Perceptual Constancy in the Reproduction of Virtual Tactile Textures With Surface Displays

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For very rough surfaces, friction-induced vibrations contain frequencies that change in proportion to sliding speed. Given the poor capacity of the somatosensory system to discriminate frequencies, this fact raises the question of how accurately finger sliding speed must be known during the reproduction of virtual textures with a surface tactile display. During active touch, ten observers were asked to discriminate texture recordings corresponding to different speeds. The samples were constructed from a common texture which was resampled at various frequencies to give a set of stimuli of different swiping speeds. In trials, they swiped their finger in rapid succession over a glass plate which vibrated to accurately reproduce three texture recordings. Two of these recordings were identical and the third differed in that the sample represented a texture swiped at a speed different from the other two. Observers identified which of the three samples felt different. For a metal mesh texture recording, seven observers reported differences when the speed varied by 60, 80 and 100 millimetres per second while the other three did not reach a discrimination threshold. For a finer leather chamois texture recording, thresholds were never reached in the 100 mm/s range. These results show that the need for high-accuracy measurement of swiping speed during texture reproduction may actually be quite limited compared to what is commonly found in the literature.

CCS Concepts: • **Human-centered computing** → **Haptic devices**; *Touch screens*; • **Hardware** → **Haptic devices**; • **Computer systems organization** → *Sensors and actuators*;

Additional Key Words and Phrases: tactile stimulation, haptic texture rendering, design requirements, speed perception

1 INTRODUCTION

Perceptual constancy is a singularly important phenomenon and was enshrined by the Gestalt school of psychology as one of the perceptual principles, *e.g.* [10]. There are indeed numerous examples of its existence. But of course, the many counterexamples where perceptual constancy also breaks down may explain why it has been the topic of countless studies, and arguments about the scope of its application, *e.g.* [22]. Perceptual constancy is vitally important for the operation of any display. Television sets would be useless without perceptual constancy because people shown on them would appear to us at their 'veridical' size. Voices and music tunes would vary at infinitum at the whim of each sound reproduction system, each of which produce vastly different acoustic fields for a same source. Fortunately, in all sensory modalities, including olfaction, most perceptual dimensions are subject to constancy since, without it, the world around us would appear to us like an undecipherable mess.

1.1 Constancy in Touch

In touch, constancy operates in an apparent manner for some perceptual dimensions. For instance a book, by-and-large, is felt to have the same heaviness whether it is held between two fingers or whether it rests on the palm of a hand supported by a table. These conditions nevertheless correspond to utterly different haptic inputs. It is also easy to render it inoperative, for instance, under the effect of the size-weight illusion [40]. Similarly, force feedback devices often exhibit widely different characteristics [45]. Yet, once a certain level of performance is achieved different models can provide similar sensations. In the haptic domain, constancy, like in vision, is known to break down for certain sensations and under certain conditions, but can be robust for other conditions. More specifically, some examples of break-down are when the perceived curvature of objects depends on the distance from the observer [21], or when, for a fingertip interacting with a moving object, the perceived speed of motion weakly accounts for the finger motion instead of relying on object motion alone [39, 53]. Conversely, strong perceptual constancy is seen in tactile suppression, the equivalent of saccadic suppression of displacement in vision, where observers perceptually suppress 2.5 mm displacements of braille dots during the short time interval between contacts with different fingertips during scanning [60].

It is known that the tactile perception of texture is relatively insensitive to changes in exploration speed [33] and exploration method [31, 59], which may also be viewed as an instance of perceptual constancy. Textural perceptual constancy is astonishing given the dramatic changes in the proximal stimulus as a function of changing scanning speeds [14, 15, 36, 55]. The brain is thus capable of extracting the invariant characteristics of a surface, even during passive touch, when there is no direct information about the sliding speed. Therefore, the brain must have developed powerful constancy mechanisms since the inter-spike intervals of peripheral afferent responses dilate or contract in proportion to speed [52].

1.2 Sensing Requirements In Tactile Displays

A tactile display is a device that stimulates a user's skin. With the recent development of numerous approaches to realise surface tactile displays able to provide sensations of texture [1, 3, 5, 18, 38, 41, 51, 54, 54, 56, 57], comes the need to specify their actuation and sensing performance. Sensing requirements can be quantified by relating spatial resolution, temporal resolution, and scanning velocity [8]. To this end, it is possible to invoke the so-called Courant-Friedrichs-Lewy (CFL) condition, $v_C < \delta/T$, that specifies the conditions under which spatio-temporal signals can be represented (and by way of consequence enable the convergence of the associated computational problems) if δ is the spatial resolution, T the temporal resolution, and v_C a not-to-be-exceeded scanning velocity. Thus, in the absence of special signal reconstruction precautions that could meet the absolute lowest rate limit of 2 kHz as required by the Nyquist-Shannon sampling theorem, a brute force approach to realising exact texture reproduction, imposes demanding sensing requirements such that a desired temporal sampling frequency would be on the order of 10 kHz (one order of magnitude to be conservative) and a spatial sampling frequency on the order of 10^6 m^{-1}. These figures would inflict drastic requirements on the finger position detection systems of any tactile display.

1.3 Human Factors

Seen from another perspective, it is wholly unlikely that our haptic sensory system be capable of the processing performance required to combine information about neuromotor commands, proprioception, and tactile inputs at the speeds necessary to fully reconstruct the mechanical signals elicited by scanning textures with bare fingers. Clearly it must employ a tradeoff, the simplest of which is to ignore the actual velocity at which a finger slides on a texture and to respond instead to quantities that do not change with exploration parameters. This is known in neuroscience as the temporal coding of tactile textures [9, 20, 24, 27, 29].

Our own work has shown the existence of a mechanical invariant that could be extracted by the brain during the exploration of isolated asperities at different speeds [7]. This finding suggests that the cumulative skin deformation elicited by a scanned asperity could represent such an invariant physical quantity whereas the previously considered instantaneous mechanical loading on the finger skin would not. This quantity is insensitive to speed but varies with other exploration conditions and surface properties such as the height of an asperity.

This and other mechanisms led us to put forward the hypothesis that significant liberties with respect to the actual finger sliding velocity could be taken during bare fingertip virtual texture reproduction that would remain undetectable. In keeping with the previous reasoning, this hypothesis is equivalent to assuming the poor capacity of the tactile system to discriminate temporal frequencies, a fact that is born out empirically [19]. It may be observed that those tactile displays operating on the principle of vibrating styluses [12] could enable even greater liberties to be taken with sliding velocity, since for a wide range of surfaces, direct contact of a finger with a surface provides the brain with a reliable source of velocity information [13, 37, 48].

1.4 How Much Resolution is Really Needed?

We investigated the aforementioned hypothesis by measuring the perceptual ability of ten observers to become aware of the differences in the textures corresponding to different scanning speeds during active bare finger sliding on a vibrating glass plate that reproduced a signal closely resembling that which is elicited by scanning the actual texture. Even with a texture having a strong character of periodicity—hence giving a signal that is highly sensitive to scanning speed—we found that reproduction speed could vary by ±60 % around a nominal velocity of $0.16\,\mathrm{m\,s^{-1}}$ before observers could notice a difference. In other words, this result implies that a desirable velocity quantum for a tactile display system, i.e. the smallest detectable velocity difference, can be of the order of $0.1\,\mathrm{m\,s^{-1}}$. Thus for a display operating in open loop having a temporal resolution of 1.0 ms, the requirement for sensing would be on the order of 0.1 mm and not 1.0 μm as the naive application of the CFL condition could lead one to conclude. Please observe that in closed-loop operation the application of the CFL condition to tactile displays would still be needed because of the possibility of noise re-injection [8].

2 MATERIALS AND METHODS

2.1 Apparatus

We used a tribometer apparatus to make recordings of the two reference stimuli. This apparatus, described in greater detail elsewhere [6], combines a finger stimulation system with a highly sensitive transducer able to measure the interfacial force components between a bare finger and natural surfaces. The transducer uses leaf springs to separate the normal contact loading component from the friction component, and does so in a wide range of frequencies, owing to its high rigidity. Sensing is performed in the tangential direction by a high dynamic range Kistler 9217A load cell with a sensitivity of 1 mN and a natural frequency over 20 kHz. An impact hammer (PCB Piezotronics, 086E80) was used to identify a linear range of the sensing platform up to 500 Hz. The sensor was sampled at 16 bits (National Instruments PCI-9221). After analog and digital noise considerations, a resolution of 1.5 mN within the desired frequency range was achieved.

The stimulator system also uses a suspension made of cantilever leaf springs, Fig. 1, but arranged to be highly compliant in the tangential direction in order to ensure a robust causality between the signal that drives the motor and the stimulus applied to the skin. To compensate for the highly undamped response of the leaf springs in the tangential direction, the stimulator included a Foucault-current damper consisting of an array of permanent magnets and a conducting fin made of aluminum that introduced, without contact, a viscous force linear in a wide range of velocities. The stimulator was actuated by an electrodynamic moving-coil voice-coil motor (NCC01-07-001-1R, H2W Technologies) with a moving mass of 3 g, a stroke distance of 3 mm, and a peak force of 2 N. It was verified to have a linear response at least up to 500 Hz when attached to the platform. The mass
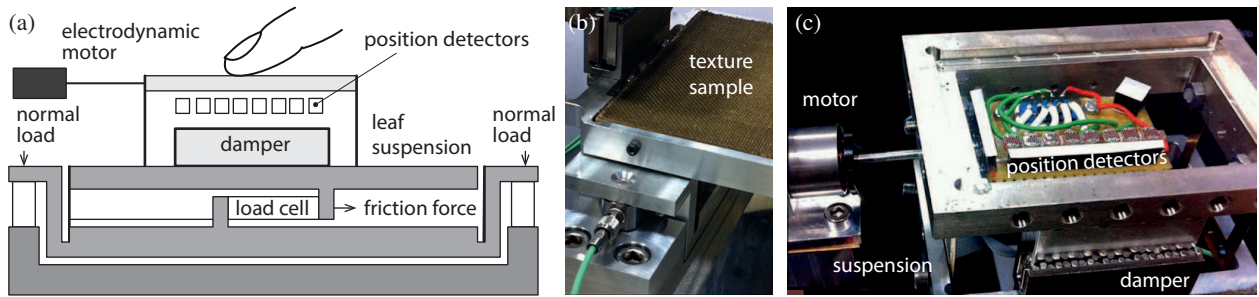
Fig. 1. Apparatus. (a) Schematic representation. (b) Texture sample mounted to the tribometer. (c) View of the stimulator.

of the stimulator system's moving platform was 81 g. At this mass, the natural frequency of the spring-damper system was 17 Hz without load. This arrangement ensured an accurate reproduction of the measured friction force signal on the skin within the desired frequency range of 500 Hz because accelerations are reproduced directly in proportion to forces due to the system being dominantly inertial. The stimulator also included a set of eight optical sensors that could detect the instant when a scanning finger would come into coincidence with their positions.

2.2 Stimulus

The two reference stimuli were 500 ms recordings of a finger sliding over a metal mesh (seen in Fig. 1b) of medium coarseness and a leather chamois (textures No. 42 and 23 from [47]), which corresponded to an exploration speed of 180 mm s^{-1}, which is at the upper end of the scale of reasonable scanning speeds, over a space of 90 mm. For the two textures, the original sample was band-pass filtered in the 60 Hz to 500 Hz range in order to remove high-frequency modes and DC bias introduced by the recording device. The samples were edited to conserve the central, steady-state portion, minimising the variations due to changes in normal force and exploration movement. The reference samples were then resampled using linear interpolation and windowed to equalise the duration, in order to prevent the observers from using the stimulus duration as a cue. The samples were frequency-shifted in this manner rather than using separate recordings at different speeds in order to ensure that observers compared equivalent stimuli between speed conditions. Figures 2a and 2d shows the temporal stimuli for speeds 180 (the reference), 120 and 100 mm s^{-1}. The frequency spectrum of these is shown in figures 2b and 2e. Due to the noisy quasi-periodic nature of the recordings, we used a non-parametric method to validate change in frequency due to this processing. The *spectral median* of each stimulus shifted linearly with decreasing speed, see Figs. 2c and 2f. This measure was determined by selecting the minimum frequency at which the cumulative intensity exceeds half of the total intensity in the Nyquist range ($\mathrm{argmin}_i \sum_{k=0}^{i} A_k > \frac{1}{2} \sum_{k=0}^{N} A_k$ for $i = 1, \ldots, N;\ N = 2500$). Finally, the stimuli were multiplied by a 500 ms Gaussian window to eliminate discontinuities and minimise any obvious start- and stop-cues at the beginning and end of playback.

Below the glass plate was an array of photocell light detectors 5 mm apart from each other, used to compute the speed over each interval. The data acquisition had a 5 kHz sampling frequency. This configuration allowed us to measure average speed between two photocells precisely since by the inverse-time method the velocity estimation error was of the order $1/(\delta/T) \approx 1 \times 10^{-3}$ mm s^{-1} [28]. The first photocell detector was used as a flag to indicate that the participant was sliding on the platform. The assumption that the finger was sliding at a relatively constant speed during the duration of the stimulation could thus be easily verified.
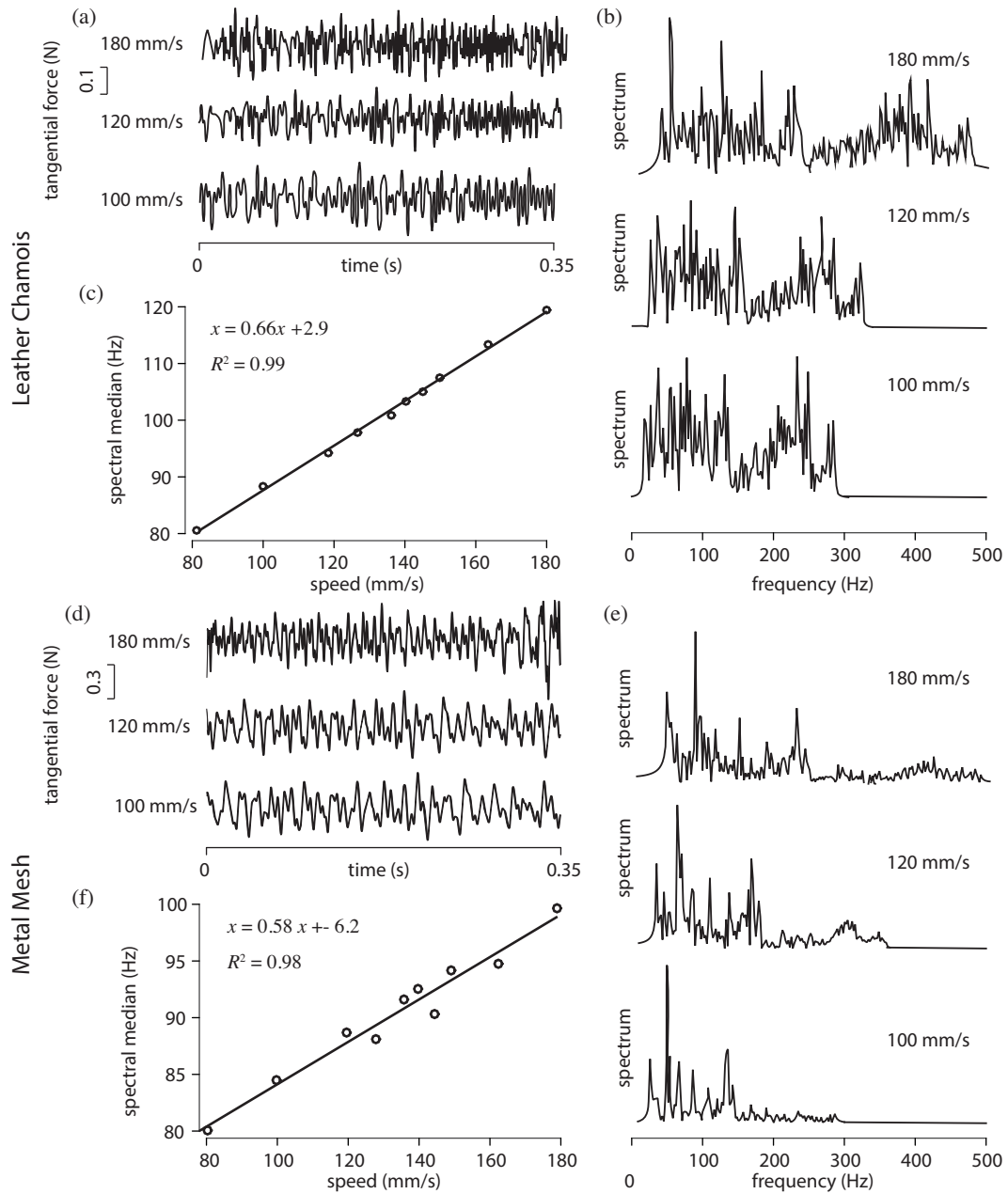
Fig. 2. The time-resampled, filtered stimuli (a) and (d) and the spectra (b) and (e) at 180, 120 and 100 mm/s. The spectral median increased with speed for both samples (c) and (f).

2.3 Procedure

The procedure was designed to overcome a methodological difficulty associated with attempting to explicitly enforce the movement speed of observers engaged in a perceptual task. Because explicit speed enforcement introduces a dual attentional task it becomes impossible to guarantee that for all observers the perceptual task remains the primary task. For this reason we allowed observers to interact with the apparatus at a speed that they spontaneously adopted to optimize their performance. This speed was carefully monitored by the experimenter. Previous research has abundantly demonstrated that human rapid movements are highly stereotypical [4, 23, 46, 49], and that their kinematics are entirely governed by their timing [43]. Moreover, a three-alternative choice paradigm guaranteed that if the participant spontaneously used slightly different speeds, any possible bias introduced would have affected the comparisons within trials identically and a possible bias would be averaged out. The procedure that we adopted follows from these observations.

The observers were given the task of detecting which one of a set of three consecutive stimuli was different from the other two. In a three-alternative forced choice paradigm (3-AFC), chance level is 33 % of correct answers. Thus, we considered that above 33 % of correct responses, an observer would begin to detect the difference between stimuli. A forced-choice task with three-alternatives has several advantages in same/different judgements. The most important is that observers, being provided with three pairs of stimuli, have the opportunity to compare pairs that are perceived to be the same to pairs that are perceived to be different, thus reducing reliance on an internal criterion of sameness. In other words, this method offered more alternatives in a set of choices that includes a status quo option [44]. The stimuli were selected from a set of speed differences comprising 5, 10, 20, 40, 60, 80 and 100 mm s^{-1} with respect to the 180 mm s^{-1} standard.

Observers were informed that they would experience three simulated textures when sliding the index of their dominant hand on the stimulator's glass plate and that they would have to notice differences between them. During training, they were instructed to slide their finger from left to right at a constant speed which felt comfortable for them while no texture was reproduced. During each stroke, the finger was applied to the glass at the beginning and lifted at the end. After a few trials of practice they were blindfolded and wore a pair of circumaural workshop ear protectors (3M) over ear buds that played pink noise for the purpose of blocking the sound of the motor. They continued to practice exploring at a constant speed but could experience the stimuli. During this period the experimenter could adjust the stimuli amplitude to ensure that observers could feel the simulated textures at a level that was natural to them. The experimenter also adjusted the level of the pink noise such that the acoustic emissions arising from the stimulator were not heard by the observer.

Once the preparation phase was completed, each observer experienced eight repetitions of triads of stimuli including one of the six speed differences with an additional twelve control trials where the triads had the same stimuli, totalling 60 trials. The order of presentation was randomised within trials and across trials for all observers. Although trials were not rejected on the basis of whether observers used a sufficiently constant monitored velocity, this condition, as justified earlier, was informally enforced by the experimenter, who attentively observed the exploration speed, and reminded observers of this requirement whenever necessary, which was infrequent. Observers could take an optional rest half way through the block of trials but frequently opted out. The procedure lasted approximately 45 minutes.

Because the perceptual task was difficult, which is a problem to contend with for same/different judgements with no sharp boundaries, the results were expected to be noisy and sensitive to individual differences. To address this problem, observers also rated on a scale of weak, medium, and high (converted to numerical values of 3, 5, and 8) the confidence that they had of their own judgements. Recently, confidence ratings have been argued to be an effective probe into one's own perceptual states because confidence ratings relate directly to our second-order ability to monitor the value of first-order perceptual judgements [16, 58]. Here, it might be argued that a judgment of sameness relates more to a second-order judgement than to a first-order judgement such as ordinal ratings, for

instance intensity. In fact, it would be hard with our textures to come up with ordinal perceptual dimensions that could be ranked since the textures were artificially constructed to have the same roughness, the same implicit periodicity, and other similarities in all their aspects. Each participant performed this procedure for only one texture. There were twelve observers for the metal mesh texture and ten for the leather chamois texture.

3 RESULTS

3.1 Metal Mesh

As anticipated, the performance of the observers increased as the difference in speed between the reference and the comparison stimuli also increased, see Fig. 3a. Data variance, however, remained by-and-large independent from performance. The speed discrimination threshold was defined to be the speed difference at which the percentage of correct answers exceeded 67 % and the 'just noticeable difference' (JND) was defined to be the speed difference at the mid-point location between 33 % and 67 % correct answers as often done in three-alternative forced-choice experiments. On average, the rate of 72 % of correct answers was attained only for a speed difference of 100 mm s^{-1}, suggesting that the threshold of 67 % was not systematically reached in a range of speed exploration from 80 to 180 mm s^{-1}. Two observers were discarded from the analysis because their performance was at chance level. This correction had no effect on the conclusions.
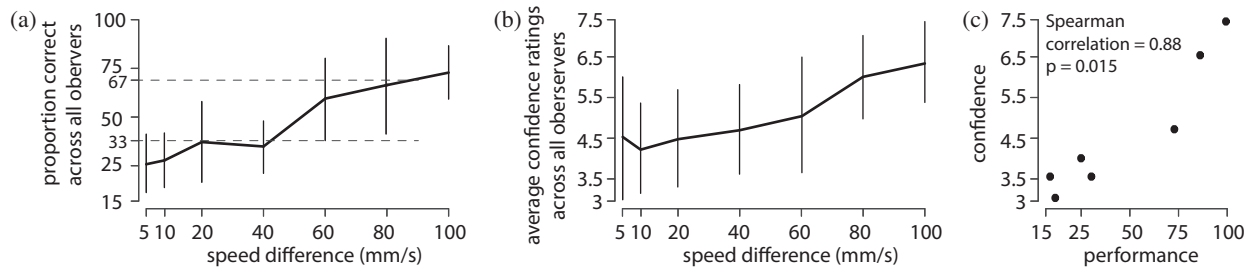

Fig. 3. Metal Mesh. (a) Fraction of correct answers across all observers. (b) Averaged confidence ratings for all observers and trials. In the two plots, error bars show standard deviation. (c) Correlation between performance and confidence.

Interestingly, the confidence ratings of the observers, Fig. 3b, tracked their performance. Figure 3c presents the same data but with confidence ratings plotted against performance, showing a high degree of correlation between the two measures. There is, however, a noticeable difference in that performance remained almost constant until a threshold of 60 mm s^{-1} and then started rising whereas confidence ratings rose gradually, even when the difference in stimulus was not consciously detectable. Because this study aimed at suggesting design guidelines for tactile displays, detection threshold values that would be useful for engineering purposes should be aligned with the results of the most sensitive observers, rather than on average. Of the ten observers one was particular sensitive. The corresponding result is shown in Fig. 4.

In the range of speed variations used, seven observers met a perceptual threshold (60, 80 and 100 mm s^{-1}), but the other three were unable to detect differences between the recordings (success rate lower than 67% for all speed differences). The lowest JND was at 40 mm s^{-1} amongst our pool of observers. For the three least sensitive observers, we could not measure the JND since their speed discrimination threshold exceeded 100 mm s^{-1}.

We conducted further analysis to better analyse the relation between performance and confidence ratings, and to evaluate possible biases introduced by the method. Figure 5(a) shows that when an answer was correct, it was more likely to be rated with high confidence. Conversely, when an answer was incorrect, it was more likely to be of low confidence albeit less strictly than in the other case.

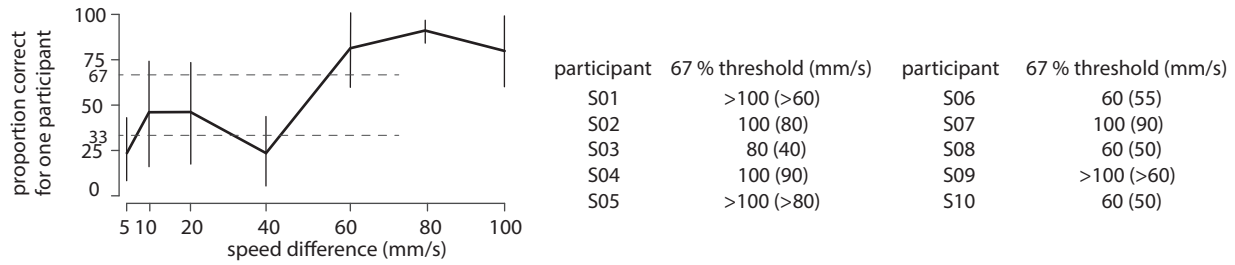| participant	67 % threshold (mm/s)	participant	67 % threshold (mm/s)
S01	>100 (>60)	S06	60 (55)
S02	100 (80)	S07	100 (90)
S03	80 (40)	S08	60 (50)
S04	100 (90)	S09	>100 (>60)
S05	>100 (>80)	S10	60 (50)

Fig. 4. Metal Mesh. Performance for one participant and individual results for the others. The JND (mm/s) is specified in parenthesis after the 67 % threshold. Error bars show standard deviation of this observer's answers.
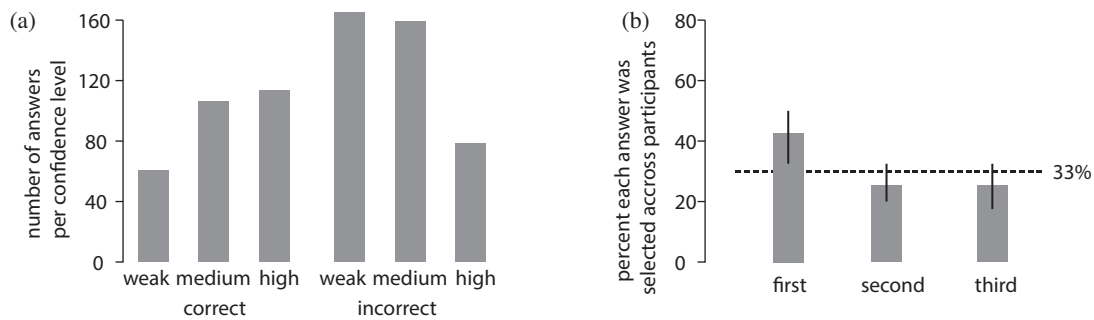

Fig. 5. Metal Mesh. (a) Distribution of confidence estimates per correct and incorrect answers. (b) Biases towards answering the first, second, or third sample in a triad with standard deviations.

On the whole, observers chose the first sample more often than the second or the third, see Fig. 5(b). Overall the average was around 30-35% which is roughly one third of all answers. This slight imbalance would not change our conclusions since the stimuli were randomised.

3.2 Leather Chamois

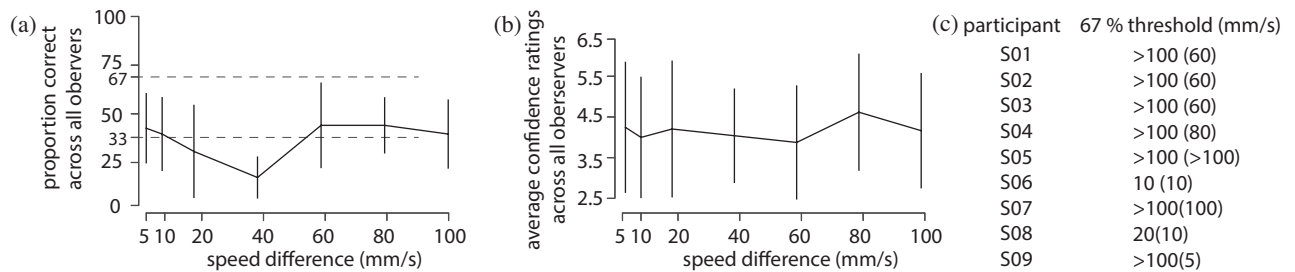| (c) participant	67 % threshold (mm/s)
S01	>100 (60)
S02	>100 (60)
S03	>100 (60)
S04	>100 (80)
S05	>100 (>100)
S06	10 (10)
S07	>100(100)
S08	20(10)
S09	>100(5)

Fig. 6. Leather Chamois. (a) Fraction of correct answers across all observers. (b) Averaged confidence ratings for all observers and trials. In the two plots, error bars show standard deviation. (c) Performance for each participant. The JND (mm/s) is specified in parenthesis after the 67 % threshold. Error bars show standard deviation of this observer's answers.

The results for a finer texture such as leather chamois were much poorer across observers, see Fig. 6a and Fig. 6c. The data from one participant was discarded for not reaching chance level and is not shown here. In fact, overall a perceptual threshold was not reached in the entire speed range (100 mm/s) and the confidence remained flat across trials, see Fig. 6b. While there seems to be a perceptual threshold at small speed differences for two observers (S06 and S08), these findings can be considered artefacts since their performance drops thereafter for the larger speed differences. Another indication that the observers were unable to complete the task successfully is the lack of correlation between confidence level and correctness, see Fig. 7a, while there was no bias towards a specific answer, see Fig. 7b.
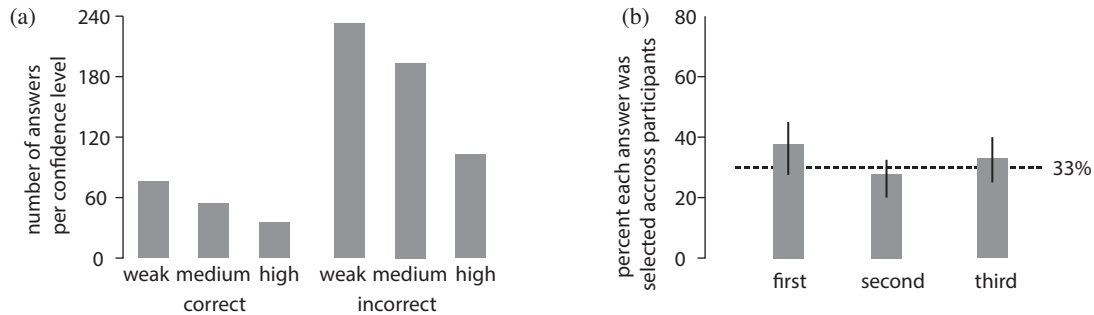

Fig. 7. Leather Chamois. (a) Distribution of confidence estimates per correct and incorrect answers. (b) Biases towards answering the first, second, or third sample in a triad with standard deviations.

4   DISCUSSION AND IMPLICATIONS

A few observers spontaneously reported that they felt that the temporal frequencies were different across samples while, interestingly, others felt that the temporal extent of the stimuli was changing when, in fact, the stimuli all had the same duration. This observation suggests that a perceived change of duration could have the interpretation that textures explored at a faster speed also led to a shorter temporal exposure, confirming that speed was the cue which most observers used to distinguish between stimuli. Similar interactions between speed, duration, and spatial extent have been reported in the past, see [2, 17, 32, 42, 50].

The mechanisms underlying textural constancy in touch are still debated [14, 26, 35, 52, 59]. One may question whether results of a texture display experiment can have bearing on perceptual constancy for natural stimuli, and what the results may mean in the context of necessarily impoverished stimuli of an artificial display as compared to nature. To answer this, it is worth considering which aspect of the natural stimuli are missing in the artificially generated stimuli. In natural stimuli, there is normally a strong correlation between the position of the temporal spectrum on the frequency scale and speed, a property that was notable in the case of the texture that we selected for our experiments. The artificial stimuli, however, abolished this correlation completely, yet constancy was still operating. This finding thus undermines models of texture perception based on temporal coding since, in our experiments, the temporal aspects of the stimuli changed dramatically without being noticed. It is also argued that texture perception instead arises from a dual coding process, one in the temporal domain and the other in the spatial domain [25]. Our results do not support well this view either, since the artificial stimuli that we

employed did not contain any spatial components. We thus may conclude that the texture constancy must rely in great part on top-down processes where the predictions of pre-internalised models of textures are matched against raw sensory inputs.

It is worth pointing out that this paper investigates bare fingertip sliding, which is different to tool-mediated texture interaction. Culberston et al. [11, 12] found that speed responsiveness was important for rendering realism but that force was not. These interactions are comparatively more complicated because many factors related to the tool/finger or tool/texture interaction mechanics interfere with the final percept [30], making a strong case for the lack of perceptual constancy. Additionally, the effect of increased speed on perceived roughness is twice as strong when using a probe than without [34], which could explain the increased necessity for speed responsiveness in probe-mediated touch. Actually, Yoshioka et al. [59] hypothesised that compliance and friction might be processed by separate groups of neurons for direct and indirect touch.

On the whole, for the metal mesh, a robust threshold (above 67 %) of speed variation was not reached by all the observers in the speed exploration range from 80 to 180 mm s^{-1}, but when looking at individual performance, some observers could detect differences. Still, considerable liberties can be taken in the reproduction of texture when it comes to scanning speed. More specifically, the results suggest that it is pertinent to reproduce texture up to a 40 mm s^{-1} difference compared to a reference exploration speed. These results were obtained for the metal mesh of medium coarseness, which was selected to provide a clear sensation of periodicity; they can be expected to apply as well to other textures having a lesser character of periodicity. The leather chamois, being considerably finer and having much less periodicity, resulted in a much poorer discrimination ability. These findings imply that speed perceptual threshold is texture-dependent, and that different considerations are necessary for device design when reproducing coarse vs. fine textures.

In future work, we would like to use more diverse texture recordings and conduct identification tasks with recorded texture stimuli that are perfectly matched with the exploration speed on the one hand and with samples recorded with a ±40 mm/s discrepancy on the other for coarse stimuli and ±80 mm/s for finer stimuli. If texture recognition ability is comparable, it would give a speed matching threshold necessary for texture reproduction allowing to engineer devices with very low speed sensing requirements.

5 ACKNOWLEDGEMENTS

REFERENCES

[1] M. Altinsoy and S. Merchel. 2012. Electrotactile feedback for handheld devices with touch screen and simulation of roughness. *IEEE Transactions on Haptics* 5, 1 (2012), 6–13.

[2] L. Armstrong and L.E. Marks. 1999. Haptic perception of linear extent. *Perception & Psychophysics* 61, 6 (1999), 1211–1226.

[3] S. Asano, S. Okamoto, and Y. Yamada. 2015. Vibrotactile stimulation to increase and decrease texture roughness. *IEEE Transactions on Human-Machine Systems* 45, 3 (2015), 393–398.

[4] C. G. Atkeson and J. M. Hollerbach. 1984. *Kinematic features of unrestrained arm movements.* AI Memo AIM-790. MIT.

[5] M. Biet, F. Giraud, and B. Lemaire-Semail. 2007. Squeeze film effect for the design of an ultrasonic tactile plate. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* 54, 12 (2007), 2678–2688.

[6] S. Bochereau, B. Dzidek, M. Adams, and V. Hayward. 2017. Characterizing and imaging gross and real finger contacts under dynamic loading. *IEEE Transaction in Haptics, In press* (2017).

[7] S. Bochereau, S. Sinclair, and V. Hayward. 2015. Looking for Physical Invariants in the Mechanical Response of a Tactually Scanned Braille dot.. In *World Haptics Conference.* 119–124.

[8] G. Campion and V. Hayward. 2005. Fundamental Limits in The Rendering of Virtual Haptic Textures. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems.* 263–270.

[9] C. J. Cascio and K. Sathian. 2001. Temporal cues contribute to tactile perception of roughness. *The Journal of Neuroscience* 21, 14 (2001), 5289–5296.

[10] S. Coren and J. S. Girgus. 1980. Principles of Perceptual Organization and Spatial Distortion: The Gestalt Illusions. *Journal of Experimental Psychology: Human Perception and Performance* 6, 3 (1980), 404–412.

[11] H. Culberston and K. J. Kuchenbecker. 2015. Should haptic texture vibrations respond to user force and speed? *Proceedings of World Haptics Conference*, 106–112.

[12] H. Culberston, J. Unwin, and K. J. Kuchenbecker. 2014. Modeling and rendering realistic textures from unconstrained tool-surface interactions. *IEEE Transaction on Haptics* 7, 3 (2014), 381–292.

[13] C. J. Dallmann, M. O. Ernst, and A. Moscatelli. 2015. The role of vibration in tactile speed perception. *Journal of neurophysiology* 114, 6 (2015), 3131–3139.

[14] B. Delhaye, V. Hayward, P. Lefèvre, and J.-L. Thonnard. 2012. Texture-induced vibrations in the forearm during tactile exploration. *Frontiers in Behavioural Neuroscience* 6, 37 (2012), 60–69.

[15] A. Dépeault, E. M. Meftah, and C. E. Chapman. 2008. Tactile speed scaling: contributions of time and space. *Journal of Neurophysiology* 99 (2008), 1422–1434.

[16] O. Deroy, C. Spence, and U. Noppeney. 2016. Metacognition in Multisensory Perception. *Trends in Cognitive Sciences* 20, 10 (2016), 736–747.

[17] L. Dupin, V. Hayward, and M. Wexler. 2015. Direct Coupling of Haptic Signals Between Hands. *Proceedings of the National Academy of Sciences* 112, 2 (2015), 619–624.

[18] F. Giraud, M. Amberg, and B. Lemaire-Semail. 2013. Merging two tactile stimulation principles: electrovibration and squeeze film effect. In *World Haptics Conference*. IEEE, 199–203.

[19] G. D. Goff. 1967. Differential discrimination of frequency of cutaneous mechanical vibration. *Journal of Experimental Psychology* 74, 2 (1967), 294–299.

[20] A. W. Goodwin, K. Sathian, K. T. John, and I. Darian-Smith. 1989. Spatial and temporal factors determining afferent fiber responses to a grating moving sinusoidally over the monkey's fingerpad. *Journal of Neuroscience* 9, 4 (1989), 1280–1293.

[21] J. Hartcher-O'Brien, A. Terekhov, M. Auvray, and V. Hayward. 2014. Haptic shape constancy across distance. In *Haptics: Neuroscience, Devices, Modeling, and Applications*. Springer, Berlin Heidelberg, 77–84.

[22] J. E. Hochberg. 1957. Effects of the Gestalt revolution: the Cornell symposium on perception. *The Psychological Review* 64, 2 (1957), 73–84.

[23] J. M. Hollerbach and T. Flash. 1982. Dynamic interactions between limb segments during planar arm movement. *Biological cybernetics* 44, 1 (1982), 67–77.

[24] M. Hollins, S. J. Bensmaïa, and E. A. Roy. 2002. Vibrotaction and texture perception. *Behavioural Brain Research* 135, 1 (2002), 51–56.

[25] M. Hollins and S. R. Risner. 2000. Evidence for the duplex theory of tactile texture perception. *Perception & Psychophysics.* 62, 4 (2000), 695–705.

[26] B. Hughes, J. Wang, D. Rosic, and K. Palmer. 2007. Texture Gradients and Perceptual Constancy under Haptic Exploration. In *Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 66–71.

[27] S. P. Jadhav, J. Wolfe, and D. E. Feldman. 2009. Sparse temporal coding of elementary tactile features during active whisker sensation. *Nature Neuroscience* 12, 6 (2009), 792–800.

[28] F. Janabi-Sharifi, V. Hayward, and C.-S. J. Chen. 2000. Discrete-Time Adaptive Windowing For Velocity Estimation. *IEEE Transactions On Control Systems Technology* 8, 6 (2000), 1003–1009.

[29] L. M. Jones, D. A. Depireux, D. J. Simons, and A. Keller. 2004. Robust temporal coding in the trigeminal system. *Science* 304, 5679 (2004), 1986–1989.

[30] R. L. Klatzky, S. J. Lederman, C. Hamilton, M. Grindley, and R. H. Swendsen. 2003. Feeling textures through a probe: Effects of probe and surface geometry and exploratory factors. *Perception & Psychophysics.* 65, 4 (2003), 613–631.

[31] G. D. Lamb. 1983. Tactile discrimination of textured surfaces: psychophysical performance measurements in humans. *The Journal of Physiology* 338, 1 (1983), 551–565.

[32] S.J. Lederman, R.L. Klatzky, A. Collins, and J. Wardell. 1987. Exploring environments by hand or foot: Time-based heuristics for encoding distance in movement space. *J Exp Psychol Learn Mem Cogn* 13, 4 (1987), 606–614.

[33] S. J. Lederman. 1983. Tactual roughness perception: Spatial and temporal determinants. *Canadian Journal of Psychology* 37, 4 (1983), 498–511.

[34] S. J. Lederman, R. L. Klatzky, C. L. Hamilton, and G. I. Ramsay. 1999. Perceiving Roughness Via A Rigid Probe: Psychophysical Effects Of Exploration Speed And Mode Of Touch. (1999).

[35] X. Libouton, O. Barbier, Y. Bergera, L. Plaghkia, and Jean-Louis Thonnard. 2012. Tactile roughness discrimination of the finger pad relies primarily on vibration sensitive afferents not necessarily located in the hand. *Behavioural Brain Research* 229 (2012), 273—279.

[36] L. R. Manfredi, H. P. Saal, K. J. Brown, M. C. Zielinski, J. F. Dammann, V. S. Polashock, and S. J. Bensmaïa. 2014. Natural scenes in tactile texture. *Journal of Neurophysiology* 111, 9 (2014), 1792–1802.

[37] E.-M. Meftah, L. Belingard, and C.E. Chapman. 2000. Relative effects of the spatial and temporal characteristics of scanned surfaces on human perception of tactile roughness using passive touch. *Experimental Brain Research* 132, 3 (2000), 351–361.

[38] D. J. Meyer, M. A. Peshkin, and J. E. Colgate. 2013. Fingertip friction modulation due to electrostatic attraction. In *World Haptics Conference*. IEEE, IEEE, 43–48.

[39] A. Moscatelli, V. Hayward, M. Wexler, and M. O. Ernst. 2015. Illusory Tactile Motion Perception: An Analog of the Visual Filehne Illusion. *Scientific reports* 5 (2015), 14584.

[40] David J. Murray, Robert R. Ellis, Christina A. Bandomir, and Helen E. Ross. 1999. Charpentier (1891) on the size-weight illusion. *Perception & Psychophysics* 61, 8 (1999), 1681–1685.

[41] T. Nara, M. Takasaki, T. Maeda, T. Higuchi, S. Ando, and S. Tachi. 2001. Surface acoustic wave tactile display. *Computer Graphics and Applications* 21, 6 (2001), 56–63.

[42] A. Ono. 1969. Interdependence in successive judgments of the duration, distance and speed of a manual movement. *Tohoku Psychologica Folia* 28 (1969), 29–53.

[43] R. Plamondon. 1995. A kinematic theory of rapid human movements, Part II. Movement time and control. *Biological Cybernetics* 72 (1995), 309–320.

[44] J. Rolfe and J. Bennett. 2009. The impact of offering two versus three alternatives in choice modelling experiments. *Ecological Economics* 68 (2009), 1140–1148.

[45] E. Samur. 2012. *Performance Metrics for Haptic Interfaces*. Springer, London, Chapter Performance Evaluation Based on Physical Measurements, 43–65.

[46] J. F. Soechting and F. Lacquaniti. 1981. Invariant characteristics of a pointing movement in man. *Journal of Neuroscience* 1, 7 (1981), 710–720.

[47] W. M. Bergmann Tiest and A. M.L. Kappers. 2006. Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility. *Acta Psychologica* 121, 1 (2006), 1–20.

[48] W. M. B. Tiest, L. M. A. van der Hoff, and A. M. Kappers. 2011. Cutaneous and kinaesthetic perception of traversed distance. In *World Haptics Conference*. IEEE, 593–597.

[49] Y. Uno, M. Kawato, and R. Suzuki. 1989. Formation and control of optimal trajectory in human multijoint arm movement. *Biological Cybernetics* 61 (1989), 89–101.

[50] S. Wapner, J. Weinberg, J.A. Glick, and G. Rand. 1967. Effect of speed of movement on tactual-kinesthetic perception of extent. *The American Journal of Psychology* 80, 4 (1967), 608–613.

[51] T. Watanabe and S. Fukui. 1995. A method for controlling tactile sensation of surface roughness using ultrasonic vibration. In *IEEE International Conference on Robotics and Automation*, Vol. 1. IEEE, 1134–1139.

[52] A. I. Weber, H. Saal, J. D. Lieberb, J.-W. Cheng, L. R. Manfredi, J. F. Dammann III, and S. J. Bensmaïa. 2013. Spatial and temporal codes mediate the tactile perception of natural textures. *Proceedings of the National Academy of Sciences* 110, 42 (2013), 17107–17112.

[53] M. Wexler and V. Hayward. 2011. Weak Spatial Constancy In Touch. In *World Haptics Conference*. IEEE, 605–607.

[54] M. Wiertlewski, D. Leonardis, D. J. Meyer, and J. E. Colgate. 2014. A High-Fidelity Surface-Haptic Device for Texture Rendering on Bare Finge. In *Haptics: Neuroscience, Devices, Modelling and Applications*. Springer, Berlin Heidelberg, 241–248.

[55] M. Wiertlewski, J. Lozada, and V. Hayward. 2011. The Spatial Spectrum Of Tangential Skin Displacement Can Encode Tactual Texture. *IEEE Transactions on Robotics* 27, 3 (2011), 461–472.

[56] M. Wiertlewski, J. Lozada, E. Pissaloux, and V. Hayward. 2010. Tactile Interface for stimulation of fingertip via lateral traction. In *12th International Conference on New Actuators*. Messe Bremen, Bremen, 520–523.

[57] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin.. 2007. T-PaD: Tactile pattern display through variable friction reduction. *World Haptics Conference*, 421–426.

[58] N. Yeung and C. Summerfield. 2012. Metacognition in human decision-making: confidence and error monitoring. *Philosophical Transactions of the Royal Society B* 367, 1594 (2012), 1310–1321.

[59] T. Yoshioka, J. C. Craig, G. C. Beck, and S. S. Hsiao. 2011. Perceptual Constancy of Texture Roughness in the Tactile System. *Journal of Neuroscience* 31, 48 (2011), 17603–17611.

[60] M. Ziat, V. Hayward, C. E. Chapman, M. O. Ernst, and C. Lenay. 2010. Tactile Suppression of Displacement. *Experimental Brain Research* 206, 3 (2010), 299–310.