Surface-Roughness-Based Virtual Textiles: Evaluation Using a Multi-Contactor Display

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Abstract—Virtual textiles, generated in response to exploratory movements, are presented to the fingertip via a 24-contactor vibrotactile array. Software models are based on surface-roughness profiles from real textiles. Results suggest that distinguishable "textile-like" surfaces are produced, but these lack the necessary accuracy for reliable matching to real textiles.

Index Terms—Evaluation/methodology, haptic I/O and standardization, user interfaces

1 Introduction

THIS study investigates virtual textures produced on the fingertip by a tactile array, i.e., a tactile display with multiple contactors. The array provides a time-varying vibrotactile stimulus which also varies with position over the fingertip, as is the case during "real" tactile exploration of a surface. This may offer a significant advantage in terms of fidelity over single-contactor displays (for example, [1], [2]), which do not address the spatial distribution of the stimulus on the skin. The present work focuses on virtual surfaces that represent textiles; it originates in the HAPTEX project [3] in which a virtual textile was manipulated (stretched, stroked, poked, etc.) using the thumb and index finger of one hand, with appropriate tactile and force feedback at the fingertips.

A number of tactile arrays have been developed, including devices whose drive mechanisms are piezoelectric [4], [5], [6], electromagnetic [7], [8] or pneumatic [9], [10]. As well as having the potential to convey both spatial and temporal aspects of virtual texture, such devices can provide information to facilitate virtual manipulation tasks [11], e.g., on the position of corners or edges on the fingertip. Some tactile arrays [8] use large-scale contactor movements to represent the shape of objects, but the majority use vibrotactile stimulation to produce touch sensations on the skin [12].

In relation to virtual textures from a tactile array, it seems likely that the perceptual dimensions of the sensations evoked will relate to the spectral content of the vibrotactile stimulation and its spatial distribution over the virtual surface. It is not clear how this might relate to perceptual dimensions such as rough/smooth, soft/hard and sticky/slippery which have been reported in studies on real surfaces, including textiles [13], [14], [15], [16]. Some investigation of the perceptual space for virtual textiles is included in the present study, which includes two experiments, the first involving matching of virtual textiles to their real equivalents, and the second involving discrimination between virtual textiles.

The literature includes only a few studies in which a tactile array provides the sensation of exploring a natural surface with the fingertip. Kyung et al. [17] used a 30-contactor array and (indirectly) compared synthetic stimuli to different grades of (real) sandpaper. Their synthetic stimuli produced a wide range of roughness sensations but might be considered unrealistic as they did not incorporate spatial variation over the contactor array. Okamoto and Yamada [18] used a single-contactor display to present virtual surfaces derived from a wide range of materials but their study does not include a comparison of the virtual and real surfaces. Martinez et al. [19] used single-point force feedback or vibrotactile stimulation to create the sensation of geometric patterns under the fingertip, and reported similar identification scores to those obtained for equivalent real stimuli. In addition, there are a number of previous studies on virtual texture in which a single actuator is used to replicate the exploration of a surface by a probe or tool, for example [2], [20], [21].

Apart from the HAPTEX project, virtual textiles have received limited research interest to date [22], [23]. The development of a suitable interface to display virtual textures has been hindered by the absence of an appropriate technology for small, lightweight tactile stimulators, and the development of realistic texture rendering has been hindered by a lack of detailed information about the excitation of skin mechanoreceptors during real touch perception. A successful implementation of realistic virtual textiles would have considerable commercial applications, particularly in relation to the wholesale of textiles and the retail of garments over the internet.

2 System Design

2.1 Hardware

The tactile display [Fig. 1a] is based on piezoelectric-bimorph actuators. It has 24 contactors in a 6×4 array with 2 mm spacing, covering around 1 cm^2 on the fingertip. (Spatial acuity on the fingertip is around 1 mm [24], [25]; 2 mm spacing was used here to limit the number of stimulation channels in order to facilitate the design and construction of the display; there is evidence to suggest that in some contexts a 2 mm array may perform no worse than a 1 mm array [26].) The area of each contactor is around 1 mm^2.

The display is designed to be in contact with, and moving with, the user's fingertip during active exploration of the virtual environment. In the present study a 2D virtual environment is used [Fig. 1b], although the eventual application of this technology is envisaged to be either in 2D or, as in the HAPTEX system [3], in 3D. A graphics tablet provides information about the position and velocity of the tactile display within the 2D workspace. This implementation is intended to represent surface properties of the textile only, with an emphasis on roughness. In the absence of force feedback, the display cannot represent global frictional forces on the fingertip, or the effect of surface resilience; furthermore, the present system does not attempt to reproduce the "softness" of the textile.

Ideally, the tactile display should present broadband stimuli in the tactile frequency range of, say, 20 to 500 Hz, containing all the frequency components that are presented to the skin in the "real" situation. However, the frequency resolution of the skin is poor: the just-noticeable-difference for frequency is around 30 percent for single-channel stimulation [27] and is expected to be worse than this for the spatially varying signals on an array. This suggests the possibility of using a low-resolution representation of the tactile spectrum based on only a few, widely spaced, frequency components, since such a reduction of spectral resolution is expected to have only a limited effect on the perceived tactile sensation. The results of Bernstein [28], using a single-channel system, suggest that the spectrum can be reduced to only two sine-wave components, providing these are chosen to separately target Pacinian and non-Pacinian receptors. This two-component strategy [4], [12] was adopted for the HAPTEX system [3] and for the present study, using tactile signals which are a mixture of sine waves at frequencies of 40 and 320 Hz to target non-Pacinian and Pacinian receptors, respectively. In the experience of the authors, the 40 Hz component suggests the gross topology of the surface and the 320 Hz component suggests a "hairy" or "tickly" aspect of the virtual textile. The use of two-component stimuli brings significant advantages in terms of reducing the amount of data required to specify the tactile stimuli, and in terms of the electromechanical design of the tactile stimulator (which does not require a flat, broadband response). Results from previous studies [4], [26], [29]

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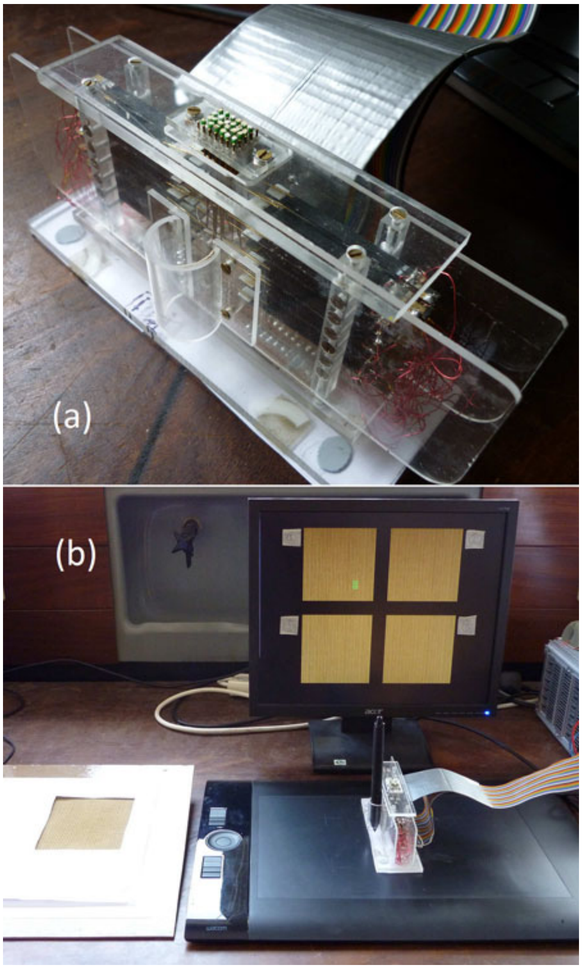

Fig. 1. (a) the tactile array, showing the contactor surface (top center) and the piezoelectric drive mechanism (black bars); (b) the 2D workspace, showing the tactile array mounted on a graphics tablet, the visual display and a sample of real textile (in the white frame).

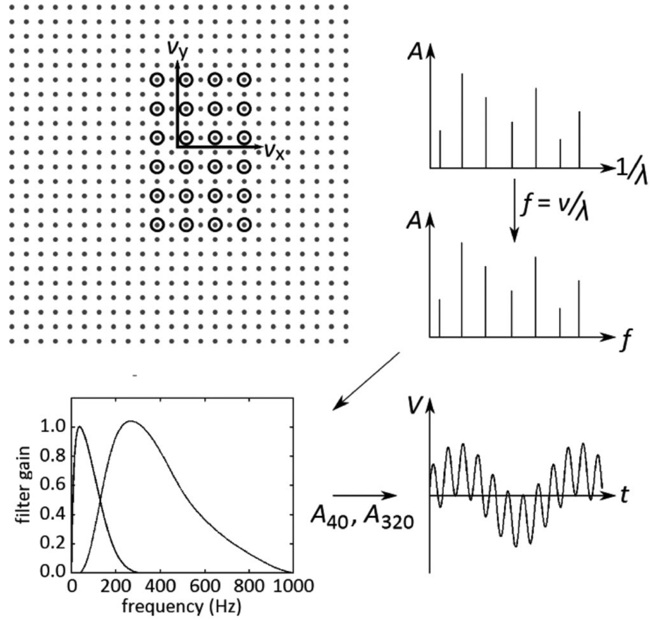

Fig. 2. Outline operation of the tactile renderer, showing (top left) the contactors moving over the 1 mm array of points which specifies the virtual surface, and (from top right) generation of the output signal: the spatial spectrum is converted to a time-domain spectrum and two band-pass filters are used to derive the amplitudes A_{40} and A_{320} which specify the contactor drive signal—only one contactor and only one of the two velocity components is considered, for simplicity.

using these two-component stimuli suggest that spatial resolution on the fingertip is better at 320 than at 40 Hz. (Pacinian receptors, particularly sensitive to frequencies around 300 Hz, are conventionally described as having large receptive fields [30]; in the present context this is better interpreted in terms of their high sensitivity rather than in terms of poor spatial acuity.)

The mechanical design of the tactile array is based on earlier devices developed in our laboratory [4], [12] and ultimately derives from the design of the Optacon [31], a reading aid for the blind. The Optacon uses a static array to present on/off patterns of vibration at a fixed amplitude and a single frequency, whereas the display used in the present study moves with the user's finger and provides vibratory patterns which have continuously variable intensity and spectral content.

2.2 Software

Representation of the textile in software is based on surface-roughness profiles obtained using the Kawabata evaluation system [32], in which an instrumented probe runs over the textile surface. The probe is designed to provide an objective measurement which correlates well with the subjective "feel" of the textile, hence the Kawabata data would seem to be a good choice on which to base a virtual representation. For each textile, roughness profiles were obtained in the warp direction (forward and reverse) and in the weft direction (forward and reverse). For some textiles the surface profiles in the four principal directions are relatively similar, whereas for other textiles the nature of the weave/knit results in much higher roughness in some directions than in others.

Localized spatial spectra were calculated from each surface profile for points at 1 mm intervals along the profile, using a Fourier transform with a Hamming window of effective width 2 mm. These spatial spectra form the basis of the software representation of the textile surface in two dimensions—as a square array of points at 1 mm spacing, with the surface in the region of each point being represented by localized spatial spectra in the four principal directions. The spectra cover an inverse-wavelength range of 0.23 to 115 mm^{-1}. Each Kawabata profile covers a distance of around 20 mm and provides a sequence of 16 spectra at 1 mm spacing–-the sequence is repeated to allow the representation of a textile with larger size.

On the basis of this software model of the virtual textile, the tactile renderer generates 40 and 320 Hz drive signals for each of the 24 channels of the tactile display, with amplitudes calculated in real time in response to exploration of the workspace by the user. The user can move in any direction within the workspace, but is requested not to rotate the display, i.e., to maintain the orientation of the display shown in Fig. 1b. (In principle, the software can accommodate rotations, but this option was not implemented for the present study.)

The operation of the renderer (Fig. 2) is as follows: A particular contactor in the stimulator array has known position and velocity in the workspace; the surface at that position is described by spatial spectra, taken from the nearest point in the 1 mm array of points which represents the textile. (The sign of the contactor's velocity component in the warp direction determines the choice between spectra measured in the forward or reverse warp directions; the weft direction is treated similarly.) The magnitude of the contactor's velocity component in the warp direction determines the conversion of the spatial spectrum in the warp direction to a time-domain spectrum; the weft direction is treated similarly. (A spatial component of wavelength λ converts to a time-domain component at frequency $f = v/\lambda$, where v is the magnitude of the appropriate velocity component.) An overall time-domain spectrum is calculated (warp and weft spectra combined), including only frequencies below 1 kHz. By applying two band-pass filters centered at 40 and 320 Hz, this spectrum is reduced to two

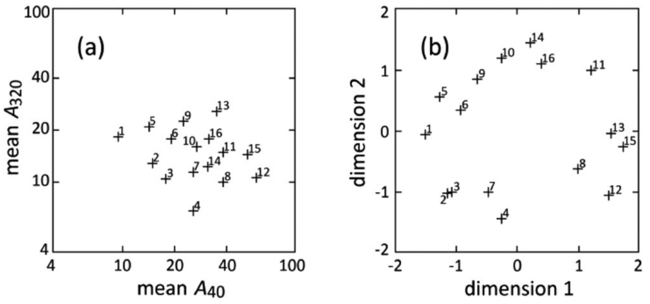

Fig. 3. (a) Mean values of the stimulus amplitudes A_{40} and A_{320} for the virtual textiles used in Experiments 1 and 2, identified by labels 1 to 16; (b) the 2D perceptual space for the virtual textiles, labelled 1 to 16 as in (a), derived from measures of dissimilarity in Experiment 2.

amplitudes A_{40} and A_{320}. These amplitudes are used to specify the drive signal to the contactor, which is a mix of 40 and 320 Hz sine waves. The amplitudes are updated every 25 ms, the update coinciding with zero crossings in the 40 and 320 Hz sine waves so as to maintain continuity in the drive waveforms. The same procedure is used for each of the 24 contactors in the stimulator array, providing values of A_{40} and A_{320} for each drive signal (all different, in the general case). The renderer runs on a standard laptop computer.

Ideally the software representation of the textile should be based on a large number of surface-roughness profiles, taken at different positions on the surface. However, in the present implementation the representation is based on only a single 20 mm profile for each principal direction. As a consequence of this economical strategy, movement of the array with a velocity component along the direction of its rows is necessary to produce variation of contactor drive signals from column to column of the array, and vice versa. This unrealistic aspect of the virtual textile is not apparent in normal use, however.

3 Materials and Methods

3.1 Stimuli

Kawabata measurements were available for 53 textiles; 21 of these had been measured on both sides, giving data for a total of 74 surfaces. The textiles covered a wide range: from smooth to rough, from fine to coarse texture, and made from a large selection of natural and synthetic materials. A preliminary experiment [33] suggested that, for virtual textiles represented by low levels of vibrotactile stimulation, the resulting sensation was generally too weak to provide a good match to the corresponding real textile; similarly, for virtual textiles represented by high levels of stimulation, the sensation was generally too strong. This was confirmed by an informal experiment (with author MP as system user) to establish for each virtual textile the change in global system gain required to provide the best match of sensation magnitude to the corresponding real textile. As expected, comparison between the drive-signal amplitudes for the original and optimized virtual textiles showed an overall trend in which the dynamic range over the stimulus set was compressed for the latter. On the basis of this overall trend, in the present study scaling was systematically applied across the various sets of spatial spectra in order to compress the dynamic range of roughness. After scaling, the dynamic ranges for stimulus amplitudes A_{40} and A_{320} across the range of textiles (measured in terms of mean values for each textile at a typical exploration speed: 10 cm s^{-1}) were around 16 and 12 dB, respectively.

A representative set of 16 real textiles (with corresponding virtual textiles) was chosen for use in the main experiments. The real textiles, intended for light clothing, outdoor clothing, car seats, etc., included eight woven and eight knitted, with a range of surface finishes; three of the set were made from natural fibers (silk, wool, jute), 11 from synthetic fibers (polyester, polyamide) and two from mixed fibers. The 16 virtual textiles are characterized in Fig. 3a in terms of mean values of the stimulus amplitudes A_{40} and A_{320} (measured at a typical exploration speed: 10 cm s^{-1}), indicating the spectral content of the stimulation. The coefficient of variation of these amplitudes (the standard deviation divided by the mean, indicating the extent to which the stimulation changes in magnitude over the surface) varies over the different textiles but is typically in the range 0.2 to 0.6 for both A_{40} and A_{320}. None of the selected virtual surfaces is strongly anisotropic.

3.2 Subjects

Eight subjects participated in Experiment 1: age range 21 to 33 years, five male and three female, all right-handed. A different set of eight subjects participated in Experiment 2: age range 22 to 33 years, four male and four female, seven right-handed and one left-handed.

3.3 Procedure

In Experiment 1 the subject was instructed to rest the right-hand index fingertip on the tactile display and to explore the workspace in the same way as using a computer mouse. The subject wore earmuffs to reduce the possibility of acoustic cues from the display. A computer monitor displayed a representation of the workspace, including the position of the tactile display (shown as an array of green dots), to facilitate navigation. After a period of familiarization with the apparatus and the experimental procedure, the subject was presented with four virtual textiles chosen from the available set of 16 (each of size 10×10 cm and arranged in the same workspace, see Fig. 1b). In addition, a similar-sized sample of a real textile (the "target") was presented, resting on a horizontal board, also for exploration with the right index finger. One of the four virtual textiles ("correct") was a representation of the selected real textile, the other three ("incorrect") were representations of different real textiles—to avoid visual clues, all the virtual textiles were shown on screen with the same appearance (of the selected real textile). The subject was allowed a free choice of exploratory paths to explore the surfaces, for either the real or virtual textiles, and was permitted to move freely between the target and the four alternatives. (In the familiarization period the subject was encouraged to explore using circular and linear movements.) The subject was instructed to rank the four virtual textiles in order of similarity to the real textile. (The virtual textiles were identified by on-screen labels 1 to 4.) For each subject, this procedure was repeated 80 times: each of the 16 real textiles was compared five times to the "correct" virtual textile, presented alongside five different sets of three "incorrect" virtual textiles (allowing all available comparisons). There was no time limit: the duration of each ranking task was typically in the range 30 to 90 s.

Experiment 2 was identical to Experiment 1, except that the target for comparison with four virtual textiles was itself a virtual textile, rather than a real textile. The intention was to establish whether the alternative virtual textiles could be reliably discriminated in a matching task. The workspace included five 10×10 cm virtual textiles: a centrally placed target and four alternative choices. As in the first experiment, 80 test items included all possible comparisons.

4 Results

In Experiment 1 the mean identification score from subjects' first choices (rank 1) was (41.3 ± 1.6) percent, significantly above the chance score of 25 percent ($p < 0.001$, Student t test). This overall performance is relatively poor. Subjects reported that in practice the real textile was sometimes not a close match to any of the four virtual textiles presented for comparison. In addition, subjects' response patterns suggest that in some cases the real textile was a better match to one of the "incorrect" alternatives than to the "correct" virtual textile. (Mean identification scores for the individual textiles showed considerable variation: the highest was 78 percent and the lowest 23 percent, i.e., close to chance.)

Two highly practiced users (the authors), who were not included in the subject group, achieved an average score of 50 percent on the test material used for Experiment 1, following exactly the same procedure as the experimental subjects. Roughly speaking, they were able to narrow down the alternatives from four to two, but the selection of one from the remaining two was at chance level.

In Experiment 2 the mean identification score for rank-1 choices was (64.1 ± 5.5) percent, significantly above the chance score of 25 percent ($p < 0.001$, Student t test) and significantly higher than the score for Experiment 1 ($p = 0.0012$, Student t test). Subjects were able to perform the matching task quite well, providing evidence to support the suggestion that the difficulties of subjects in Experiment 1 were largely attributable to the inaccuracy of the virtual representations, rather than to the nature of the matching task. The two highly practiced users (not included in the subject group) achieved an average score of 91 percent on the test material of Experiment 2, following exactly the same procedure as the experimental subjects. It may be that these practiced users employed a different strategy to the members of the subject group, taking advantage of the range of spectral, spatial and directional cues provided by the system, rather than relying only on the more obvious cues provided by overall sensation magnitude. Given the wide range of cues provided by the system, it seems likely that new users can learn to obtain more information from the system with extended use.

Experiment 2 involves matching of virtual textiles only, and so the means of subjects' rankings (1 to 4) provide measures of dissimilarity between the various pairs of virtual textiles. The ALSCAL algorithm of the SPSS statistical software package (IBM Corporation) was used to produce perceptual spaces of 1, 2, 3, 4 and 5 dimensions in which the virtual textiles were positioned on the basis of these dissimilarity measures. (Non-metric solutions were implemented, which optimized the match between rank orders of the dissimilarity measures and the corresponding inter-point distances.) Fig. 3b shows the two-dimensional solution (the configuration of points can be rotated as its angular position is not uniquely determined); the addition of further dimensions produces some improvement to the overall fit, but at the expense of complexity in interpretation.

Attempts were made to match the dimensions of this perceptual space to various objective properties of the virtual textiles, in terms of the correlation between these properties and coordinates in the perceptual space. The selected properties included the mean values of the stimulus amplitudes A_{40} and A_{320}, anisotropy between the four principal directions in the surface, and spatial variation over the 1 mm array that specifies the surface. The mean amplitudes A_{40} and A_{320}—perhaps the most obvious choice—provide a relatively successful match. The 2D plot of these values in Fig. 3a can be compared to the configuration of the textiles in the 2D perceptual space. This is shown in Fig. 3b at the angular position which gives the best match: the correlation coefficient between the mean values of A_{40} and the values of dimension 1 in the perceptual space is 0.93 (it can be seen from Fig. 3 that the ordering of the virtual textiles along the A_{40} axis and the ordering along the dimension-1 axis is very similar); the correlation coefficient between the mean values of A_{320} and the values of dimension 2 in the perceptual space is 0.55 (the ordering of the virtual textiles along the A_{320} axis and the ordering along the dimension-2 axis show similarities, but some textiles do not follow this pattern). It should be noted that the configuration of mean amplitudes A_{40} and A_{320}, calculated in Fig. 3a for a typical exploration speed of 10 cm s^{-1}, would be different if calculated for a different exploration speed. Consequently the comparison with Fig. 3b, for the case in which each subject may use speeds higher and lower than 10 cm s^{-1}, is not straightforward.

If the objective measures are instead chosen to be the sum and difference of the mean amplitudes A_{40} and A_{320}, an equivalent match is observed if the perceptual space in Fig. 3b is rotated by 45 degrees. In this case the principal perceptual dimensions may be interpreted as overall stimulus intensity (sum of low-frequency and high-frequency amplitudes, A_{40} and A_{320}) and overall spectral balance (difference between A_{40} and A_{320}).

5 Discussion and Conclusion

Anecdotal reports from the experimental subjects (together with questionnaire results and comments recorded at a demonstration to the public [34]) indicate that the multiple contactors of the tactile array provide touch sensations that are "textile-like". This suggests that matching of real and virtual textiles is possible in principle. In addition, the results for the matching of virtual textiles in Experiment 2 (and particularly the high scores of the two practiced subjects for the same task) suggest that the 16 virtual textiles can be discriminated from each other. Consequently, as suggested above, it seems likely that the difficulties of subjects in matching real and virtual textiles in Experiment 1 are largely attributable to the inaccuracy of the virtual representations, rather than to the nature of the matching task. It may be concluded that, although the Kawabata surface-roughness data can be used to produce generic representations of textile surfaces, they do not provide a basis to accurately represent a particular textile. However, the nature of the matching task puts great demands on the performance of the software and hardware: the differences between some of the real textiles are not very marked, and it may be unrealistic to expect these differences to be reproduced with sufficient accuracy to avoid confusions—the virtual textiles used for Experiment 1 might be adequate in a less demanding context.

The Kawabata system [32] also measures variation in surface friction over the textile; it is possible that a software model incorporating friction as well as roughness will produce a more realistic virtual representation. However, a better strategy may be to use data extracted from the textile surface by a probe which is a closer model of the human finger than that used in the Kawabata system. Such an "artificial finger" [35], [36] has embedded transducers to register signals corresponding to those detected by touch receptors in the skin. This type of device may in any case be necessary to extend the present work to surfaces other than textiles.

The investigation by Culbertson et al. [21] has similarities to the present study: it involves software models of textures which are derived from probe measurements on the original surfaces (rough plastic, canvas, floor tile, silk, and vinyl), and uses a 2D workspace. However, rather than using a tactile array, touch stimuli are delivered via a single actuator in a scenario which represents exploration of the surface with a tool. In pairwise comparisons, virtual and real versions of the same surfaces were rated as similar, and virtual and real versions of different surfaces were rated as similar in some cases and dissimilar in others—this suggests that a matching task with the same stimuli might produce similar confusions to those observed in Experiment 1 of the present study.

Together with the two-component (40 and 320 Hz) stimuli, the 24-channel tactile display used in this investigation can provide a range of discriminable textures, as well as giving information about the position of the edges and corners of virtual objects on the fingertip. The device is easy to use and is readily accepted by new users. However, a commercial application of this system may require a different choice of drive mechanism since the present stacks of piezoelectric bimorphs are inconveniently large.

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