Results from a Tactile Array on the Fingertip

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Abstract

Data from a 100-contactor tactile array on the fingertip (1 mm × 1 mm matrix) suggest that it may be possible to target different receptor populations in the skin by using different frequencies of vibratory stimulation (40 Hz and 320 Hz). Results from perception of a moving target within a uniform "background" vibration indicate that there is greater spatial acuity for perception at 320 Hz than at 40 Hz. In the absence of a background vibration, discrimination between moving-bar stimuli presented at resolutions of 1 mm, 2 mm and 3 mm is difficult, particularly at 40 Hz, suggesting that a 100-contactor tactile array may offer little advantage over a 25-contactor array (2 mm × 2 mm matrix) in some contexts.

1. Introduction

In "natural" touch perception, sensations are produced by spatiotemporal patterns of mechanical disturbance at the skin surface. At Exeter we have developed a stimulator array which is designed to simulate such sensations on the fingertip by artificially generating the appropriate patterns of tactile stimulation. The spatial resolution required for stimuli is determined by the density of touch receptors in the skin – around 1 mm^{-2} on the fingertip. To achieve this, the array has been designed with 100 contactor pins arranged on a 1 mm × 1 mm square matrix over an area of 1 cm^2 which covers the fingertip (see Figure 1). Each contactor is driven by a piezoelectric actuator (see Figure 2) – the 100 drive waveforms can be individually specified in software and are delivered via a purpose-built interface.

In previous tactile arrays, such as the widely used Optacon device, the stimulus waveform from each contactor has generally been limited to a fixed frequency (~250 Hz) at a fixed level, with stimulus patterns produced by simple on/off keying. The Exeter array has a significant advantage in this respect: within the working bandwidth of 25-400 Hz, a wide variety of stimulus waveforms is possible from each contactor. This allows, for example, targeting of different receptor systems in the skin, which differ in terms of their frequency response [1].

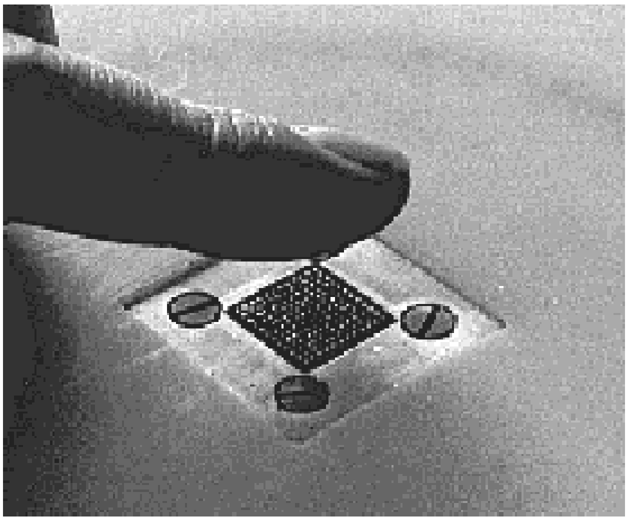

Figure 1. The array has 100 contactors over an area of 1 cm^2. The displacement waveform of each contactor can be individually specified.

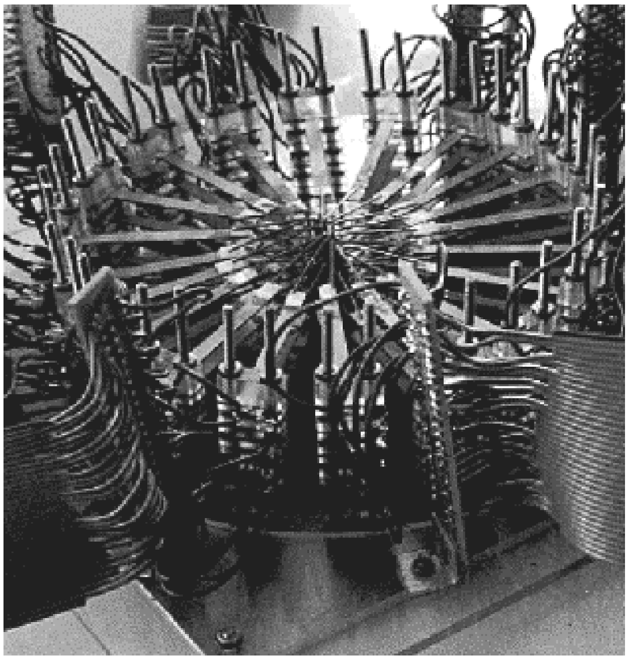

Figure 2. The underside of the array: 100 piezo-electric drivers are arranged in five tiers.

2. First experiment

This is an investigation of the perception of a moving target (created by contactor pins driven at amplitude *S*) against a uniform background (created by the remainder of the array driven at amplitude *N*, with $N < S$).

2.1. Method and results

Subjects are required to identify the direction of motion: up, down, left or right. The target is in the form of a line of *L* array elements (L = 1, 3, 5, 7), moving across the array in a direction perpendicular to the line: a horizontal line moves up or down and a vertical line moves left or right. (For $L = 1$, the "dot" moves in any one of the four directions.) In all cases the target moves from one side of the array to the other in one second, i.e., at a speed of 1 cm per second. In this experiment, all the contactor pins (both target and background) are driven with sinewaves at the same frequency *f*. Half of the test blocks were run with f = 40 Hz and the remainder with f = 320 Hz. These frequencies were chosen in the hope of targeting non-pacinian and pacinian touch receptors, respectively.

With the target amplitude *S* held constant, discrimination scores were determined for 8 subjects as a function of the background amplitude *N*. Curve fitting with a suitable psychometric function was used for each of the 8 test conditions (4 values of *L* with two values of *f*) to obtain in each case an estimate of the critical background amplitude at which the targets are just discriminable. This was specified as the value of *N* corresponding to a discrimination score of 62.5 % (i.e., halfway down the psychometric functions, which run from 100 % to the chance score of 25 %). Figure 3 shows these values of critical background amplitude (in arbitrary units, with S = 120 in the same units).

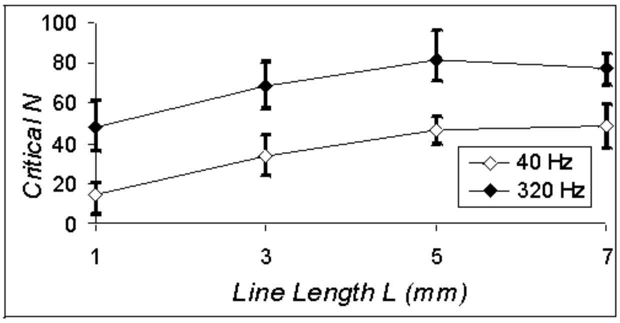

Figure 3. Critical values of background amplitude *N* (at which the direction of movement of a target of amplitude *S* = 120 is discriminable with 62.5 % success rate [chance = 25 %]) as a function of length of the target line. Data are shown for stimulus frequencies of 40 Hz and 320 Hz.

At 320 Hz, amplitude 100 corresponds to around 4 microns peak-to-peak, hence the target at amplitude 120 corresponds to around 5 microns peak-to-peak; at 40 Hz, amplitude 100 corresponds to around 40 microns peak-to-peak, hence the target at amplitude 120 corresponds to around 50 microns peak-to-peak. The conversion between displacement amplitude and sensation level is not straightforward – the detection threshold varies with stimulation area (and presumably varies differently at the two stimulation frequencies). However, the bar stimuli are all at a "comfortable" sensation level and the 1:10 ratio of the amplitudes at 320 Hz and 40 Hz means that corresponding 40 Hz and 320 Hz stimuli are at roughly the same sensation level.

2.2. Discussion

Both data sets flatten at a line length of 5 mm (i.e., L = 5). This value may relate to the size of the receptive fields involved in the task. There is a significant difference between the data at 40 Hz and at 320 Hz. This suggests that different receptors may have been targeted with the two different stimulus frequencies. Certainly, the sensations are very different: 40 Hz stimuli produce a much better approximation to "real" touch sensations than do 320 Hz stimuli. However, there is a problem with this interpretation in terms of different receptor populations: there are suggestions in the literature that non-pacinian receptors have greater spatial acuity [2], and so it might be expected that discrimination in this "signal-in-noise" task would be easier at 40 Hz than at 320 Hz. However the experimental data suggest that the converse is true: equivalent performance is obtained with much higher background amplitudes at 320 Hz than at 40 Hz, suggesting that spatial acuity is greater at the higher frequency.

3. Second experiment

Future plans include construction of a device to address four fingers and thumb on one hand, each digit with a 5 × 5 array of 2 mm pitch. It is thus of some interest to predict the difference in performance between the present 10 × 10 array and a 5 × 5 array, each addressing 1 cm^2 on the fingertip. Here we describe an experiment on perception of stimuli at different spatial resolutions.

3.1. Method

Test stimuli are in the form of a line of 10 array elements moving across the array at a speed of 1 cm per second in a direction perpendicular to the line. The active contactor pins are driven with sinewaves at frequency *f*. Stimuli move across the array via 9 increments of 1 mm, 4 increments of 2 mm, 3 increments of 3 mm, 2 increments of 4 mm or 1 increment of 6 mm. For each stimulus, subjects are required to identify the spatial pattern of the motion.

Eight volunteer test subjects were trained and subsequently tested for their ability to distinguish between stimuli at the different spatial resolutions. Each subject was presented with eight test blocks; half with $f = 40$ Hz and half with $f = 320$ Hz. At each frequency f, separate test blocks were run for each direction of movement: up, down, left or right. Each block consisted of 20 test items, distributed between the 5 different spatial resolutions. Noise masking via headphones was used to eliminate any acoustic cues.

3.2. Results and discussion

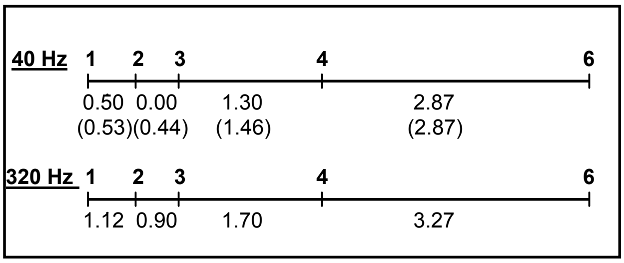

Figure 4. Representation (not to scale) of discrimination index between the five stimulus resolutions. (Data pooled over stimulus direction; upper line: 40 Hz stimuli; lower line: 320 Hz stimuli.) The labels above the tic marks indicate the stimulus resolution in millimetres. The numbers below each line indicate the calculated discrimination index *d'* for neighbouring stimulus types. At 40 Hz the *d'* between 2 mm and 3 mm resolution was calculated as being very slightly negative – this *d'* value was thus forced to zero. A second set of data at 40 Hz, taken in a pilot experiment with a different group of subjects, is shown in brackets.

Data from the identification task were obtained in the form of confusion matrices, indicating the extent to which the five spatial resolutions were distinguishable. No significant differences in performance were observed between the four directions of movement. Hence data were pooled over direction of movement and, using a method similar to that described by Braida and Durlach [3], the pooled confusion-matrix data were processed to obtain values for discrimination index d', as shown in Figure 4. (Note: A d' value of less than 1 indicates that discrimination is difficult; d' values are cumulative, e.g., the d' at 320 Hz for stimuli at 2 mm and 4 mm resolution is $0.90 + 1.70 = 2.60$.)

These data show poor discrimination between stimuli at 1 mm, 2 mm and 3 mm resolution, particularly at 40 Hz. This is an important result, since it suggests that a 10×10 array (1 mm pitch) offers little advantage in this context over a 5×5 array (2 mm pitch) – and the 10×10 array has significant disadvantages in terms of cost, control and ease of construction.

The better performance for 320 Hz stimuli, compared to that for 40 Hz stimuli, can be related to the fact that discrete "jumps" in the moving 320 Hz stimuli are reported to be clearly detectable at all resolutions, whereas these jumps are only apparent in the 40 Hz stimuli at the lower resolutions.

4. Conclusion

Each experiment provides evidence, albeit indirectly, that the position of moving stimuli on the skin is more accurately perceived at 320 Hz than at 40 Hz. It is possible that this relates directly to the nature of the stimulus provided by the array. However, the design of the array provides no obvious mechanism for this, and hence we believe that differences between results at 40 Hz and 320 Hz are attributable to differences in the perceptual mechanism at the two frequencies, and may be explained in terms of the involvement of different populations of receptors.

References

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