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TACTILE DISCRIMINATION OF TEXTURED SURFACES: PSYCHOPHYSICAL PERFORMANCE MEASUREMENTS IN HUMANS

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SUMMARY

1. Psychophysical experiments were designed to assess the tactile discriminative abilities of human subjects when touching textured surfaces.

2. Plastic strips were produced which had raised dots in a square arrangement (standard surface) or in one of a number of rectangular arrangements (modified surfaces) in which the spacing of the dots differed from the standard surface by some constant amount in one direction. Subjects were presented with pairs of surfaces and asked to discriminate whether each pair consisted of (a), two identical standard surfaces, or (b), a standard surface and a modified surface. Performance measurements were analysed using decision theory.

3. When subjects moved their fingers over the surfaces (active touch) their responses were virtually unbiased, and there was a linear relationship between discriminative performance and the difference between the spacing of the dots on the two surfaces. At the 75% correct level, subjects could distinguish surfaces in which the period of the dots differed by only 2%. Performance was virtually independent of the method of movement used, despite large differences in the velocity profiles of the various movements.

4. Experiments in which the surfaces were moved under the subject's stationary finger (passive touch) displayed the same linear relationship between performance and period difference as in the active-touch experiments. Furthermore, the discriminative performance levels were very similar in the two types of experiments. In the passive-touch experiments, subjects could distinguish smaller differences in period in the surface dimension parallel to (along) the direction of movement than they could distinguish in the dimension perpendicular to (across) the direction of movement.

5. The hypothesis is advanced that normal active discrimination of surfaces is made possible by using similar movements in successive surface contacts and a relatively simple neural code.

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INTRODUCTION

A neural code is that aspect, or those aspects, of a neural signal which contain 'behaviourally usable information' (Uttal, 1969, 1973; Johnson, 1980*a*, *b*). Despite such a simple definition, the identification of a neural code is not straightforward. For example, it is not sufficient to show that a particular aspect of some neural response contains information, it must also be shown that the organism can in some way use that information. For this reason, many previous studies on neural coding have used complementary neurophysiological and psychophysical experiments, the former providing data about the form of the neural responses and the latter providing data about the minimum amount of information which the organism actually extracts (Talbot, Darian-Smith, Kornhuber & Mountcastle, 1968; Mountcastle, Talbot, Sakata & Hyvarinen, 1969; Johnson, Darian-Smith & LaMotte, 1973).

It is clear that to relate neural signals to the psychophysical estimates of information transfer, it is necessary to record from all the pathways which might transmit salient information. When a human touches a surface with his fingertips and makes some judgement about that surface, the only pathway for information transmission is via either the median or the ulnar nerve, both of which are easily accessible for neural recording. If the person performs at above chance levels then the necessary information enabling the judgements *must* have been present in the appropriate peripheral neural responses.

This paper describes the psychophysical assessment of the amount of information that a human subject must extract from the peripheral neural signals evoked by touching various textured surfaces, in order to discriminate between such surfaces. The following paper (Lamb, 1983) describes the corresponding neural responses of the three mechanoreceptor populations of the fingertips of anaesthetized monkeys when stimulated by the same surfaces. Hence, assuming a close similarity in the peripheral neural responses of man and monkey, it is possible to examine the adequacy of a number of candidate neural codes in accounting for the observed psychophysical performance.

METHODS

Surfaces. Plastic surfaces were constructed which consisted of square or rectangular arrays of identical raised circular 'dots' with flat tops. All dots were 0·65 mm high. Each surface was produced by using a computer controlled plotter to draw, at 15 × final scale, an array of circles of the appropriate diameter and spacing. The resulting patterns were photographically reduced (by a factor of approximately 2·5), and a number of identical copies of each reduction were then precisely joined using a magnifying lupe. The procedure of reduction and joining was then repeated twice until elongated strips were obtained which had dimensions identical to the desired plastic surfaces. Photographic negatives of the final reductions were used to produce plastic surfaces by the technique described by Darian-Smith & Oke (1980). The final surfaces were inspected under the microscope; no aberrations in the microstructure were observed, and all dots seemed virtually identical at 100 × magnification.

The standard (square array) patterns had periods (centre to centre spacings) of either 1·0 or 2·0 mm with the dots being one third of the period in diameter. For both period sizes, two different series of modified surfaces were also produced in which the period of the dots in one of the two planar dimensions was made incrementally longer than in the standard surface, by some constant amount. The first series had increases in the period in the dimension corresponding to the intended direction of movement (i.e. *along* the long dimension of the strip) of approximately 1·0, 2·0, 3·0, 5·0 and 8·0% (Fig. 1). The second series had the same incremental increases in the period in the surface dimension perpendicular to, or *across*, the intended direction of movement.

Subjects. In preliminary experiments the four best subjects, out of a total of eight, were selected. All four were female students between 18 and 23 years of age. In all experiments each subject contacted the surface with the index or middle finger of her right hand.

Paradigm. A two-alternative discrimination paradigm was used. In both the active and passive touch experiments, surfaces were presented in pairs and subject were required to respond with either of two equally likely response alternatives after consecutively feeling the two surfaces. If the standard (square array) surface is denoted as A and a modified (rectangular array) surface is denoted as B, the surface pairs can be described as either A,A or A,B, with the subjects always feeling a standard surface (A) first. Subjects were asked to respond either 'A' or 'B' according to whether they thought the second surface in each pair was an A or B surface. Subjects were never asked whether the surfaces of a pair were the same or different. The A,A and A,B pairs were presented in random order with equal probability of occurrence, and hence the paradigm corresponds exactly to one of the special case designs of Johnson (1980*a*) (SSSM). The surfaces were regularly cleaned or replaced with appropriate unused surfaces.

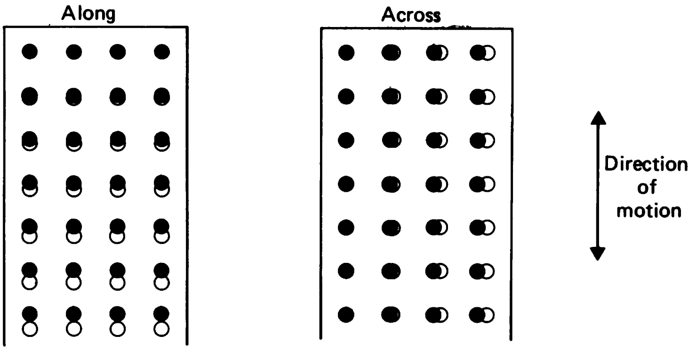

Fig. 1. Simplified diagram indicating the positions of the raised dots in the modified surfaces (open circles) relative to the standard square array surface (filled circles). Modified surface strips were made with the period of the dots 1, 2, 3, 5 or 8% longer than in the standard surface, in either the dimension parallel to (along), or perpendicular to (across), the direction of movement between the skin and the surface. For the active-touch experiments the 2·0 mm period surface strips were approximately 40 dots long and 8 dots wide, and for the passive-touch experiments were 160 dots long and 8 dots wide.

For every experimental condition, the discriminative performance with each modified (B) surface was normally examined with between 160 and 200 presentations of the appropriate surface pairs, although for some easily discriminable surfaces only one hundred presentations were made. Each B surface was investigated using groups of twenty consecutive pair presentations, with the groups for the different B surfaces being randomly ordered within each daily one-hour session. Before each group of twenty test presentations, the appropriate A,A and A,B pairs were repeatedly presented and named to each subject until she thought she clearly recognized the difference or felt she could do no better. Within all practice and test sequences the subject was told whether her response was correct. Furthermore, at any time the subject could ask to again be familiarized with the appropriate surfaces. Typically this occurred once within every twenty presentations.

Active touch

Experiments were performed in which the subject placed her arm through a curtain and actively moved her finger over a pair of surface strips which had been mounted on a card (Fig. 2). Separate cards were made with the appropriate A,A and A,B surface pairs, and on each card the (8 cm × 1·7 cm) strips were identically positioned. Three different methods of active movement were examined (Fig. 2): (a), moving the finger in a single distal-to-proximal sweep with the finger axis *parallel* to the long axes of the strips; (b), moving the finger in a single left-to-right sweep with the axis *perpendicular* to the long axes of the strips, and (c), moving the finger with a *cyclic* motion back and forth two or three times across each strip with the finger oriented as in part (b). For each method the subject used the specified motion first on the A surface and then on the unknown surface, and was then allowed to repeat the procedure once in case there had been any difficulty in guiding the unseen movement. The contact force and the amplitude and speed of motion were entirely under the subject's control.

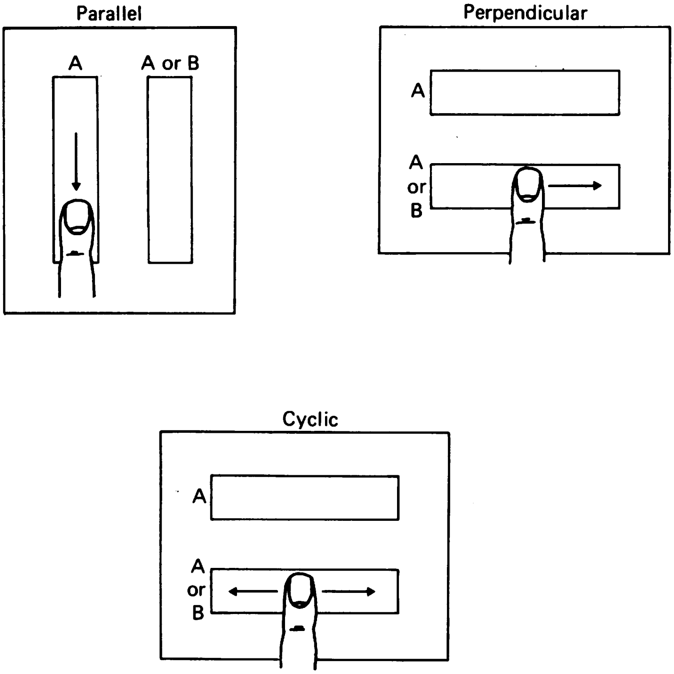

Fig. 2. Three methods of movement used in active-touch experiments. With her hand through a curtain, the subject was required in a particular experiment to use one of the three methods of moving her finger successively over the two surface strips on the present card. The card had either two standard surfaces (two A surfaces) or a standard surface A and a modified surface B, in the positions indicated. For the parallel and perpendicular methods the subject moved her finger in single sweeps in the direction indicated, and for the cyclic method she moved her finger back and forth.

Velocity profile measurement. The velocity profiles used in the three methods of contacting the surfaces were measured in one experimental session for each subject by high-speed photography (Bolex 16 mm camera at 64 frames/sec). During normal discrimination trails the camera recorded the finger movement over three or four consecutive repetitions, for each of the three methods of movement. The developed film was replayed on a film-editing machine, frame by frame, and the finger position was measured on a superimposed scale.

Contact force measurement. The mean contact force used by each subject during normal discrimination was measured in a single experimental session by placing each surface card on a Perspex plate which was connected by a lever to a force transducer and recorder.

Passive touch

Surface strips, with structural dimensions identical to those used in the active experiments, were mounted side by side around the perimeters of a number of interchangeable Perspex drums, each of which had a circumference of 320 mm. Any of the drums could be mounted in a counterbalanced yoke and rotated by a motor at a constant circumferential velocity (40, 73, 145 or 220 mm/sec). Electronic signals indicating the rotational position of the drum were used to control a solenoid which, when retracted, allowed the drum to move upwards and contact the subject's index finger with a constant force (65 or 100 g wt.). The drum could be silently and quickly slid back and forth by the experimenter between any axial positions, so that any particular strip could be positioned under the subject's finger. The finger was supported and constrained by an aluminium structure, approximately 1 mm above the rest position of the drum. Surfaces were presented to the finger once every 4 sec for approximately 1·2 sec (0·3 sec in one experiment). A contact time of 1·2 sec was thought by all subjects to be adequate for discrimination. Subjects had to respond after every second presentation, as described earlier, knowing that the previous strip presented was a standard A surface. Hence the paradigm is the same as in the active-touch experiment, except that subjects felt each surface only once.

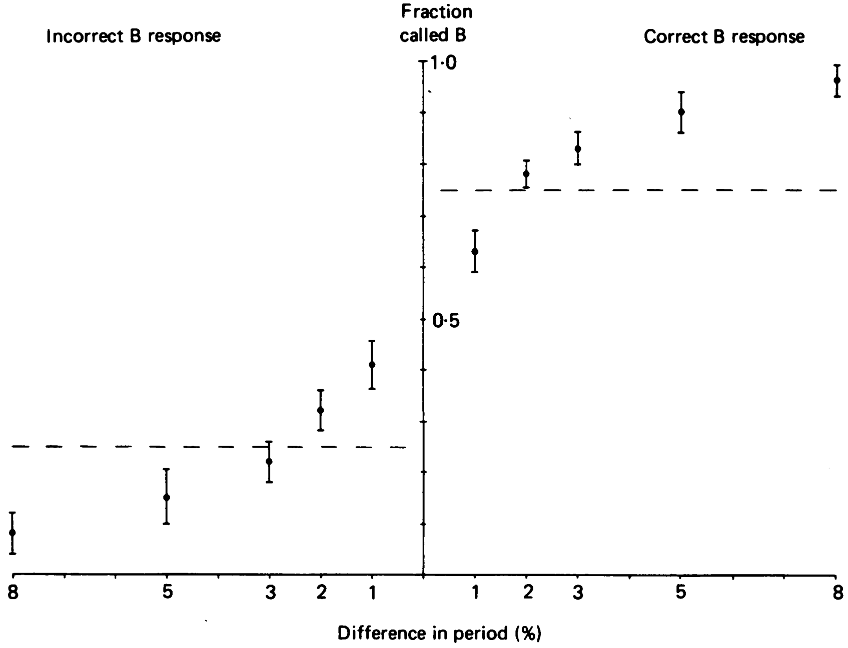

Fig. 3. Psychometric curve for a subject investigating the large-dot (2·0 mm period) 'along' surfaces using the parallel method of active movement. The abscissa displays the percentage difference between the periods of the A and B surfaces, that is, the incremental increase in period in the B surface. For each of the five modified B surfaces, the Figure shows the mean fraction of responses (± 1 S.E. of the mean) in which a correct or incorrect B response was made. The dashed lines indicate 75 % correct performance.

Contact area. The contact area used in both the active- and passive-touch experiments was measured by inking the subject's finger and placing paper on the surface cards or around the stationary drum, as appropriate. Tests with a transparent Perspex drum showed that the contact area changed very little whether the drum rotated or remained stationary.

Analysis. For each group of twenty responses, the fraction of *correct* responses to an A,B pair (F_C) and the fraction of *incorrect* responses to an A,A pair (F_I) were calculated and plotted against the percentage difference between the periods of the A and B surfaces. Graphs of the mean performance were plotted using data from all relevant experimental sessions (Fig. 3). All data was utilized in producing such psychometric functions, as there was no evidence of improvement of performance once the subjects understood the task.

The data was further analysed using decision theory techniques (Johnson, 1980*a*) that use the Z scores corresponding to the fraction of correct and incorrect B responses (derived from standard tables) to identify both the performance level (separation index), d', and the response bias $\bar{Z}$. These are defined as:

$$d' = Z_C + Z_I; \quad \bar{Z} = \frac{Z_C - Z_I}{2},$$

where

$$Z_C = Z \text{ score for } F_C \text{ and } Z_I = Z \text{ score for } (1{\cdot}0 - F_I).$$

The percentage period difference, ΔS, which produces a separation index, d', of 1·35 units is equivalent to the classical difference limen, i.e. difference limen (75 % correct) = ΔS ($d' = 1{\cdot}35$). If a subject has no bias at all, by the above definition $\bar{Z}$ will be zero. If the subject had a bias to responding B, $\bar{Z}$ would be positive.

RESULTS

Active touch

Fig. 4 shows the separation indices (d') obtained for the four subjects using both active and passive touch. A separation index (d') of zero indicates that the subject could not differentiate the two surfaces at all – her performance was no better than chance. The dashed line at $d' = 1{\cdot}35$ corresponds to the 75 % correct performance level, and is used as the arbitrary index of performance in later discussion.

Inspection of the active-touch data in Fig. 4 indicates that: (i), the range of modified surfaces used produced performance ranging from chance ($d' = 0{\cdot}0$) to near perfect performance ($d' = 3{\cdot}0$ is equivalent to 93·3 % correct responses); (ii), for small period differences (less than 3 %), the value of d' is linearly related to the period difference. (It will be shown in the Discussion that the 'saturating' behaviour of d' at larger period differences is merely an exaggeration of a small number of errors at near-perfect performance levels); (iii), such a linear function intersects the origin, indicating that any incremental change in the B surface will produce above-chance discriminative performance. The performance of subjects in discriminating two pairs of identical surfaces (all standard square arrays) is indicated by the symbols on the ordinate axis (0 % period difference). The subjects were not aware that all surfaces were of identical dimensions. The performance levels reveal that the subjects could not distinguish the two pairs of surfaces and hence very little information was provided to the subjects in the form of unintentional 'cues', such as bends in the cards, irregularities in particular surface, noises, etc.; (iv) there was comparatively little variation between the performance measurements of the four subjects.

Comparison of methods of movement in active touch. The sensitivity functions found using the parallel and cyclic methods of movement were virtually identical to that shown in Fig. 4 for the parallel method; the functions were linear for small period differences and showed 'saturation' at large differences (approx. 5 % and above). The $d' = 1{\cdot}35$ intercept of the three functions showed that the incremental increase in period which could be detected at the 75 % correct level of performance were 2·1, 2·0 and 1·8 % of the standard 2·0 mm period for the parallel, perpendicular and cyclic method respectively. The d' data for the three methods, excluding the less reliable 8 % different values, were subject to an analysis of variance to investigate the effect of: (a), method of movement; (b), difference in the stimulus period and (c), subject. The effect of the period difference and subject were both found to be significant

($P < 0.01$), and the effect of the method of movement was not significant ($P > 0.05$), although higher order factors involving the method (period difference × method, subject × method) were significant. To quantify the relative effect of each factor, values expressing the 'proportion of variation' due to each were calculated by dividing the sum of the squares due to each factor by the total sum of the squares.

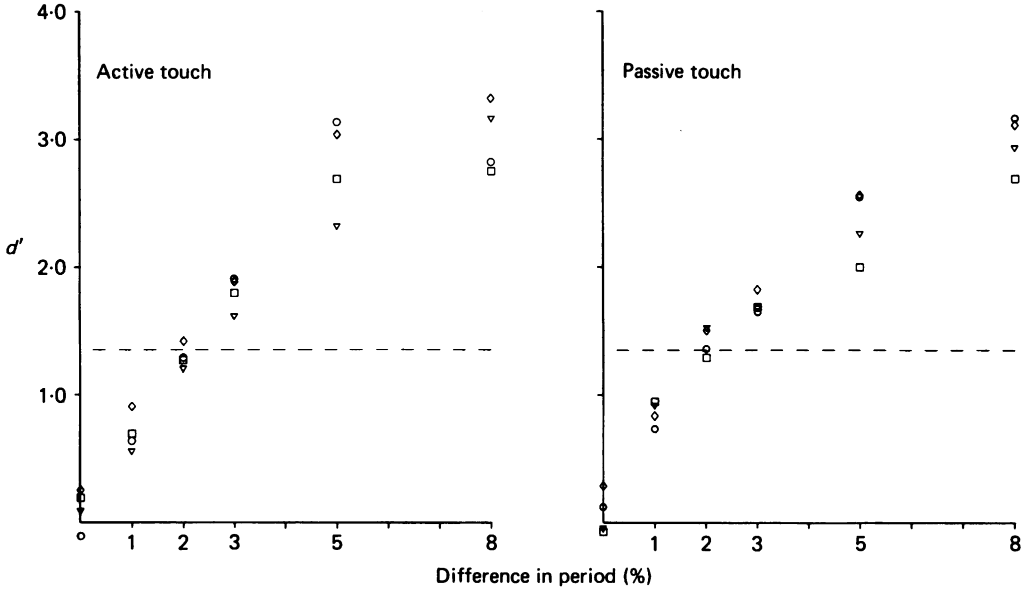

Fig. 4. Separation indices (d'), in standard deviation units, for each of the four subjects when attempting to discriminate between a standard surface (A) and one of a number of modified surfaces (B), using active- or passive-touch. The abscissa of both graphs indicates the percentage increase in the period of the dots on each B surface relative to the A surface. The standard surface (A) had dots in a square array with a 2·0 mm period; incremental period changes were made in the 'along' dimension (Fig. 1). Subjects used the parallel method of active-touch (Fig. 2). The dashed line at $d' = 1.35$ indicates the 75 % correct performance level. The velocity of surface movement was 73 mm/sec in the passive-touch experiment.

In this manner the size of the period difference directly accounted for 88·7 % of the total variation, and the subject directly accounted for 2·1 %. The sum of the proportions of variation due to the direct effect of method and both higher order factors involving method was only 5·7 %. Hence, it can be said that the discrimination was relatively unaffected by both the particular subject involved and the method of movement used actively to examine the surfaces.

Velocity profiles. Some examples of the velocity profiles used by the subjects in actively touching the surfaces are shown in Fig. 5. The estimate of the instantaneous velocity in each frame was made by measuring the distance the finger moved between each frame and the previous frame, and is only accurate to the nearest 2 cm/sec. Fig. 5*A* shows the velocity profile of a subject using the parallel method for two consecutive sweeps, and Fig. 5*B* the profile for the same subject using the perpendicular method for three consecutive sweeps. It is apparent that, though the subject used a similar movement in consecutive sweeps within each method of movement, there were substantial differences between the velocity profiles for the parallel and perpendicular methods. Furthermore, there were only relatively short periods (approx. 0·1 sec) over which the velocity was constant to within 5%. The other three subjects also showed: (a), an ability to reproduce similar movements in consecutive sweeps; (b), substantially different velocity profiles for the parallel and the perpendicular methods of movement, and (c), only short periods of constant-velocity movement.

An even larger difference between profiles was apparent when the movements used by different subjects were compared. For instance, Fig. 5*C* shows that the subject used a constantly accelerating motion when examining a surface with the perpendicular method, though with the parallel method the profile exhibited periods of relatively constant velocity similar to that in Fig. 5*A*. The cyclic method profiles could be characterized as being roughly sinusoidal or saw-toothed, though the peak velocities and amplitudes were quite different for the different subjects (Fig. 5*D*, *E*).

The mean velocities used by the four subjects with the parallel method of movement, the method most closly resembling that used in the following passive-touch experiments, were approximately 100, 160, 170 and 200 mm/sec.

Other active-touch experiments. Two further experiments were conducted using the parallel method of active touch. In the first, subjects again contacted large-dot (2·0 mm period) surfaces, but the period had been incrementally changed in the dimension perpendicular to, or 'across', the direction of motion. The form of the d' function was virtually identical to that seen for the 'along' series of surfaces, that is, it was linear for small period differences and showed 'saturation' with larger differences, and had an intercept with the ordinate approximately at the origin. However, the period difference required to produce 75% correct performance ($d' = 1{\cdot}35$) was 2·8% and was thus considerably larger than that seen for the 'along' dimension.

The final active-touch experiment involved surfaces with much smaller surface detail (one third of 1·0 mm diameter dots; period of standard surface was 1·0 mm). The shape of the sensitivity function was the same as those previously described, and 75% correct discrimination was seen for surfaces which differed in their period by 2·5%.

Passive touch

The discriminative performance of the same four subjects was examined for the passive-touch mode usually using a contact force of 65 g wt. and a contact time of 1·2 sec (Fig. 4). Such values of contact time and force were thought by all subjects to be adequate for discrimination. The form of the function in Fig. 4 is almost identical to that found in the active-touch experiments, as was the case in all passive-touch experiments. Furthermore, as in the active-touch experiments, the ability of subjects to discriminate different surfaces of identical dimensions (0% difference) was investigated and found to be no better than chance. In Fig. 6*A* the period differences which produced 75% correct performance in the passive-touch experiments are plotted against the velocity of movement used. Some active-touch

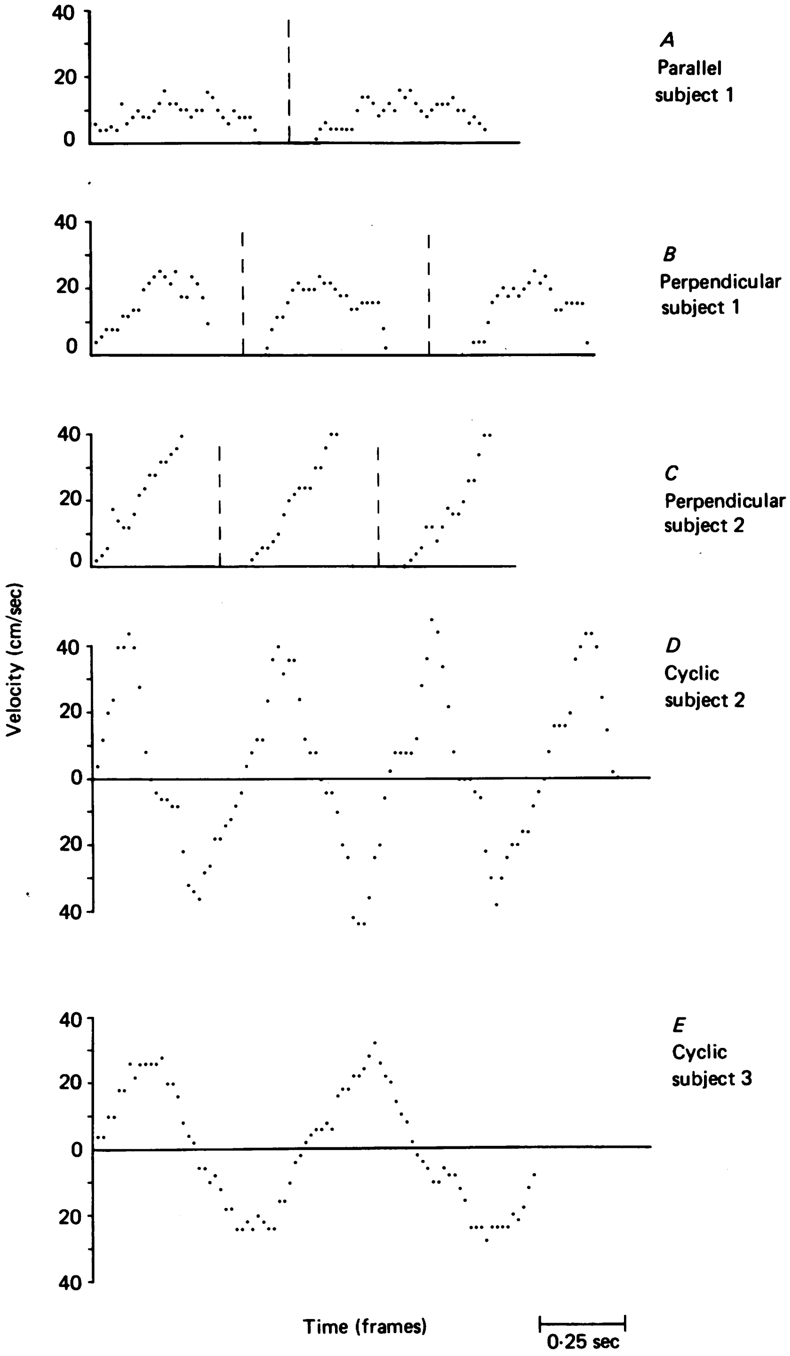

Fig. 5. Velocity profiles used by some subjects when actively touching the large-dot surfaces. Each dot represents the instantaneous velocity of finger movement (± 12 cm/sec) between successive photographic frames 1/64th of a sec apart. The vertical dashed lines in *A*, *B* and *C* separate the profiles for consecutive finger movements.

data are also shown. In Fig. 6*B* the passive-touch data obtained using the 'along' surface series are replotted against the frequency with which the lines of dots struck the skin. The significance of such a plot against frequency will be raised in the Discussion in terms of vibratory frequency discrimination.

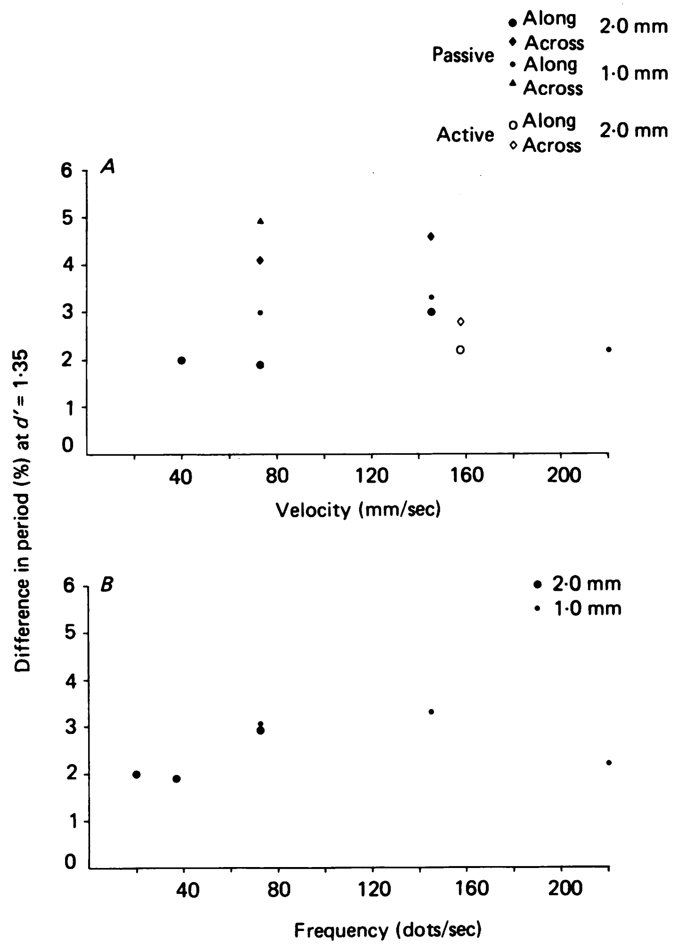

Fig. 6. Summary of the mean values of the period increment, for the four subjects, which could be discriminated at the 75 % correct level ($d' = 1{\cdot}35$). In *A*, the values for the passive experiments are plotted against the velocity of surface movement used, and the values for the active-touch experiments using the parallel method of movement are plotted at the mean velocity used by the four subjects as determined by high-speed photography. *B*, shows the same data for the passive presentation of the large and small dot 'along' surfaces plotted against the frequency with which the lines of dots struck the skin.

Bias

The mean biases for each value of period difference were calculated from the data for all subjects and all stimulation conditions, and these are shown in Fig. 7. Inspection of the corresponding graphs for the individual conditions of active and passive touch, and for 1·0 mm and 2·0 mm period surfaces, showed the same constancy of bias across the range of period differences, although the mean values for the individual conditions ranged from +0·086 to −0·056 standard deviation units. The largest mean bias seen (0·086) corresponds to a subject giving an average 10·6 B responses and 9·4 A responses in a group of twenty presentations. The constancy of the bias means that the subjects adjusted their criterion for distinguishing A and B with each new B surface.

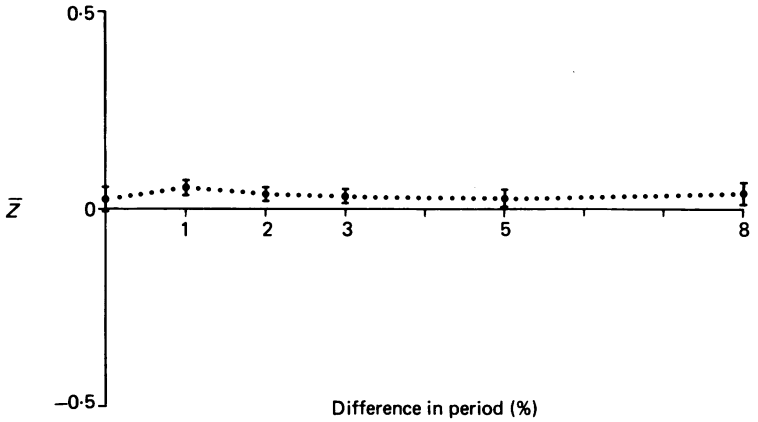

Fig. 7. Mean bias (±1 s.e. of the mean) for all four subjects under all experimental conditions, plotted against the difference in the period between the A surface and the appropriate B surface (see also legend of Fig. 4).

The effect of contact force and area

The importance of contact force in surface discrimination was investigated by repeating the passive-touch experiments with the 2·0 mm 'along' surfaces using 100 g force instead of 65 g. The mean performance was unchanged, as a period difference of approximately 1·9 % produced 75 % correct performance. However, examination of the data for the individual subjects indicated that the unchanged mean performance, when using 100 g force, was the result of one subject improving performance, one showing a decrease in performance, and two showing little change.

The areas of skin in contact with the drum were measured at 65 g force for each subject and were approximately 53, 63, 64 and 92 mm^2. These areas were dependent on the sizes and shapes of the subjects' fingers, as well as on the amount each subject chose to have her finger protruding past the support. These areas were also found to be virtually unchanged when measured in the case of 100 g force.

When the performance was correlated with the contact area it was found that the subject whose performance dropped when using 100 g force had the least contact area, and consequently the greatest pressure on her finger. Similarly the subject who had improved her discrimination with 100 g force had the greatest contact area, and consequently least pressure on her finger at 65 g force. Thus it might be hypothesized that performance was unaltered if the pressure of contact was between 0·9 and 1·4 g/mm^2, and decreased if pressures greater or smaller than this range were used.

In support, the mean forces used by the subjects in *actively* investigating the surfaces corresponding to pressures of: 0·9, 1·3, 1·3 and 1·2 g/mm^2. This illustrates that when choosing the force themselves the subjects used pressures in the range found to give optimal performance in the passive-touch experiments.

Effect of contact time

To examine how much information was conveyed to the subject in the initial contact with the surface, the performance was examined when the contact time was only 0·3 sec. The performance was only determined after considerable practise, and throughout these experiments individual 'control' runs with 1·2 sec contact were made. Subjects were not aware of which surfaces were being examined, or of their previous performance. The mean performance of the four subjects dropped to about 60% of that observed previously with 1·2 sec contact, which the control runs showed could still be obtained.

Subjective descriptions

Without any terms or choices being suggested to them, the subjects consistently described the incrementally larger-period surface (B) as 'rougher' than the standard (A), for both the small- and large-period surfaces, and for both the 'along' and 'across' series of surfaces. Furthermore, the subjects all claimed that the small-dot surfaces were relatively 'smooth' compared to the 'rough' large-dot surfaces. In a few instances subjects used 'sharper' as a synonym for 'rougher'.

DISCUSSION

Decision theory. Decision theory (Johnson, 1980*a*, *b*) is an extension of signal detection theory (Green & Swets, 1966) that encompasses experiments in which there is only one response for two stimulus presentations, and it provides a mathematical framework for models of the underlying decision process. Quantification of performance using the separation index (d') function reveals the relationship between the stimulus change and performance over the whole range from chance to perfect discrimination, whereas use of the classical difference limen provides only one point in that relationship.

Performance. Any incremental change in the period of the dots produced d' values greater than zero; in other words, the subjects could detect to some degree any change in the period of the dots, no matter how small. There was no evidence of 'threshold' behaviour in this discrimination task, and the subjects showed fine discriminative abilities, as they could discriminate a systematic period change of only 20–40 μm, at the 75% correct level of performance. This differs from the discriminative performance seen when subjects were asked to distinguish the orientation of grating surfaces without any tangential movement of the fingers (Johnson & Phillips, 1981); in such a task the performance did not rise above chance levels unless the spatial period was greater than 0·8 mm. The superior discriminative performance seen in the tasks described here might result from both (a), more vigorous activation of any or all of the mechanoreceptor populations, and (b), an ability to use a neural code based on both temporal and spatial aspects of the population responses, which is made possible by the relative tangential movement between the skin and the surfaces (see Johnson & Lamb, 1981).

The general shape of the performance functions probably resulted from an underlying linear relationship between the separation index, d', and the size of the period difference over the *whole* range of period differences. This can be concluded from Fig. 8 which shows the theoretical effect of random performance ('guessing') on one response in twenty, when it is proposed that there is a linear relationship between the two variables. The 'saturating' behaviour seen at d' values of 2·5 S.D. units and above is merely the result of the analysis and graphing procedure exaggerating small differences between perfect and near-perfect performance.

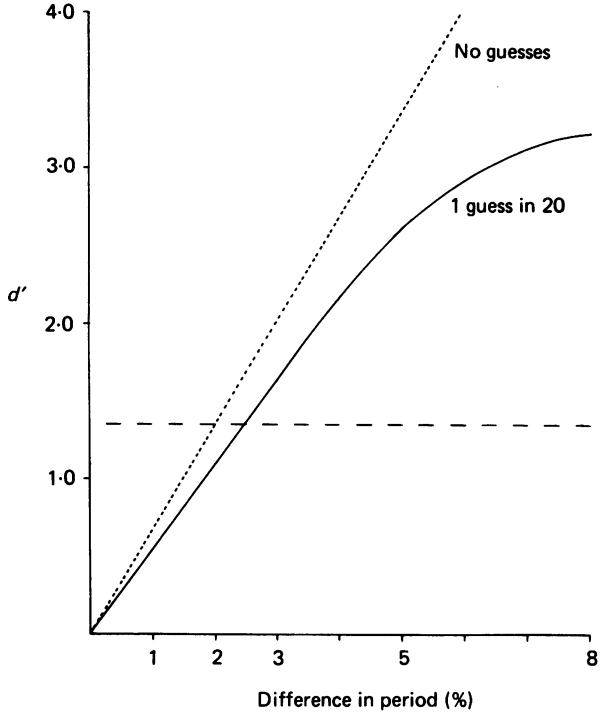

Fig. 8. Effect on discrimination ability of random performance ('guessing') for one response in twenty. In this hypothetical example the small dashed line displays a linear relationship between the separation index (d') and the difference in the periods of the two surfaces, and arbitrarily intersects the75 % correct response level ($d' = 1·35$) at a 2 % period difference. The continuous line shows the d' values which would be obtained if the discrimination performance were identical to that described above for nineteen out of every twenty responses and totally random for the twentieth response; this curve shows 'saturation' at large period differences due to the fact that d' is expressed in S.D. units.

Importance of method of movement. Comparison of the performance for the three methods of active movement investigated revealed that the discriminative abilities of the subjects were virtually independent of the method used. Such similarity in performance is at first very surprising in view of (a), the complexity of the time-varying velocity profiles used by the subjects, and (b), the radical differences between the profiles used by different subjects, and also between the profiles seen for the same subject when using the three different methods of active movement. However, it is important to note that for each method of movement each subject used similar movements in successive sweeps (Fig. 5*A–C*). Hence it might be concluded that subjects obtained sufficient information for discriminating the two surfaces by investigating both with nearly identical movements, irrespective of the precise velocity profile or method used. Such replication of movement might presumably enable two surfaces to be discriminated merely by the direct comparison of some simple aspect of the neural response to each (e.g. the mean discharge rate). The use of such a procedure by the subject would allow discrimination even though the velocity profile of the movement might be very complex, and even if that profile was not known or perceived by the subject.

In an active-touch experiment, if knowledge about the velocity profile of the relative movement is necessary for discrimination, it might be obtained from either the motor and proprioceptive signals involved or by examination of the cutaneous neural image evoked by the movement. However, in a passive-touch experiment only the latter source could provide such information. Nevertheless, Fig. 4 shows that, at least at a velocity of 73 mm/sec, passive-touch produced virtually the same discriminative performance as active touch. Despite reservations about direct comparisons of the active- and passive-touch data due to small differences in the experimental designs, it can be concluded that subjects either did not require information about the velocity profile of the relative surface movement, or obtained all such information from the cutaneous image alone. (A further psychophysical experiment which would resolve whether subjects could extract and use information about the velocity profile is one in which each surface is presented passively to the subject with a different velocity profile). In any case, the *extraction* of such velocity information from the cutaneous neural response, and its subsequent *utilization* in the discrimination process, must be considered a much more complex form of neural processing than the alternative outlined earlier.

Frequency coding. It is interesting to examine the discriminative performances seen with the '*along*' surfaces in terms of a frequency code. Fig. 6*B* shows the discriminable period differences plotted against the 'frequency' with which the successive lines of dots on the standard surface passed over a given point of the skin. Those discriminable period increments can also be thought of in terms of frequency, as a 3 % increase in the period in the '*along*' dimension produces a 3 % decrease in the frequency of the lines of dots, at any given velocity. Thus, it is possible to propose that the observed discrimination was produced by the ability of subjects to discriminate differences in the frequency with which the dots struck the skin. Such a hypothesis could account for the similarities of the data in Fig. 6*B* with the results found for vibratory frequency discrimination using a punctate probe. Using a similar psychophysical paradigm, Mountcastle *et al.* (1969) found: (a), that at each frequency the performance (d') was approximately a linear function of the frequency difference between the two stimuli (cf. Fig. 4), and (b), the discriminable frequency difference was approximately a constant percentage of the standard frequency, over a range from 5 to 200 Hz (cf. Fig. 6*B*).

However, despite the similarities with the vibratory studies, the hypothesis of surface discrimination by means of the differentiation of the dot frequency is *totally* inadequate for explaining the discriminative performance observed with the '*across*' series of surfaces. In those series of surfaces the period of dots in the direction of movement was identical for both the A and B surfaces, and hence the frequency of the dots striking the skin was identical for both, at any given velocity. When the performances for the 'across' surfaces are considered (Fig. 6*A*) it is apparent that, though they are about two-fold poorer than those for the 'along' series, they still indicate an extremely high discriminative ability.

Contact time. The performance of subjects was found to drop substantially when their fingers only contacted the surface for 0·3 sec instead of 1·2 sec. Previous neurophysiological studies using tangential stimulation of the type used here have shown the presence of a transient increase in the response of individual mechanoreceptors in approximately the first 0·2 sec of contact, due to the indenting movement of the drum into the skin (Darian-Smith & Oke, 1980; Johnson & Lamb, 1981). Thus, the psychophysical results show that a substantial amount of the information needed for discriminating the surfaces was conveyed in the neural discharge following such transient responses.

Subjective descriptions. It is of interest that for both the small and large period surfaces, and for both the 'along' and 'across' surfaces, subjects described the surface with the incrementally larger period (B) as 'rougher'. Perhaps this indicates that the discrimination in all four combinations of conditions is produced by the same neural determinants. Further evidence for such an hypothesis is presented in the following paper (Lamb, 1983).

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