

An Investigation of Tactile Hyperacuity¹

JACK M. LOOMIS

Department of Psychology, University of California, Santa Barbara, California 93106

Received May 21, 1980

Whereas the spatial discriminative capacities of vision have been mapped out in some detail, virtually nothing is known about tactile spatial sensitivity aside from two-point resolution, point localization, and size discrimination. The purpose here was to assess several spatial discriminative capacities of the distal pad of the index finger: discrimination of spatial misalignment, spatial interval discrimination, point localization, and spatial resolution. It was found in some cases that judgments of relative spatial position are remarkably acute—the thresholds for spatial interval discrimination and for detection of misalignment in a three-dot target were less than one-fifth the two-point threshold. The threshold for point localization, determined under what were deemed optimal conditions, was approximately 0.17 mm. These results indicate that under some conditions touch is capable of spatial discriminations nearly as acute as those made by vision, as judged by scaling the discrimination thresholds in terms of the respective resolution thresholds.

In the usual textbook treatments of cutaneous sensibility, two measures of spatial sensitivity, two-point resolution and point localization, and the difference between them (Boring, 1930, 1942; Weinstein, 1968; Zigler, 1935) are generally given mention but are rarely discussed in terms of underlying process. Similarly, the study of vision has seen a long period where the different measures of spatial sensitivity (minimum visible, minimum separable, vernier acuity) have received little theoretical attention. Recently, however, there has been a renewed effort to reach an understanding of these and related indices of visual capacity (Andrews, Butcher, & Buckley, 1973; Beck & Schwartz, 1979; Sullivan, Oatley, & Sutherland, 1972; Westheimer, 1976, 1977, 1979; Westheimer & Hauske, 1975; Westheimer & McKee, 1977a, 1977b; Westheimer, Shimamura, & McKee, 1976).

In view of the fact that the cutaneous sense, like vision, has as its first stage a two-dimensional receptive surface, one might expect cutaneous sensibility to exhibit some functional similarity with vision. In particular, one might ask whether the various spatial discriminative capacities of vision denoted as "hyperacuties" by Westheimer (1976, 1977) are matched by similar capacities in the realm of touch. We already know of several tactile spatial discriminations qualifying as examples of tactile hyperacuity by virtue of their having thresholds much finer than resolution acuity: size discrimination (Jones & Vierck, 1973; Vierck & Jones, 1969) and the aforementioned point localization. The purpose of this research was to investigate further the spatial discriminative capacities of the cutaneous sense using several of the spatial configurations employed in vision.

¹ This work was supported by grants from the National Institutes of Health (NINCDS NS 15129) and the Academic Senate, University of California, Santa Barbara. The author thanks Pauline McNulty for her assistance in this work. Requests for reprints should be addressed to Dr. Loomis, University of California, Santa Barbara, CA 93106.

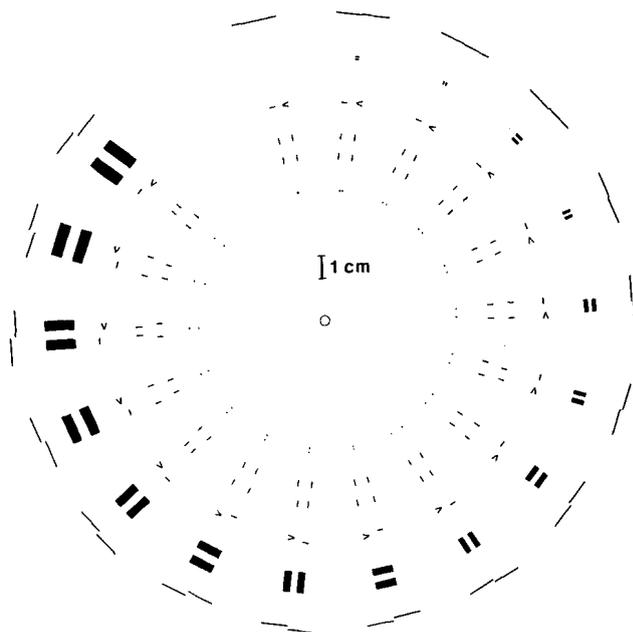


FIG. 1. The stimuli of Experiment 1 as they were arranged on the metal plate. The patterns pictured here are exact facsimiles of the upper surfaces of the embossed patterns.

Toward this end, three experiments were undertaken. Experiment 1 compared spatial discrimination thresholds obtained in a variety of tasks with two measures of spatial resolution. Experiment 2 was a more thorough investigation of one of these tasks, vernier alignment discrimination. Finally, Experiment 3, using the same psychophysical procedures, determined the precision of static point localization.

EXPERIMENT 1

Method

The stimuli used in this work were produced by photoengraving. First, the stimulus patterns were composed using transfer lettering materials. The artwork was then taken to a photoengraver, who photographed it at 50% magnification and used the resulting negative to make a contact exposure against a zinc plate treated with a photosensitive emulsion. The plate was then etched to give an embossed facsimile of the original artwork. In this first experiment a total of 10 stimulus configurations were employed, five of which are shown in Fig. 1. The plate was mounted horizontally so that, by rotation, any desired pattern could be positioned beneath the right index finger (Fig. 2). It can be seen that the stimulus presented on any given trial was among those on a line extending to the right from the center of the plate (Fig. 2). Consequently, the palm was in the clockwise direction of Fig. 1 relative to the finger. A vertically mounted finger guide, just touching the finger on both sides, kept the finger properly situated. The other fingers, the hand, and the arm were all comfortably supported to minimize fatigue.

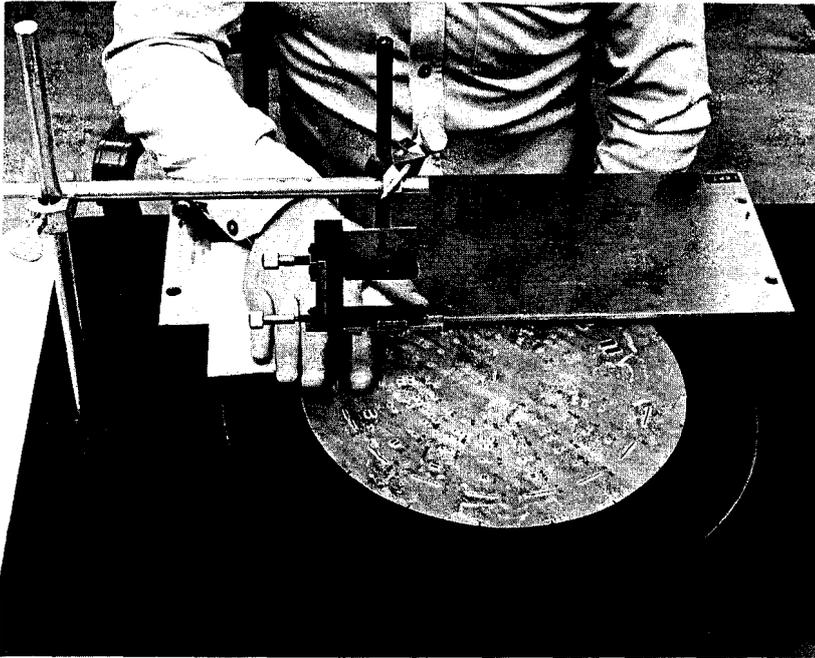


FIG. 2. The experimental apparatus for determining the tactile spatial thresholds in Experiment 1.

Throughout this work, static touch was used.² The experimenter positioned the desired stimulus beneath the finger and gave a ready signal, after which the subject lightly touched the stimulus pattern for about 1 sec with no lateral motion whatsoever. Subsequent measurements made with a Mettler electronic balance indicated that subjects were exerting a finger force of 5–10 g while touching the patterns.

As mentioned above, five of the stimulus sets were those of Fig. 1. The outermost array is a set of conventional vernier targets with the upper line (that nearest the end of the finger) offset in varying amounts to the left and right of the fixed lower line. The next concentric array of patterns is a set of König bar targets used to measure spatial resolution (Westheimer, 1977). The subject's task was to say whether the bars were vertical or horizontal. Adjacent to the König targets is a set of modified vernier targets, each consisting of a lower chevron of fixed position and an upper vertical segment which was offset in varying amounts to the right and left of the chevron center; this is like one of the targets that Westheimer and McKee (1977b) have used. The subject's task was to say whether the upper

² In this initial work on hyperacuity, we confined our investigation to static touch. Although one would hope that eventually there will be an understanding of normal active touch, the rationale here has been to start out with an analysis of cutaneous sensibility using static touch and work from there up to more complex modes of touching. If scanning were permitted, say, in the resolution task, frictional resistance between the finger and the "grain" of the König target alone would indicate to the subject the direction of the bars, yet this very well may have little to say about the spatial sensitivity of the finger. Besides frictional resistance, scanning provides other sources of information which, though helpful to the observer, greatly complicate the situation and thus impede our understanding.

segment was offset to the left or right. The second innermost array of patterns, each consisting of two pairs of horizontal lines, constitutes a task that Westheimer and McKee (1977b) have called spatial interval discrimination. The pair of lines on the left, with spacing of 5 mm (bar center to bar center), defined the standard (fixed) interval which the subject touched first. The pair on the right, which the subject touched shortly thereafter, was the variable interval. The subject had to say whether the right interval was larger or smaller than the left. (For this configuration only, the finger guide was widened to permit the finger to touch the two pairs of lines in close succession. In the actual course of making contact with each pair, the subject was permitted to move the finger only vertically, i.e., without lateral motion). Finally, the innermost array of patterns was used to provide a second index of spatial resolution, the conventional two-point limen. Thresholds were obtained separately for targets oriented in both the longitudinal and transverse directions of the finger pad. Unlike the discrimination tasks, the task of two-point resolution requires the subject to report directly on his internal state, there being no correctness or incorrectness of the response. As is the convention (Kenshalo, 1978; Sinclair, 1967), the subject was instructed to judge whether the target felt as "two separate points" or as "a single point." The subject was aware that two points were always being presented and thus was reporting on sensory impressions rather than knowledge.

The remaining five configurations were different sizes of the Ludvigh target (Beck & Schwartz, 1979; Ludvigh, 1953); it consists of three dot elements arranged along an imaginary vertical line, with the middle dot variable in its lateral alignment with this line. The dots were all 0.3 mm in diameter. The five vertical center-point separations (*S*) between adjacent dots were 1.0, 2.0, 3.0, 5.0, and 7.5 mm. A set of stimuli for each size of the configuration was arranged in the same circular fashion on the plate. Each set consisted of 17 stimuli with the middle dot offset to the left and right in progressive increments of 0.25 mm over the range from 0 to 2.0 mm. The subject's task was to indicate whether the middle dot was offset to the left or right.

By virtue of the etching process, the edges of the embossed figures are inclined downward away from the vertical so that the patterns spread out with increasing depth. For the plate of Fig. 1, this skirt angle (re the vertical) is about 20° and for the plate with the Ludvigh targets, about 45°. Because the skin tissue is not able to conform perfectly in the vertical dimension (Taylor & Lederman, 1975), this slight spreading of the patterns appears inconsequential. Proofs of the embossed plates made by inking the raised surfaces showed that the upper surfaces were exact facsimiles of the original artwork; accordingly, the lateral dimensions of the patterns given above are those of the upper surfaces. The two plates were both etched to a depth of 0.9 mm so that the raised patterns were of this height.

For each of the patterns requiring a judgment of misalignment (the vernier, modified vernier, and Ludvigh targets) it would be possible for a subject to judge the direction of offset merely by attending to the displaced element if the target as a whole were always presented to the same location on the finger. To ensure that subjects would make relational judgments, the pad of the finger was displaced laterally from trial to trial so that when the finger was lowered onto the pattern,

the pattern made contact with different portions of the finger. This was readily accomplished by means of the $x-y$ positioner (Edmund Scientific) which served as the finger guide (Fig. 2). Prior to the stimulus presentation on a given trial, the experimenter moved the finger left or right to one of seven positions equally spaced at 1-mm intervals. The central one of these seven positions was that at which the pattern made contact with the middle of the pad during the initial alignment procedure. The random schedule of absolute positions was independent of the schedule used in determining the sequence of stimulus values. Thus, the subject was unable to use absolute target position as a cue to the alignment judgment.

On the basis of pilot work, a range of stimulus values (e.g., in the vernier task, left and right offsets from 0.25 to 1.0 mm together with zero offset) was tested for each of the nine forced-choice discrimination conditions. The data for each condition were collected all in one session; the experimenter switched randomly from one stimulus to another during the session with the constraint that a total of 30 trials was tested at each value (such as, a left offset of 0.5 mm). Collecting all of the data for a given condition in a single session seemed the least disruptive procedure from the subject's standpoint although it introduced the possibility of a sequence effect over sessions; however, the effects of learning were minimized by the considerable practice subjects had acquired in the pilot work.

For each of the nine discrimination tasks, the percentage of judgments in one direction (e.g., "left offset," "larger interval on the right") was determined at each stimulus value resulting in a psychometric function. The just noticeable difference or discrimination threshold was defined conventionally (Engen, 1972, p. 26; Westheimer & McKee, 1977a, 1977b) as the semi-interquartile range (one-half the distance between the stimulus values corresponding to 25 and 75%). Probit analysis (Finney, 1971) was employed in determining these discrimination thresholds. The standard error of the semi-interquartile range was also computed.³

The two-point threshold was measured in quite a different way inasmuch as it reflects the subject's judgment of when two points feel separated in space. Ten presentations of each target with center point separations ranging from 1.0 to 4.5 mm were given. Threshold was defined as the interpolated separation which elicited an even split of "separate" and "single-point" responses.

Three subjects participated in the experiment and in 20–30 hr of pilot work. J.P. and M.T. were females approximately 20 years of age and J.L. (the author), a male of 33. M.T. withdrew from the experiment before completing all of the conditions.

Results

The thresholds for the 10 configurations tested are given in Table 1. But for two exceptions, the thresholds for the putative hyperacuity targets were smaller than the thresholds for the two resolution targets. (For the two exceptional cases,

³ The standard error of the semi-interquartile range was determined in the following way. Finney (1971, p. 34) provides an expression for the variance $V(x_p)$ associated with the predicted x value that corresponds to a given percentage p . The variance of the interquartile range is thus $V(x_{75}) + V(x_{25})$ and that for one-half the interquartile range, $[V(x_{75}) + V(x_{25})]/4$; accordingly, the standard error of the semi-interquartile range is $([V(x_{75}) + V(x_{25})]/4)^{1/2}$.

TABLE 1
THE THRESHOLDS (mm) AND THEIR STANDARD ERRORS FOR THE STIMULUS
CONFIGURATIONS OF EXPERIMENT 1^a

Ludvigh				
1.0 mm	2.0 mm	3.0 mm	5.0 mm	7.5 mm
1.16 ± 0.18	0.24 ± 0.04	0.31 ± 0.05	0.27 ± 0.05	0.37 ± 0.05
—	0.68 ± 0.12	0.50 ± 0.08	0.52 ± 0.08	0.44 ± 0.07
—	0.55 ± 0.08	0.49 ± 0.10	0.77 ± 0.14	0.75 ± 0.13
—	0.49 av	0.43 av	0.52 av	0.52 av
Interval discrimination	Vernier	Modified vernier	König resolution	Two-point resolution
0.21 ± 0.03	0.86 ± 0.13	0.37 ± 0.05	1.67 ± 0.28	2.8
0.33 ± 0.06	0.76 ± 0.11	0.48 ± 0.06	1.77 ± 0.24	2.8
0.27 av	0.81 av	0.43 av	1.72 av	2.8 av

^a Starting at the top of each cell are the values for J.L., J.P., M.T., and the average threshold. M.T. withdrew from the experiment before being tested on the configurations in the second row.

threshold was not obtainable with the available range of offsets.) The two-point thresholds for each of the two subjects (J.L. and J.P.) were averages over the transverse and longitudinal directions. For J.L. the separate thresholds were 2.2 and 3.3 mm, respectively; for J.P. they were 2.7 and 2.9 mm.

Discussion

As the modulation transfer function has come into increasing acceptance as the way of specifying the spatial sensitivity of a (linear and homogeneous) image processing system (Kelly, 1965; Sekuler, 1974), spatial resolution has increasingly come to be measured in terms of the highest spatial frequency transmitted by the system at some criterion level of modulation; accordingly, sine-wave gratings of varying spatial frequency are the appropriate test stimuli, for they have energy confined to only one spatial frequency. On the other hand, many of the conventional resolution targets, like the König two-bar target, the three-bar target (Kelly, 1965), and the two-point target, despite being broadband targets, possess certain advantages and continue to be used for determining figures of merit pertaining to resolution (Kelly, 1965; Westheimer, 1977). With the König bar target, the conventional index of resolution is the gap between the bars in the smallest resolvable target; it would be more useful, however, to use the separation between bar centers (twice the gap size), for this measure corresponds to the point-center separation in the two-point target and relates more directly to the spatial frequency definition of resolution. This is so, for the amplitude spectra of these targets have a concentration of energy within a band of frequencies, the periods of which are close to the bar-center separation (Kelly, 1965; Westheimer, 1977). However, as Kelly (1965) has pointed out, even the bar center separation of the just "resolved" three-bar target would underestimate the period of the upper limiting spatial frequency, because the band of energies carrying information about bar orientation extends somewhat below that frequency having a period

equal to the bar-center separation; this underestimation would be even more pronounced with the König two bar target, for its frequency spectrum is even broader. All of this means that the König gap threshold of 1.7 mm corresponds to a cutoff spatial frequency of period somewhat greater than 3.4 mm.

One might expect that the two-point threshold (being measured in terms of the point-center separation) would be close to this value. However, its somewhat smaller value [2.8 mm in this experiment and 3.1 mm as measured by Weinstein (1968)] can be understood as the subject's not strictly judging whether the two points are separated. The two-point target is useful in measuring spatial resolution only when the two points are correctly reported as resolved. It suffers as a resolution target, for subjects have difficulty in adopting the proper criterion of separateness (Boring, 1921). Were the two-point target used in a forced-choice task in which the subject had to discriminate between the two-point target and a single point, this problem would be exacerbated, for then the subject would make no attempt to satisfy the criterion of separateness, but would instead simply judge whether the target felt the least bit elongated (Boring, 1921). This would be possible, for the axis of orientation of the two-point target is conveyed by spatial frequencies much lower than that frequency having a period of the point-center separation. Under these circumstances, the result would be a gross underestimation of the resolution threshold (as defined above). The advantage of the König target in assessing resolution is that the criterion problem (Westheimer, 1977) inherent in the use of the two-point target is eliminated, for the target is square; put differently, the subject is forced to use the higher spatial frequencies that convey information about the orientation of the gap, whereas with the two-point target, much lower frequencies are informative about the axis of its elongation. In what follows thresholds for the other targets will be compared against the König thresholds as obtained, since this is the conventional manner of specifying the resolution threshold (Westheimer, 1977); however, it should be kept in mind that spatial resolution as defined in terms of the period of the cutoff spatial frequency would be more than twice as large.

The major concern of this work is, of course, with the putative hyperacuity tasks. To assess the relative precision of the thresholds associated with the various conditions, the thresholds were expressed as proportions of the average König resolution threshold, which in this experiment was 1.72 mm. These proportions were 0.28, 0.25, 0.30, and 0.30 for the Ludvigh targets with dot separations of 2, 3, 5, and 7.5 mm, respectively, and 0.16, 0.47, and 0.25 for the interval discrimination, vernier, and modified vernier tasks. (For J.L., whose performance was the best, these values were 0.14, 0.19, 0.16, 0.22, 0.13, and 0.22, respectively). Thus, as with vision, these spatial discriminations, like point localization and size discrimination, warrant the "hyperacuity" label (Westheimer, 1976, 1979; Westheimer & McKee, 1977a, 1977b) by virtue of having thresholds much finer than resolution acuity. On the other hand, these thresholds, when compared with the König resolution threshold, are not as fine as visual hyperacuity thresholds, which are frequently less than 10% of the König threshold⁴ (Beck & Schwartz, 1979;

⁴ The visual resolution thresholds with the König bar target were taken as 1.0 min of arc for both S.M. and L.K. In a separate experiment (Westheimer, 1977) S.M. had a measured bar target threshold of 1.0 min and another subject (not L.K.), one of 1.05 min.

Ludvigh, 1953; Sullivan *et al.*, 1972; Westheimer & McKee, 1977b). However, in this initial exploratory investigation of tactile hyperacuity there was not sufficient time to give extensive training to the subjects, and prolonged training has been shown to reduce visual hyperacuity thresholds substantially (McKee & Westheimer, 1978).

In addition to the basic finding, there are several other points of interest. For one thing, there was a drastic increase in threshold for the Ludvigh target with the smallest dot separation, the threshold being outside the range of available stimulus offsets for two of the subjects. Evidence of a similar increase in threshold with a related visual two-dot target was found by Westheimer and McKee (1977b, Fig. 2, Cond. A) for the smallest separation. The present result is not unexpected, for the 1-mm vertical dot separation was considerably less than the König resolution threshold, meaning that the dots were perceptually merged. It might seem surprising then that J.L.'s offset threshold of 1.16 mm should be less than his resolution threshold (1.67 mm). However, there is no paradox here, for although the three dots of the target were not resolved, the merged pattern had the shape of an isosceles triangle, with the apex in the direction of offset. Thus, the task amounted to one of discriminating isosceles triangles pointing in opposite directions.

Another interesting and unexpected result was the relatively poor showing of vernier alignment discrimination, in comparison with the other tasks. Part of the reason for this might have been the slight variation in orientation of the target (re the finger) as the finger was moved from one position to another, for orientation is important in judgments of this sort (Beck & Schwartz, 1979; Sullivan *et al.*, 1972). However this can only be a part of the reason, because the modified vernier task, which would be similarly affected, had a threshold half the size. The next experiment was undertaken to learn more about tactile vernier acuity.

EXPERIMENT 2

Method

Fifteen variants of the conventional vernier acuity target, shown in Fig. 3, were investigated in this experiment. As before, stimuli were created using photo-engraving; this time, the raised patterns were 1.0 mm high with a skirt angle (re the vertical) of 60°. For each variant, 10 stimulus offsets ranging from 1.25 mm left to 1.25 mm right in steps of 0.25 mm (zero offset not included) were arranged in concentric circles on the metal plates.

In the previous experiment, the metal plate was stationary while the finger was moved laterally between trials so that there would be some variation in the position at which the stimulus contacted the finger pad. Because the finger is anchored at one end, this had the effect of varying just slightly the orientation of the stimulus patterns on the finger pad. To avoid this problem in the present experiment, the plate was mounted on a massive translation stage which could be moved continuously in the direction transverse to the axis of the finger. The vertically mounted finger guide held the finger fixed in space, and the translation stage was used to position the stimulus randomly on each trial at one of the three positions spaced apart by 1 mm. Thus, on each trial the vernier target made contact with either the center of the distal pad or with one of the positions just to either side.

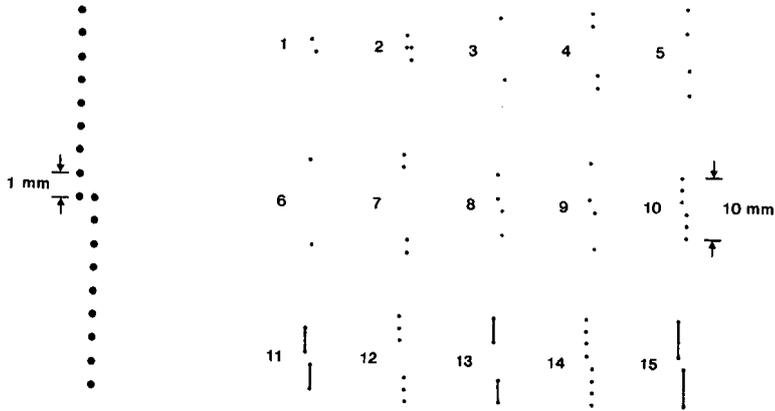


FIG. 3. The 15 variants of the vernier alignment configuration studied in Experiment 2. These were all based on the template of 18 dots shown at the left (illustrating an offset of the upper portion to the left).

This procedure ensured that the subject would respond to the relative offset of the upper portion of the vernier target rather than to its absolute position on the finger surface. As before light static touch was used, with stimulus contact lasting about 1 sec. The task was to say whether the upper portion of the target was offset to the left or right. Feedback was given after each trial.

During each block of 100 trials, the stimulus was varied randomly (without replacement) over the 10 values of offset for a given variant of the vernier configuration. After a block was completed, testing on one of the other 14 variants began, with the schedule of conditions being random within and between sessions. This alternation between conditions constituted a change from the procedure in Experiment 1. Data collection for each subject continued until 50 trials at each offset for each condition had been recorded. However, the last 40 trials only were used in the data analysis, the first 10 serving for practice.

In addition to the main experiment, König bar resolution was determined for the two subjects under the present conditions, these being 50 trials at each stimulus value and varying position of the stimulus on the finger.

Two females in their twenties participated as subjects. One of these, J.P., was a subject in Experiment 1. The other, Z.L., had participated extensively in experiments on tactile character recognition and in Experiment 3 which follows. It was her first experience with this sort of discrimination.

Results

The thresholds and standard errors determined by probit analysis are given in Table 2 for each subject and condition. Although for each subject there are some reliable differences between the thresholds for the various configurations, it would be unwarranted to make much of the variation in the average threshold across conditions given the differences between subjects. The only condition which stands apart from the others is variant 1; the thresholds for it were the smallest for both subjects.

TABLE 2
THE THRESHOLDS (mm) AND THEIR STANDARD ERRORS FOR THE 15 CONFIGURATIONS
OF EXPERIMENT 2 (SEE FIG. 3)^a

1	2	3	4	5
0.40 ± 0.05	0.43 ± 0.04	0.63 ± 0.06	0.53 ± 0.05	0.52 ± 0.05
0.33 ± 0.04	0.62 ± 0.06	0.57 ± 0.06	0.55 ± 0.06	0.77 ± 0.08
0.37 av	0.53 av	0.60 av	0.54 av	0.65 av
6	7	8	9	10
0.73 ± 0.07	0.70 ± 0.07	0.60 ± 0.06	0.51 ± 0.05	0.45 ± 0.05
0.46 ± 0.05	0.52 ± 0.05	0.79 ± 0.08	0.88 ± 0.09	0.72 ± 0.08
0.60 av	0.61 av	0.70 av	0.70 av	0.59 av
11	12	13	14	15
0.46 ± 0.05	0.58 ± 0.06	0.54 ± 0.06	0.61 ± 0.06	0.56 ± 0.06
0.48 ± 0.05	0.49 ± 0.05	0.49 ± 0.05	0.68 ± 0.07	0.78 ± 0.08
0.47 av	0.54 av	0.52 av	0.65 av	0.67 av

^a The upper values in each cell are those of J.P. and the lower values, those of Z.L.

The König resolution thresholds were 1.73 ± 0.19 mm for J.P. and 1.65 ± 0.20 mm for Z.L.

Discussion

The 15 variants of vernier acuity investigated here were created with several thoughts in mind. First, a range of configurations was tried in hopes that the resulting variations in performance would suggest which variables are most potent in influencing vernier alignment sensitivity. Second, a comparison between vernier targets composed of dots (variants 10, 12, 14) and the corresponding line targets (variants 11, 13, 15) was planned. Third, several targets with single dots in the upper and lower segments were to be compared with targets having two or three dots in each segment, the centroid of which coincided with the single dots in the corresponding targets; thus, variant 1 was to be compared with 2, 3 with 4 and 5, and 6 with 7. As it turned out, the variations in threshold were not so large and consistent as to justify any strong conclusions.

What the results do show is that tactile vernier acuity most definitely qualifies as an example of hyperacuity: the grand average of all the thresholds for variants 1 through 15 is 35% of the average König resolution threshold. It appears that performance was somewhat improved over what it was for the vernier target of Experiment 1, perhaps reflecting the fact that target orientation was not permitted to vary in this experiment. At any rate, vernier alignment sensitivity seems to be quite good for the finger pad, even though not nearly as good as visual vernier alignment sensitivity, when judged in relation to visual resolution.

Having established the precision with which various relational spatial judgments can be made, we undertook a third experiment to determine how precisely absolute position on the finger pad can be sensed. Previous experiments using cruder techniques have shown that localization is accurate to nearly 1 mm on the index finger (Dallenbach, 1932; Weinstein, 1968). An experiment by Loomis and

Collins (1978), using more refined methodology, indicated possibly much finer localization than this, but their task involved discriminating the direction of rapid displacements of a single point and thus did not measure localization per se. The following experiment makes use of the same procedure (forced-choice discrimination), this time in investigating localization.

EXPERIMENT 3

Method

For this experiment still another apparatus was constructed. The point stimulus was a tack, the tip of which had been smoothed to a hemispherical shape (diam = 0.7 mm). It was mounted in a piece of wood such that its tip was 1.3 mm above the wood surface. At its base the stimulus was 1.6 mm in diameter. The piece of wood was attached to an x-y positioner in such a way that the point stimulus, which was oriented vertically, could be displaced laterally in 0.1-mm steps (the resolution of the vernier scale on the positioner).

Seven positions spaced at 0.1-mm intervals on a line running from right to left (with respect to the finger pad) were used. The middle position was defined as the reference position. During the alignment procedure, the subject adjusted the finger guide laterally so that the stimulus at this central position felt more or less in the center of the finger pad. A short practice session was given (usually 10 to 20 trials) to allow the subject to internalize the reference position. The experimenter set the stimulus to one of the seven positions (including center); the subject then lightly touched the point, indicated whether it appeared to the right or left (two alternatives only), and was given feedback. After this initial practice, the procedure continued with data being recorded. The intertrial interval was 3–5 sec. At each of the positions 60 stimulus presentations were given. If for some reason the experiment was interrupted, the alignment procedure was repeated.

The three subjects in this experiment were J.L., J.P., and Z.L. This experiment actually preceded Experiment 2. It gave Z.L. her first experience as a psychophysical observer.

Results

Psychometric functions for the three subjects are given in Fig. 4. The localization thresholds determined by probit analysis were 0.15 ± 0.02 mm for J.L., 0.18 ± 0.02 mm for J.P., and 0.18 ± 0.02 mm for Z.L. These values are slightly larger than the thresholds obtained by Loomis and Collins (1978) for rapid displacement of a stimulus over the pad of the right index finger, with J.L. an observer in both experiments. This could indicate that there is greater sensitivity to displacement of a stimulus than to its absolute position, perhaps reflecting a sensitivity to motion per se. On the other hand, additional sources of variation might have been present in this experiment. For one thing, very slight variation of the position of the finger within the finger guide cannot be ruled out. More likely, there was apt to be some variability associated with the subject's internalization of the reference position over the course of many trials. Whatever the reasons for these slightly larger thresholds, the precision of absolute localization on the finger pad is remarkably good, far surpassing earlier estimates of approximately 1 mm (Dallenbach, 1932; Weinstein, 1968).

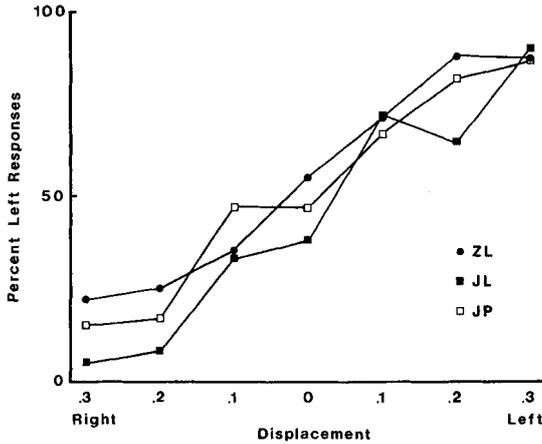


FIG. 4. The psychometric functions for point localization. The abscissa values indicate the displacements of the point stimulus away from the central reference position.

GENERAL DISCUSSION

We have presented evidence of tactile hyperacuties in addition to those which have been previously identified, point localization, and size discrimination. Should we find it surprising that spatial resolution does not limit a wide variety of spatial discriminations? The answer is decidedly no, for spatial resolution (as measured by the König bar target) is closely related to the upper limiting spatial frequency transmitted by the sensory system (vision or touch), while all of these discriminations, in principle, can be made on the basis of information conveyed by much lower frequencies. (This is not to imply, however, that processing is carried out in the frequency domain.) The interest in studying hyperacuity is to discover what sensory mechanisms make possible such fine discrimination and, where possible, extend this to a more general understanding of the sense in question. In the study of vision, many of the hyperacuties are particularly intriguing, for they indicate that the localization of elements of a spatial pattern (e.g., the dots of a Ludvigh target) is much finer than the diameter of a foveal cone (Beck & Schwartz, 1979; Berry, 1948; Hartridge, 1922; Ludvigh, 1953; Westheimer, 1976; Westheimer & McKee, 1977a, 1977b). The implication of this is that localization of a point is based not only upon the "local signs" of the foveal cones but upon their relative excitations as well. Strange though it may seem at first, it is the normal light spreading of a retinal point image that permits its being localized more precisely than the diameter of a foveal cone by giving rise to graded excitation of neighboring cones (Beck & Schwartz, 1979; Hartridge, 1922; Sullivan *et al.*, 1972; Westheimer, 1976, 1979; Westheimer & McKee, 1977b). Although the precise localization of a tactile point stimulus is not perhaps as startling, it is no less impressive when considering the size of the receptive fields in the finger pad, few of which have diameters smaller than 2 mm (Vallbo & Johansson, 1978). Very much the same argument as above has been offered to explain the precision of tactile point localization (Loomis & Collins, 1978). Briefly, localization depends upon the local signs and the relative excitations of neighboring mechanoreceptors,

the receptive fields of which are greatly overlapping (Johansson & Vallbo, 1976, 1979; Vallbo & Johansson, 1978). The overlap of the receptive fields accomplishes the same result that spreading of light does in the visual case.

It might be thought that the spatial discriminations involving the other hyperacuity configurations are limited simply by the precision with which each of the elements of the configuration is localized. For touch, this is definitely not the case, for, as this work shows, the point localization threshold was considerably smaller than the thresholds of all of the remaining hyperacuity configurations. For vision, it also cannot be the general case that hyperacuity thresholds merely reflect the localization of the elements, for the spatial separation between the elements is a potent factor influencing performance in many hyperacuity tasks (Beck & Schwartz, 1979; Berry, 1948; Ludvigh, 1953; Sullivan *et al.*, 1972; Westheimer & McKee, 1977b). Thus, it is evident that an understanding of these more complex instances of hyperacuity will require consideration of, in addition to the registered locations of the elements, the registered spatial relations between them.

REFERENCES

- ANDREWS, D. P., BUTCHER, A. K., & BUCKLEY, B. R. Acuities for spatial arrangement in line figures: Human and ideal observers compared. *Vision Research*, 1973, 13, 599–620.
- BECK, J., & SCHWARTZ, T. Vernier acuity for dot test objects. *Vision Research*, 1979, 19, 313–320.
- BERRY, R. N. Quantitative relations among vernier, real depth, and stereoscopic depth acuities. *Journal of Experimental Psychology*, 1948, 38, 708–721.
- BORING, E. G. The stimulus-error. *American Journal of Psychology*, 1921, 32, 449–471.
- BORING, E. G. The two-point limen and the error of localization. *American Journal of Psychology*, 1930, 42, 446–449.
- BORING, E. G. *Sensation and perception in the history of experimental psychology*. New York: Appleton–Century–Crofts, 1942.
- DALLENBACH, K. M. A comparative study of the errors of localization on the fingertips. *American Journal of Psychology*, 1932, 44, 327–331.
- ENGEN, T. Psychophysics. I. Discrimination and detection. In J. W. Kling and L. A. Riggs (Eds.), *Woodworth & Schlosberg's experimental psychology*. New York: Holt, Rinehart, & Winston, 1972. Vol. 1, pp. 11–46.
- FINNEY, D. J. *Probit analysis*. Cambridge, England: Cambridge Univ. Press, 1971. 3rd ed.
- HARTRIDGE, H. Visual acuity and the resolving power of the eye. *Journal of Physiology*, 1922, 57, 52–67.
- JOHANSSON, R. S., & VALLBO, A. B. Skin mechanoreceptors in the human hand: Receptive field characteristics. In Y. Zotterman (Ed.), *Sensory functions of the skin in primates*. New York: Pergamon, 1976.
- JOHANSSON, R. S., & VALLBO, A. B. Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin. *Journal of Physiology*, 1979, 286, 283–300.
- JONES, M. B., & VIERCK, C. J., JR. Length discrimination on the skin. *American Journal of Psychology*, 1973, 86, 49–60.
- KELLY, D. H. Spatial frequency, bandwidth, and resolution. *Applied Optics*, 1965, 4, 435–437.
- KENSHALO, D. R., SR. Biophysics and psychophysics of feeling. In E. C. Carterette and M. P. Friedman (Eds.), *Handbook of perception*. New York: Academic Press, 1978. Vol. VIB, pp. 29–103.
- LOOMIS, J. M., & COLLINS, C. C. Sensitivity to shifts of a point stimulus: An instance of tactile hyperacuity. *Perception & Psychophysics*, 1978, 24, 487–492.
- LUDVIGH, E. Direction sense of the eye. *American Journal of Ophthalmology*, 1953, 36, 139–143.
- McKEE, S. P., & WESTHEIMER, G. Improvement in vernier acuity with practice. *Perception & Psychophysics*, 1978, 24, 258–262.
- SEKULER, R. Spatial vision. *Annual Review of Psychology*, 1974, 25, 195–232.
- SINCLAIR, D. *Cutaneous sensation*. London: Oxford Univ. Press, 1967.

- SULLIVAN, G. D., OATLEY, K., & SUTHERLAND, N. S. Vernier acuity as affected by target length and separation. *Perception & Psychophysics*, 1972, 12, 438-444.
- TAYLOR, M. M., & LEDERMAN, S. J. Tactile roughness of grooved surfaces: A model and the effect of friction. *Perception & Psychophysics*, 1975, 17, 23-36.
- VALLBO, A. B., & JOHANSSON, R. S. The tactile sensory innervation of the glabrous skin of the human hand. In G. Gordon (Ed.), *Active touch*. New York: Pergamon, 1978. Pp. 29-54.
- VIERCK, C. J., JR., & JONES, M. B. Size discrimination of the skin. *Science*, 1969, 63, 488-489.
- WEINSTEIN, S. Intensive and extensive aspects of tactile sensitivity as a function of body part, sex, and laterality. In D. R. Kenshalo (Ed.), *The skin senses*. Springfield, Ill.: Thomas, 1968.
- WESTHEIMER, G. Diffraction theory and visual hyperacuity. *American Journal of Optometry and Physiological Optics*, 1976, 53, 362-364.
- WESTHEIMER, G. Spatial frequency and light-spread descriptions of visual acuity and hyperacuity. *Journal of the Optical Society of America*, 1977, 67, 207-212.
- WESTHEIMER, G. Spatial sense of the eye (Proctor Lecture). *Investigative Ophthalmology & Visual Science*, 1979, 18, 893-912.
- WESTHEIMER, G., & HAUSKE, G. Temporal and spatial interference with vernier acuity. *Vision Research*, 1975, 15, 1137-1142.
- WESTHEIMER, G., & MCKEE, S. P. Integration regions for visual hyperacuity. *Vision Research*, 1977, 17, 89-93. (a)
- WESTHEIMER, G., & MCKEE, S. P. Spatial configurations for visual hyperacuity. *Vision Research*, 1977, 17, 941-947. (b)
- WESTHEIMER, G., SHIMAMURA, K., & MCKEE, S. P. Interference with line-orientation sensitivity. *Journal of the Optical Society of America*, 1976, 66, 332-338.
- ZIGLER, M. J. The experimental relation of the two-point limen to the error of localization. *Journal of General Psychology*, 1935, 13, 316-331.