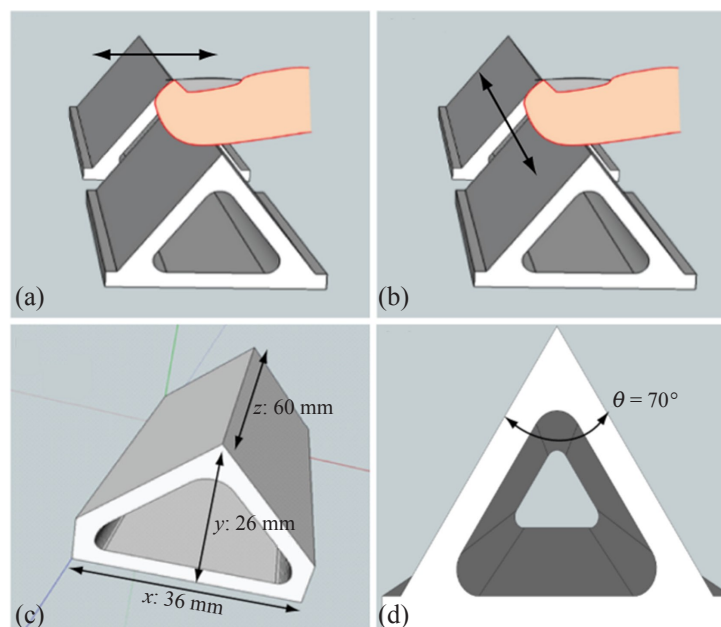


Figure 1. [In colour online, see <http://dx.doi.org/10.1068/p7713>] Test stimuli showing (a) proximal-distal exploration, (b) medial-lateral exploration, (c) dimensions and fabrication axes, and (d) definition of sharpness as angle between two surfaces.

If we consider the various mechanoreceptors responding to cutaneous stimulation, the response characteristics of SA1 would appear to make them ideal for discrimination of edge sharpness (eg Goodwin & Wheat, 2004). These cells respond to sustained skin deformation from points, edges, and curvature, and respond linearly to the depth of indentation (eg Phillips & Johnson, 1981); SA2 receptors are much more sensitive to stretch than indentation, so likely play a lesser role. However, our previous study (Skinner et al., 2013) demonstrated that discrimination relying on a static touch—a strategy for exploration that, because of its relatively slow and sustained nature, is likely to activate predominately SA1 receptors—resulted in poorer discrimination of edge sharpness than more active strategies, which are likely to additionally recruit more rapidly adapting receptors. It therefore seems likely that perception of edge sharpness additionally benefits from input from rapidly adapting mechanoreceptors that respond to dynamic touch (and are insensitive to static touch).

In line with the role of FA receptors aiding, at least partly, in edge sharpness perception (see also LaMotte & Srinivasan, 1987, for evidence of the role of FA receptors in discrimination of step-shapes of various curvatures), Skinner et al. (2013) suggested that the active exploration across an edge may result in similar sensations as texture perception. An important finding

from the literature on texture perception is that two coding mechanisms appear to mediate texture perception: for coarse textures ($>200\text{ }\mu\text{m}$ spatial period) a spatial code, mediated by SA1 receptors, appears to dominate, while for fine textures ($<200\text{ }\mu\text{m}$ spatial period) vibration (induced through movement) appears to dominate, mediated by FA2 (see Hollins & Bensmaïa, 2007, for a review). A single edge does not create a texture, but moving the dermal ridges (fingerprints, thought to magnify subsurface strain, eg Cauna, 1954; see also Scheibert, Leurent, Prevost, & Debrégeas, 2009) across the edge will create a vibration. In the proximal-distal movement the slow movement of the anterior dermal ridges of the fingerpad (ie those parallel to the test edge) across the edge leads to a low-frequency vibration. This might be analogous to the stimulation from a rough texture, and so may predominantly activate FA1 receptors (and possibly to a lesser degree FA2) and SA1 receptors. Subjectively, the sensation generated as the epidermal ridges move across the edge is similar to that experienced from vibrotactile stimulation. On the other hand, in the medial-lateral movement the fingerpad moving does not create a large height profile change, instead giving a sensation similar to a very fine texture (the manufacturing of the edges ensures a smooth top edge), resulting in considerably less activation of FA1 cells. It is therefore possible that both SA1 and FA cells contribute to the dynamic discrimination of edge sharpness in the proximal-distal movement, but only SA1 in the medial-lateral movement, suggesting discriminability could be higher using the proximal-distal movement pattern with the added information from FA receptors.

The simple aim of the study reported here was to test which of the two movement patterns, proximal-distal or medial-lateral, is most informative in aiding participants to discriminate edge sharpness. Participants completed a two-alternative forced-choice (2AFC) task combined with the method of constant stimuli, identical to the task used by Skinner et al. (2013) except that exploration movement direction was manipulated such that participants explored using either a proximal-distal or medial-lateral movement. In each condition the just-noticeable difference (JND) was determined, and these JNDs were used to compare discrimination performance for the two movements.

2 Results

Figure 2 (left panel) shows the mean proportion correct for each difference in sharpness for the proximal-distal and medial-lateral movement conditions. There is a reliable and large difference between the two movement patterns. The apparent asymptote in figure 2 for the medial-lateral condition around 15° is likely an artefact of averaging (see figure A1 in the appendix for individual participants' data) as supported by the results of the model fitting below.

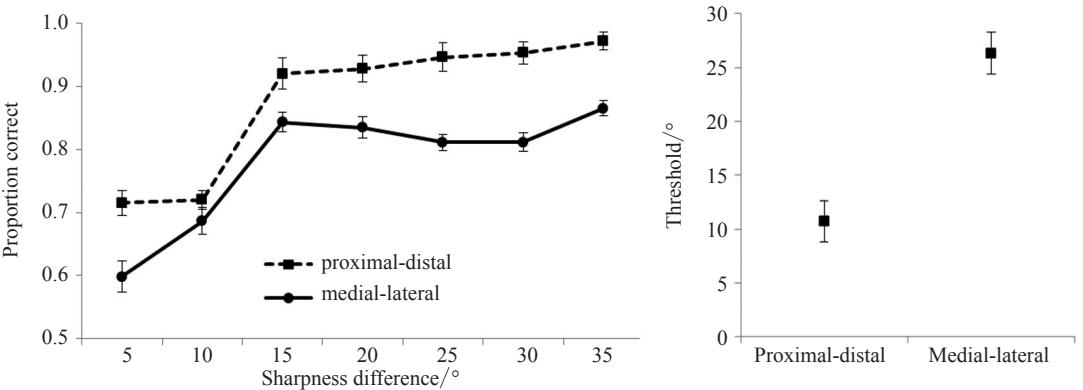


Figure 2. Left panel: mean proportion correct for each sharpness difference as a function of movement condition. Right panel: mean estimated thresholds from the best-fitting Weibull function. Error bars represent the standard error. The same fifteen participants completed both conditions.

Following Skinner et al. (2013), we fitted a series of logistic and cumulative Weibull functions to our data; the purpose of this exercise was to determine the best model to fit those data and to determine the JND. This process is described in more detail by Skinner et al. (2013); but briefly, the logistic function models the relation between proportion correct (P_{correct}) and sharpness difference ($\Delta\theta$) as

$$P_{\text{correct}} = \{(1 - \omega)[1 + \exp(-\Delta\theta/\lambda)]^{-1/2}\} + 0.5,$$

where ω is a lapse-rate parameter that allows for asymptotic performance below perfect accuracy. Similarly, the Weibull function describes the relationship between proportion correct and sharpness difference as:

$$P_{\text{correct}} = \left[(1 - \omega) \frac{f(\Delta\theta, \lambda, k)}{2} \right] + 0.5,$$

where $f(\Delta\theta, \lambda, k)$ is the cumulative Weibull at sharpness difference $\Delta\theta$. Note that both functions have been scaled to produce values of P_{correct} that can range between 0.5 and 1. For both functions we term ' λ ' the location parameter; the effect of an increase in λ is to stretch the functions along the abscissa. In comparison with the logistic, the Weibull has an additional shape parameter which changes the form of the function and allows it to describe a greater range of relationships between proportion correct and sharpness difference. Our choice of the Weibull was motivated by the knowledge that it is widely used in visual psychophysics to model 2AFC data (eg May & Solomon, 2013; Nachmias, 1981; Watson, 1979; Watson & Pelli, 1983) and by the fact that, in our previous work (Skinner et al, 2013), it provided a demonstrably better description of the data than the more commonly used logistic.

In order to determine the best model for our data, we carried out a hierarchical model selection procedure. All models could have parameters that are free to vary between subjects/conditions or are constrained to be the same across all subjects. We also tested models that incorporated or did not incorporate the lapse-rate parameter. For model selection we used the Akaike Information Criterion (AIC). This is a metric that balances goodness of fit with model complexity. The important comparison is the AIC differences (ΔAIC ; see table A1 in the appendix for all models fitted). The model with the lowest ΔAIC is the most preferred model, with the ΔAIC s giving a metric of preference between that and the other models. By far the most preferred model (the nearest competitor $\Delta\text{AIC} = 30$, Burnham & Anderson, 2002, page 170) is the Weibull function, with a location parameter that varies between subjects, a shape parameter that is fixed across subjects, and no lapse rate parameter.

In the following we therefore report the results of that model. The value of the shared shape parameter was 0.875; thresholds were calculated at the 81.6% accuracy level. This is a common choice of threshold accuracy level in visual psychophysics where 2AFC data have been fitted with the scaled cumulative Weibull. The reason for choosing this particular accuracy level is because this is the point at which a family of scaled cumulative Weibulls with the same location, but different shapes, would cross. Figure 2 (right panel) shows the mean difference in thresholds between the proximal-distal and medial-lateral movement conditions. A paired-sample t -test confirmed there was a reliable difference in the individual threshold estimates between the movement patterns ($t_{14} = 4.01$, $p = 0.001$, $\text{SEM} = 3.88$, $d = 1.03$), with thresholds lower when using the proximal-distal movement (average 10.72°) compared with the medial-lateral movement (average 26.30°). The proximal-distal movement pattern resulted in higher levels of discriminability for all but one of the fifteen participants compared with the medial-lateral movement pattern (the difference ranged between 1.66° and 50.93° , and was -3.12° for the single participant showing the opposite effect).

3 Discussion

Our results demonstrate an unambiguous and large advantage when using the proximal-distal movement pattern than when using the medial-lateral movement pattern. Why does the proximal-distal movement lead to such an improvement in discriminability?

Most suprathreshold stimuli presented to the fingertip typically activate multiple different types of mechanoreceptors. It is therefore difficult to uniquely identify one particular channel responsible for the gain in discrimination without neurophysiological studies. Nonetheless, as outlined in the introduction, the findings from texture perception suggest it is likely that the proximal-distal movement maximally activated SA1 cells, but importantly also FA1 and FA2 cells, whereas the medial-lateral movement likely activated these afferents to a much lesser extent. It is therefore possible that discrimination of sharpness is improved in the proximal-distal condition because participants are able to infer the sharpness of an edge from the pattern of vibrations caused by the dermal ridges of the fingerpad and detected by the FA receptors. It is also possible that the proximal-distal movement pattern more effectively activated the SA1 receptors compared with the medial-lateral movement pattern due to the prominence of the edge moving over the skin (we thank an anonymous reviewer for suggesting this possibility). Future studies (including neurophysiological studies) will need to explicitly test this hypothesis in order to fully explore the neural mechanisms underlying the proximal-distal advantage.

Studies should also investigate more closely other forms of information guiding discriminability, including the use of proprioceptive information and the direction of movement. Although we instructed participants to move their fingerpad over or along the edge only (and specifically to not explore the sides of the shapes), thus minimizing any proprioceptive information that might help discriminate the sharpness of the edge, the proprioceptive feedback was nonetheless quite different in the two movement patterns. Future studies will need to stabilize the finger and move the stimulus across the fingerpad (similar studies have been conducted looking at discrimination of movement direction; see Essick, 1998, for a review, but not for sharpness). Likewise, the movement of the finger itself (to or from the body versus across the body) is confounded with whether the fingerpad moves across or along the stimulus edge. Rotating the stimuli 90° should provide the opposite pattern of results. However, the problem arises that the fingerpad is relatively narrow, and this results in very little contact between the fingerpad and the stimulus. Controlling the amount of skin contacted by the edge will be an important manipulation for future work to consider.

The task used here and in our previous study (Skinner et al., 2013) explored discrimination of changes to the ‘apex’ of an edge, and deliberately minimized information from the two sides whose juncture formed that edge. We reasoned that, as is the case in 2-D angle perception (eg Wijntjes & Kappers, 2007), these two sources of information may contribute in different ways to the perception of the angle at which two planes meet. However, while it is appropriate to study these two factors in isolation, in reality we rarely feel the edge of an object without sensing some information from the surfaces too, so future work will need to consider how these two sources of information are integrated to provide real-world judgments of edge sharpness.

Given the large disparity in discriminability between the two movement patterns, it is perhaps surprising that participants in Skinner et al. (2013) persisted with using the medial-lateral movement throughout the experiment. Indeed, comparing the thresholds from the current study with those estimated by Skinner et al., in which the free exploration condition resulted in a mean threshold of 5.0° and the static condition resulted in thresholds of 11.1° and 8.6° (for experiments 1 and 2, respectively), shows that adopting the medial-lateral movement pattern (mean threshold of 26.30°) is a very poor strategy, worse even than a single static touch. The proximal-distal movement pattern (mean threshold of 10.72°) is more in line

with the single static touch, but the free exploration strategy results in a threshold that is half that of the proximal-distal movement pattern, clearly suggesting that more information can be gained from incorporating information from other movements (perhaps including static, medial-lateral, and even noncardinal movements) and/or repeated sampling of the stimuli (in the free exploration condition of Skinner et al. participants could touch the stimulus multiple times and switch between exploring each stimulus).

The frequent use of the medial-lateral movement pattern, despite the lack of discriminating information it provides, highlights an important point: participants may be unaware of the optimal strategy to use to extract information. The findings from this study, and others on haptic exploration patterns, may have implications for the design of haptic displays and tactile aids. There is a growing awareness in the literature about the need to better understand how exploratory procedures affect task performance (eg Cooke, Wallraven, & Bülthoff, 2010). The design of tactile aids and haptic interfaces—for example, in augmented reality or for assistive technologies for the visually impaired—utilize sensitive touch. For example, some current forms of assistive technology (eg raised-edge drawings) require the user to trace along edges. Devices currently in development (eg Kim, Israr, & Poupyrev, 2013; Sodhi, Poupyrev, Glisson, & Israr, 2013) are more dynamic and versatile than current displays, and so should enable appropriate exploration strategies. For example, if the orientation of an edge is fixed parallel in front of the participant, adopting a strategy in which exploration is proximal-distal to the edge might allow the best discrimination of edge sharpness. Future work will clearly need to investigate the generality of the proximal-distal benefit for edges aligned at different orientations to the body. The rapidly growing use of haptic displays highlights the fact that it is ever more important to understand the limits of the human haptic system when designing interfaces, making the collaboration between engineers and psychologists critical to successful uptake of new technologies utilizing haptic interfaces. Failure to understand the users' intentions and limitations will lead to poor user experience and discontinued use of the device (eg Manduchi & Coughlan, 2012). Likewise, remote sensing devices can benefit from understanding how the human finger perceives basic properties of shapes. Indeed, inspired by the properties of the dermal papillae (the internal projections of the dermal ridges into the epidermis), researchers have already designed haptic sensors which mimic the role that the dermal papillae play in transmitting mechanical deformations to the SA1 and FA1 cells (eg Chorley, Melhuish, Pipe, & Rossiter, 2010; see also Kuroki, Kajimoto, Nii, Kawakami, & Tachi, 2008). Using simple stretch detection algorithms one such device, TACTIP, can successfully detect edges with a good degree of sensitivity (Chorley et al., 2010).

In summary, we explored whether proximal-distal or medial-lateral movement patterns resulted in greater performance in discrimination of edge sharpness, and found that proximal-distal provided a clear advantage. One explanation for this is that the proximal-distal movement benefits from the additional greater activation of FA mechanoreceptors, and that perception of edge sharpness may share some mechanisms with perception of texture.

4 Method

4.1 *Ethics statement*

This study complied with the regulations of both the University of Bristol's Faculty of Science Ethics Committee and the World Medical Association Helsinki Declaration. All participants provided written consent, and were healthy volunteers with no known problems with their tactile perception.

4.2 *Participants*

Fifteen University of Bristol undergraduates (mean age: 23 years, twelve female, two left-handed) participated in return for £10.

4.3 Materials

Eight hollow, rectangular-based prisms (base dimensions: 60×36 mm, height: 26 mm; see figure 1c) were made from a RCP30 nano-cured ceramic photo polymer on an envisionTEC Perfactory 3 printer. The printer had a $30 \mu\text{m}$ XY resolution and $15 \mu\text{m}$ Z resolution. To maximize the smoothness of the test edge, the Z plane was used for the prisms' apex. The set of stimuli varied in sharpness, with sharpness defined as the internal angle of the apex (see figure 1d). The reference sharpness was 70° , with comparison sharpness ranging from 65° to 35° in steps of 5° . Each prism had a magnetic strip applied to the bottom, enabling them to be fixed to a tabletop wooden frame. The frame ensured that the stimuli did not move when touched and were consistently located in front of the participant. The stimuli were oriented such that their longest side faced the participant. A raised marker was placed midway between and in front of the two shapes for the participant's thumb to rest on, controlling their orientation and distance from the stimuli.

4.4 Design and procedure

Our 2AFC task used the method of constant stimuli. The reference stimulus was paired with each comparison stimulus 40 times over two sessions. The left–right positioning of the stimuli was counterbalanced. The sessions comprised four blocks of 70 trials, lasting approximately one hour in total. Movement pattern alternated over blocks, and was counterbalanced such that eight participants started with the proximal-distal movement in the first session and medial-lateral movement in the second session and the remaining participants vice versa. Stimulus pairs were randomized across the blocks, such that every pairing occurred equally often in each block.

Participants used the fingertip of their index finger on their dominant hand to explore the stimulus edge. In the proximal-distal movement participants moved their fingertip in a fore–aft movement over the stimulus edge. In the medial-lateral movement participants moved their fingertip in a side-to-side movement along the stimulus edge. On each trial participants were allowed one untimed exploration per stimulus. Participants explored the left stimulus first, then the right stimulus, using the current exploration strategy. Participants reported which stimulus they judged to be sharper. Each trial was separated by an audio tone, which signaled when participants could begin exploration. After each block participants were allowed a short break. The participants were blindfolded throughout the experiment.

References

- Burnham, K. P., & Anderson, D. R. (2002). *Model selection and multimodel inference: A practical information-theoretic approach* (2nd ed.). New York: Springer-Verlag.
- Cauna, N. (1954). Nature and functions of the papillary ridges of the digital skin. *The Anatomical Record*, **119**, 449–468.
- Chorley, C., Melhuish, C., Pipe, T., & Rossiter, J. (2010). Tactile edge detection. *Proceedings of IEEE Sensors 2010* (pp. 2593–2598). Piscataway, NJ: IEEE Publications. <http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5678851>
- Cooke, T., Wallraven, C., & Bülthoff, H. H. (2010). Multidimensional scaling of haptic exploratory procedures. *ACM Transactions on Applied Perception*, **7**(1):7. doi:10.1145/1658349.1658356
- Essick, G. K. (1998). Factors affecting direction discrimination of moving tactile stimuli. *Advances in Psychology*, **127**, 1–54.
- Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, **69**, 477–491.
- Goodwin, A. W., & Wheat, H. E. (2004). Sensory signals in neural populations underlying tactile perception and manipulation. *Annual Review of Neuroscience*, **27**, 53–77.
- Goodwin, A. W., & Wheat, H. E. (2008). Physiological responses of sensory afferents in glabrous and hairy skin of humans and monkeys. In J. H. Kaas, E. P. Gardner (Eds.), *The senses: A comprehensive reference. Somatosensation* (Vol. 6, pp. 39–54). Amsterdam: Elsevier.

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- Hollins, M., & Bensmaïa, S. J. (2007). The coding of roughness. *Canadian Journal of Experimental Psychology*, **61**, 184–495.
- Johansson, R. S., & Flanagan, J. R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience*, **10**, 345–359.
- Kappers, A. M. L. (2011). Human perception of shape from touch. *Philosophical Transactions of the Royal Society of London B: Biological Science*, **366**, 3106–3114.
- Kim, S., Israr, A., & Poupyrev, I. (2013). Tactile rendering of 3D features on touch surfaces. *Proceedings of UIST'13* (pp. 531–538). New York: ACM. doi:10.1145/2501988.2502020
- Kuroki, S., Kajimoto, H., Nii, H., Kawakami, N., & Tachi, S. (2008). Proposal of the stretch detection hypothesis of the Meissner Corpuscle. In M. Ferre (Ed.), *EuroHaptics 2008, LNCS 5024* (pp. 245–254). Berlin: Springer-Verlag.
- LaMotte, R. H., & Srinivasan, M. A. (1987). Tactile discrimination of shape: Responses of slowly adapting mechanoreceptor afferents to a step stroked across the monkey fingerpad. *The Journal of Neuroscience*, **7**, 1655–1671.
- Levy, M., Bourgeois, S., & Chapman, C. E. (2007). Haptic discrimination of two-dimensional angles: Influence of exploratory strategy. *Experimental Brain Research*, **178**, 240–251.
- Manduchi, R., & Coughlan, J. (2012). (Computer) vision without sight. *Communications of the ACM*, **55**, 96–104. doi:10.1145/2063176.2063200
- May K. A., & Solomon J. A. (2013). Four theorems on the psychometric function. *PLoS ONE* **8**(10): e74815. doi:10.1371/journal.pone.0074815
- Nachmias, J. (1981). On the psychometric function for contrast detection. *Vision Research*, **21**, 215–223.
- Park, J., Doxon, A. J., Provancher, W. R., Johnson, D. E., & Tan, H. Z. (2012). Haptic edge sharpness perception with a contact location display. *IEEE Transactions on Haptics*, **5**, 323–331.
- Phillips, J. R., & Johnson, K. O. (1981). Tactile spatial resolution II: Neural representation of bars, edges, and gratings in monkey primary afferents. *Journal of Neurophysiology*, **46**, 1192–1203.
- Scheibert, J., Leurent, S., Prevost, A., & Debrégeas, G. (2009). The role of fingerprints in the coding of tactile information probed with a biomimetic sensor. *Science*, **323**, 1503–1506.
- Skinner, A., Kent, C., Rossiter, J. M., Benton, C. P., Groen, M. G., & Noyes, J. M. (2013). On the edge: Haptic discrimination of edge sharpness. *PLoS ONE*, **8**(9): e73283. doi:10.1371/journal.pone.0073283
- Sodhi, R., Poupyrev, I., Glisson, M., & Israr, A. (2013). AIREAL: Interactive tactile experiences in free air. *ACM Transactions on Graphics*, **32**, 134. doi:10.1145/2461912.2462007
- Watson, A. B. (1979). Probability summation over time. *Vision Research*, **19**, 515–522.
- Watson, A. B., & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics*, **33**, 113–20.
- Wijntjes, M. W. A., & Kappers, A. M. L. (2007). Angle discrimination in raised-line drawings. *Perception*, **36**, 865–879.

Appendix

Table A1. The first column states the general model family used. Columns two to four describe the models used, with a 0 indicating a parameter shared across participants and a 1 indicating a parameter free to vary across participants. No value indicates that this parameter was not employed in the model. The fifth shows the Akaike Information Criterion (AIC) differences, which are calculated as the difference between each AIC and the smallest AIC value generated within the set of models.

Model	Location	Shape	Lapse rate	Δ AIC
Logistic	0		0	428
Logistic	1		0	86
Logistic	0		1	596
Logistic	1		1	340
Logistic	0			536
Logistic	1			227
Weibull	0	0	0	428
Weibull	1	0	0	93
Weibull	0	1	0	338
Weibull	1	0	1	379
Weibull	0	1	0	30
Weibull	1	0	1	274
Weibull	0	1	1	381
Weibull	1	1	1	252
Weibull	0	0		451
Weibull	1	0		0
Weibull	0	1		337
Weibull	1	1		32

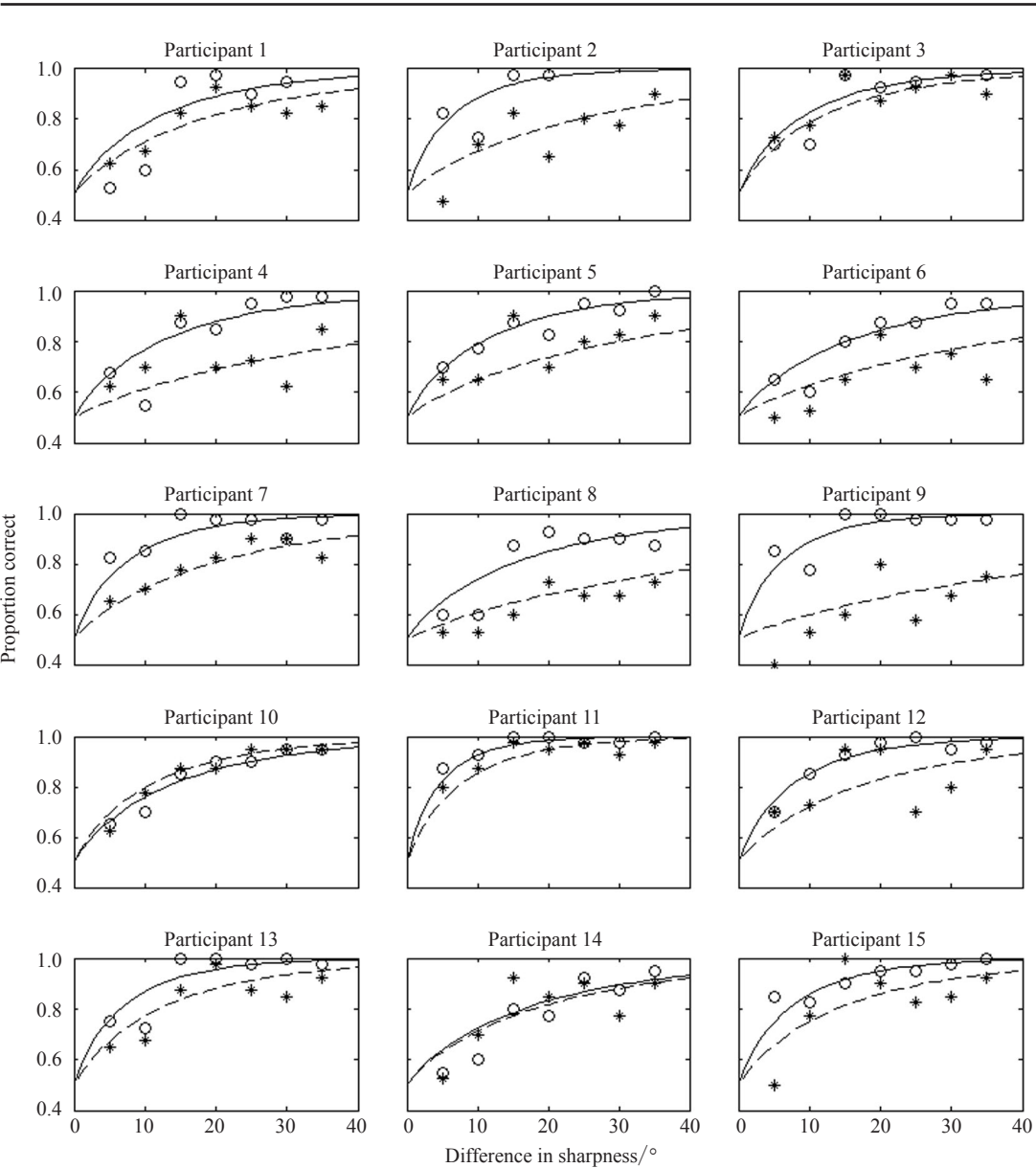


Figure A1. Mean proportion correct for each difference in sharpness for each participant (separate panels) in the proximal-distal (circles) and medial-lateral (asterisks) movement condition. Solid (proximal-distal) and broken (medial-lateral) lines are the best-fitting Weibull function for each participant.