Psychophysics experiments on a tactile renderer

Ian R. Summers and Alan C. Brady

Abstract— **In the context of a virtual environment, in response to actions of the user, a tactile renderer generates drive waveforms for each contactor of the tactile stimulator which is in contact with the user's skin. The intention is to produce time-varying excitation patterns in the various populations of touch receptors in the skin, so as to reproduce the sensations which are experienced during "real" tactile exploration. This paper describes psychophysics measurements using a rendering scheme based on signal components at 40 Hz and 320 Hz only. In an "odd-one-out-from-three" task, subjects were required to discriminate relatively small changes in the amplitudes of these signal components. Data were obtained for different mixtures of the 40 Hz and 320 Hz components, and for different types of spatial variation over the virtual surface. Results show generally good discrimination of changes in the surface and a complex interaction between spectral and spatial aspects of the stimulus.**

I. Introduction

NATURAL touch perception involves a mechanical disturbance of the skin which varies with time and with position on the skin surface. Touch sensations are produced when this mechanical disturbance is detected by the various populations of touch receptors, located close to the skin surface. Similarly, virtual touch sensations can be produced by a touch stimulator, in the form of an array of moving contactors on the skin, which provides appropriate spatiotemporal patterns of mechanical disturbance. The intention is not to use the contactor array to reproduce the surface topology of "real" objects – the goal is to produce an appropriate excitation pattern over the touch receptors in the skin. A working bandwidth of around 10 to 500 Hz is required for the drive mechanism of each contactor in the array, corresponding to the frequency range over which the various touch receptors are sensitive. In practice, such an array forms part of a haptic interface (see Figure 1), integrated with a force-feedback device which represents the gross mechanical properties of the virtual object. Encounters with virtual objects, during active exploration of the workspace by the user, produce appropriate patterns of touch stimulation on the skin.

The 24-contactor array used in the present study requires 24 independently specified analogue drive signals, each within the working bandwidth of around 500 Hz. The amount of data to be generated "on-the-fly" may therefore be considerable. However, for the present study the data required have been much reduced by driving each contactor with a mixture of only two sinewaves, at 40 Hz and 320 Hz. The drive signal to each contactor is specified by the amplitudes of the two sinewave components. A virtual tactile surface is specified in terms of amplitude maps for each of the two frequency components. The present study is designed to investigate the subjective aspects of the virtual surfaces which may be generated in this way.

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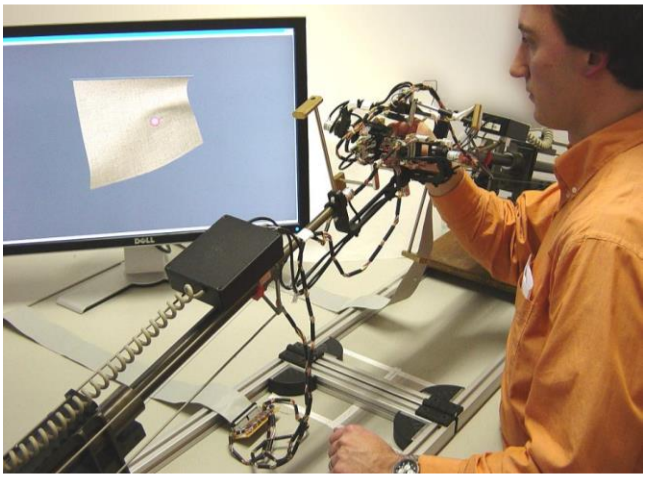

Figure 1. The prototype HAPTEX system for virtual textiles [1]. The finger and thumb of the user manipulate the virtual textile and receive force feedback to represent the gross mechanical properties of the fabric and tactile feedback to represent the surface properties. Tactile feedback is spatially distributed, with 24 contactors on each fingertip. The modelled movement of the entire textile is shown on the visual display.

II. Experimental methods

A. Overview

In the present study, virtual surfaces are explored within a two-dimensional workspace. The test subject rests the index finger of the right hand on a contactor array (see Figure 2) whose movement in the workspace is shown on a monitor screen (see Figure 3). Positional information is obtained via a graphics tablet. Drive signals to the contactors are generated in response to movements of the array within the workspace, giving the sensation of a textured surface under the finger.

B. Stimuli

Virtual surfaces are specified on the basis of a strategy developed within the HAPTEX project (EU IST-6549) on virtual textiles [1, 2]. In that case, surface properties of the

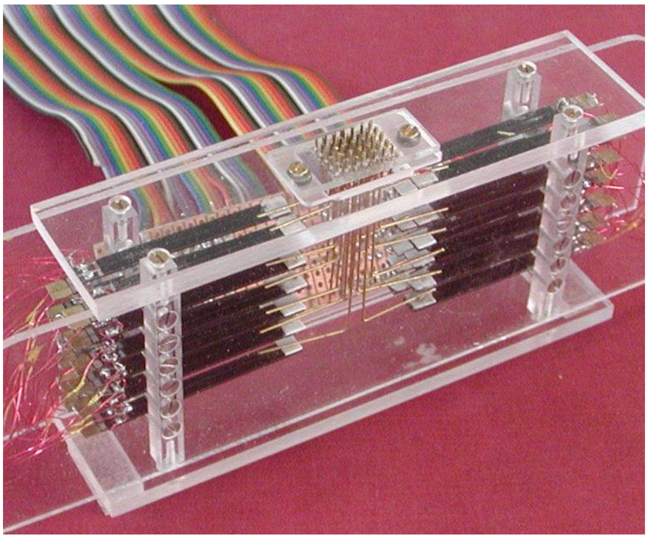

Figure 2. The tactile stimulator; the contactor surface is top centre (6×4 contactors at 2 mm spacing); the black elements are the piezoelectric bimorphs which move the contactors.

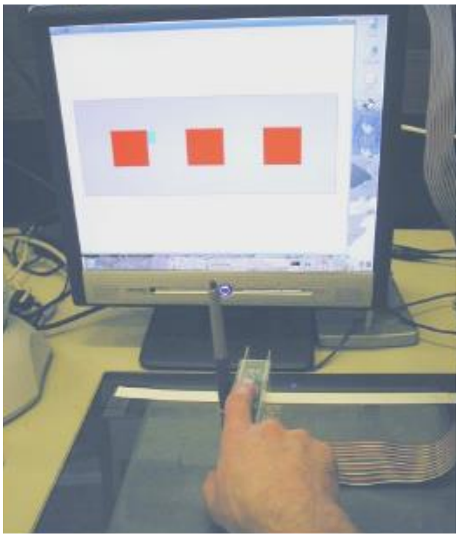

Figure 3. The 2D workspace, showing the index finger resting on the tactile stimulator, the graphics tablet which provides positional information and the visual display which shows the position of the exploring finger in relation to the surfaces available for exploration.

textile were specified as:

(1) a small-scale description of the surface, at 0.01 mm resolution over an area of a few mm^2, represented as 2D *k*-space;

(2) a large-scale description of the non-uniformity of the surface, specified at 1 mm resolution over an area of several tens of cm^2.

For the present study, stimuli are specified in terms of :

(a) baseline amplitudes A_{40} and A_{320} for stimulus components at 40 Hz and 320 Hz, determining the mean intensity and spectral balance of the stimulus;

(b) a description of the spatial variation of the surface, at 1 mm resolution, determining local variations in intensity of the signal specified by (a).

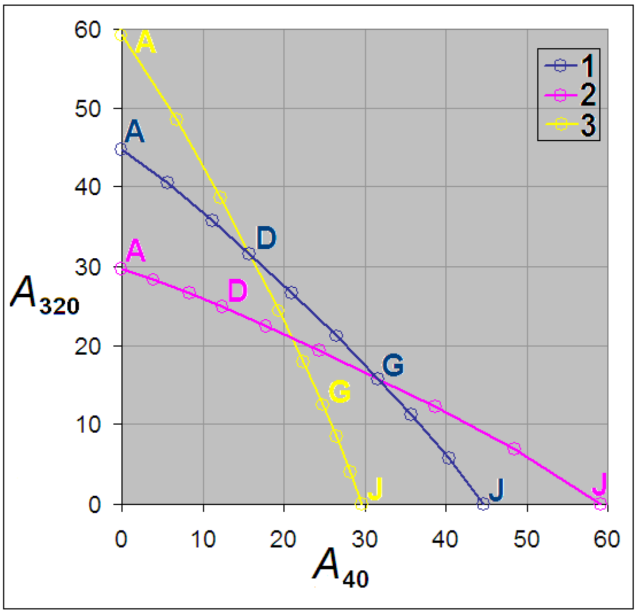

Figure 4. The circles indicate the baseline amplitudes A_{40} and A_{320} for the various virtual-surface stimuli. They lie on three trajectories: 1, 2 and 3, at ten positions labelled A to J on each trajectory. For each baseline-amplitude combination, two stimuli were prepared with different spatial variation over the surface (see text for details), giving 60 virtual surfaces in all. The axes are labelled in arbitrary units, normalised between the two scales for approximately equal subjective intensity.

A range of virtual-surface stimuli was selected for investigation. Baseline amplitudes A_{40} and A_{320} for these are shown in Figure 4. It can be seen that the stimuli lie on three trajectories:

- at ten positions on trajectory 1 (labelled A to J, see Figure 4), intended to produce the same subjective intensity (on the basis of preliminary measurements), separated by steps of spectral balance which are intended to be approximately equal (subjectively);
- at ten positions on trajectory 2 (also labelled A to J) with the same spectral balance as those on trajectory 1 (same A_{40}: A_{320} ratio), but with subjective intensity intended to increase as the spectral balance moves away from 320 Hz and towards 40 Hz.
- At ten positions on trajectory 3 (again labelled A to J) with the same spectral balance as those on trajectory 1 (same A_{40}: A_{320} ratio), but with subjective intensity intended to decrease as the spectral balance moves away from 320 Hz and towards 40 Hz.

Two sets of stimuli were prepared for each of these 30 baseline-amplitude combinations, using two different types of spatial variation over the virtual surfaces:

- *uniform* – no spatial variation;
- *Gaussian* – random intensity fluctuations over the surface, standard deviation 2 dB, range ± 4 dB.

(Spatial variation is specified at 1 mm resolution, as mentioned above. However, variation in the Gaussian case is low-pass filtered to match the 2 mm resolution of the information presented to the skin by the contactor array.)

The experiment involves discrimination between pairs of stimuli along one of the three trajectories shown in Figure 4. From the ten stimuli along a particular trajectory, pairs were selected with different step sizes (i.e., separated by different numbers of steps along the trajectory):

- "step size 1" pairs BC, EF and HI (for each of the three trajectories and for the two types of spatial variation, i.e., 18 pairs in total);
- "step size 2" pairs BD, EG and GI (similarly 18 pairs in total);
- "step size 3" pairs AD, DG and GJ (again 18 pairs in total).

These pairs were selected to include stimuli over different spectral ranges:

- pairs BC, BD and AD (for each of the three trajectories and for the two types of spatial variation, i.e., 18 pairs in total) have spectral balance in the "high" range – the 40 Hz component is dominated by the 320 Hz component;
- pairs EF, EG and DG (similarly 18 pairs in total) have spectral balance in the "mid" range – the 40 Hz and 320 Hz components are approximately equal in subjective intensity;
- pairs HI, GI and GJ (again 18 pairs in total) have spectral balance in the "low" range – the 40 Hz component dominates the 320 Hz component.

C. *Procedure*

Discrimination of each stimulus pair involved an "odd-one-out-from three" task with three virtual surfaces presented within the workspace, two the same and one different (see Figure 5). The test subject was asked to explore the virtual surfaces, following a similar exploratory path to that shown in the figure, using a constant speed of exploration (so that a single pass took around 10 s). Over a series of test blocks, six samples of each stimulus pair were presented to each subject, i.e., 324 pairs in all.

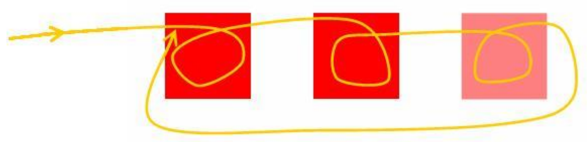

Figure 5. Diagram of the workspace for the "odd-one-out-from three" task, showing the intended form of exploratory movement.

III. RESULTS AND DISUSSION

The experimental variables are step size (1, 2 or 3), spectral range (low, mid or high), trajectory (1, 2 or 3) and spatial variation (uniform or Gaussian). Figure 6 shows the mean discrimination scores from eight young adult subjects as a function of step size. All of these scores are well above the chance score of 33%, even for stimulus pairs differing only slightly in spectral balance and intensity (step size 1). As expected, scores rise as the step size increases. Analysis of variance (ANOVA) shows the main effect of step size to be significant ($p<0.001$). Calculated mean values for discrimination index *d'* are as follows: *d'* = 1.31 for step size 1; *d'* = 2.45 for step size 2; *d'* = 2.99 for step size 3. The interactions between step size and the other experimental variables are found to be not significant.

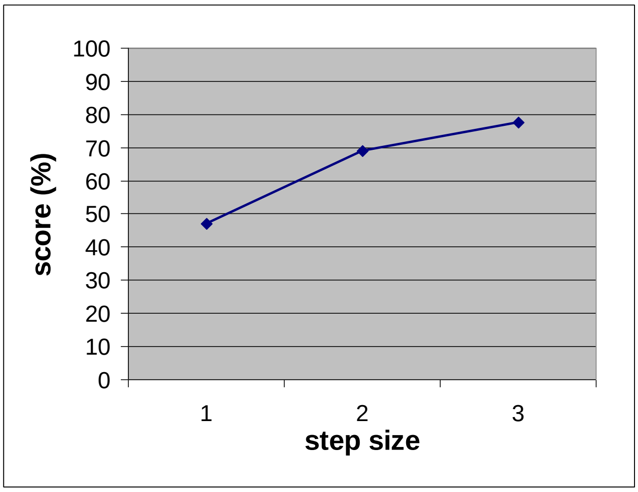

Figure 6. Mean discrimination scores from eight subjects as a function of step size (data pooled over other experimental variables). The chance score is 33%.

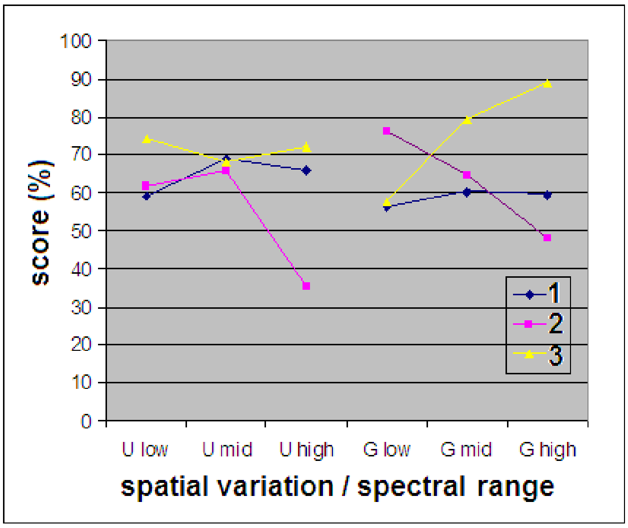

Figure 7. Mean discrimination scores from eight subjects for stimulus pairs on the three trajectories (1, 2, 3), as a function of spectral range (low, mid, high). The lines on the left show scores for stimuli with uniform spatial variation (U); the lines on the right show scores for stimuli with Gaussian spatial variation (G). Data are pooled over step size. The chance score is 33%.

Figure 7 shows mean discrimination scores from the eight subjects as a function of spectral range, for stimulus pairs on the three trajectories and with both uniform and Gaussian spatial variation. Data are pooled over step size. The average discrimination score for pairs on trajectory 3 is 72%, compared to averages of around 60% for trajectory 1 or trajectory 2. Analysis of variance shows the main effect of trajectory to be significant ($p<0.001$). The average discrimination scores for each spectral range (low, medium, high) are similar, as are the average scores for uniform and Gaussian stimuli.

The data in Figure 7 display a complex interaction between the experimental variables. For example, in the case of Gaussian spatial variation (lines to the right of the figure), scores show little variation with spectral range for discrimination along trajectory 1, but fall with spectral range (i.e., from left to right) for discrimination along trajectory 2, and rise with spectral range for discrimination along trajectory 3. A different pattern is observed in the case of uniform spatial variation (lines to the left of the figure). Analysis of variance shows this interaction of trajectory, spatial variation and spectral range to be significant ($p<0.001$).

There is another form of interaction between the spatial and spectral aspects of the stimuli – the Gaussian spatial variation is much easier to perceive in surfaces where the 320 Hz component dominates than in surfaces where the 40 Hz component dominates (although this does not effect the results of the present experiment in any obvious way).

For both the uniform and Gaussian cases, the cumulative discrimination index along trajectory 3 is around 11.0, compared to values of around 9.0 for trajectory 1 or trajectory 2. These values indicate the numbers of just-discriminable steps along the various contours, suggesting that a substantial number of distinct virtual surfaces is available within the overall perceptual space offered by this rendering strategy.

REFERENCES

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[2] D. Allerkamp, G. Böttcher, F.-E. Wolter, A. C. Brady, J. Qu and I. R. Summers, “A vibrotactile approach to tactile rendering,” *The Visual Computer*, vol. 23, pp. 97–108, 2007.

APPENDIX: SECOND EXPERIMENT

In this experiment subjects were required to discriminate the contrast between uniform surfaces and non-uniform surfaces with random (Gaussian) spatial variation of intensity, in an odd-one-out-from-three task (using a similar procedure to the first experiment). There were two experimental conditions: (i) non-uniform surfaces with standard deviation 1 dB, range ± 2 dB, (ii) non-uniform surfaces with standard deviation 2 dB, range ± 4 dB. The spectral content of stimuli was varied (corresponding to positions A, D, G and J in Figure 4). Results from six young adult subjects are shown in Figure A1. The main effect of Gaussian amplitude (i.e., range of intensity variation) is significant ($p = 0.021$), i.e., the spatial non-uniformity is more apparent at the higher amplitude; the main effect of spectral content is significant ($p = 0.025$), i.e., the spatial variation is more easily detected at high frequencies (320 Hz) than at low frequencies (40 Hz).

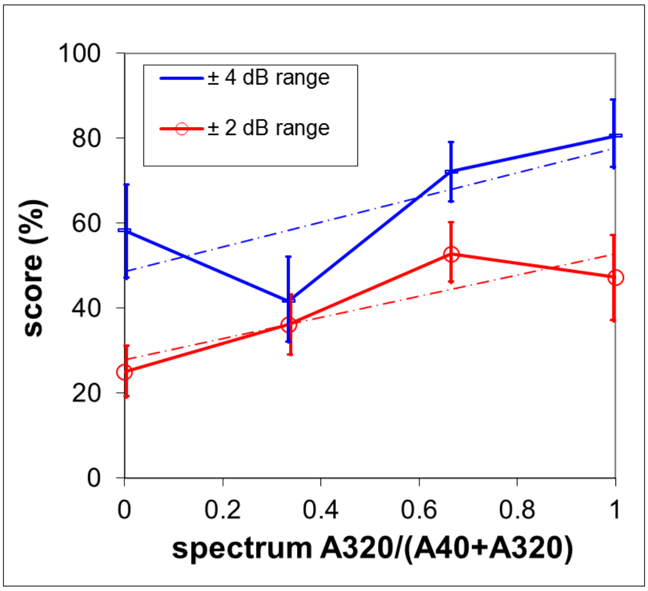

Figure A1. Mean discrimination scores from 6 subjects for the contrast between uniform and non-uniform stimuli, the latter with intensity variation of range ± 4 dB (blue) or ± 2 dB (red). The horizontal axis represents the spectral content of the 40 Hz + 320 Hz stimuli, running (left to right) from 40 Hz only to 320 Hz only. The chance score is 33%.