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Measuring the error of localization

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We describe a procedure to measure the error of localization on the skin. The procedure, which provides for rapid measurement of the error of localization and rapid analysis of the data, uses a digitizing tablet interfaced with a computer. A photocopy of the part of the body to be tested is placed on the digitizing tablet. The subject localizes the stimulus by touching the pen of the digitizing tablet to the photocopy. The location of the pen contact is stored, and the error of localization is determined by the computer. A graphic representation of each subject's test area can be stored. Both stimulus and response locations can be displayed on this graphic representation. The procedure also allows the same sites on the skin to be tested over a period of weeks or months.

Since the middle of the 19th century, there have been two standard measures of tactual spatial acuity: the two-point limen and the error of localization (Boring, 1942). These two measures have been used both in clinical assessments (Sunderland, 1968) and in laboratory studies of cutaneous sensitivity (Sherrick & Cholewiak, 1986; Vierck, Favorov, & Whitsel, 1988; Weinstein, 1968). As might be expected with widely used measures that have a long history, a number of devices and techniques have been developed to make these measurements, particularly the two-point limen (Johnson & Phillips, 1981; Woodward, Kenshalo, & Oliff, 1990). Less attention has been devoted to the error of localization (EOL), perhaps because it is less frequently used than the two-point limen and perhaps because it is assumed that it is a less problematical measure. With regard to the latter point, several studies of the two-point limen have investigated the subject's criterion for responding whether one or two points are perceived (see Richardson & Wuillemin, 1981), a problem not generally associated with the EOL.

The basic paradigm for measuring the EOL appears to be straightforward. Some point on the subject's skin is touched, and the subject indicates the point where he or she perceives having been touched. The distance between the actual and indicated points is the EOL. From this rather simple and apparently straightforward situation has grown an array of various techniques. The techniques differ from one another both in how the stimulus is presented and how the subject is permitted to respond. For the former, for example, the skin can be touched directly, the subject's finger can be moved over the skin above the point to be localized, or, in some cases, the skin is not touched at all but rather a photograph of the skin is touched (Boring, 1942). The most common way for the subject to respond is to touch the skin where he or she thought the stimulus was presented. In other procedures, the subject points to the skin without touching it (Parrish, 1897) or points to a location on a picture of the part of the body being tested (Pillsbury, 1895). In a typical EOL measurement, a ruler is used to measure the distance between the point stimulated and the point indicated by the subject. The experimenter often lays the ruler on the skin and, in doing so, may provide additional (and perhaps unwanted) feedback to the subject concerning the size and direction of the EOL. More importantly, the distance measurements must be recorded by hand and then analyzed at some later time. The present paper addresses two difficulties with determining the EOL: (1) the measurement of the distance between the point touched and the point indicated by the subject and (2) the rapid analysis and presentation of the data. The procedure we devised uses a digitizing tablet to record the subjects' responses.

Prior to using a digitizing tablet, we tried several other ways to measure the EOL. We wanted to avoid having the measurement procedure itself modify the subject's perception of locations in tactile space and thus wanted to use a method that minimized feedback for the subject. We adapted a method described by Green (1982) and used a clear plastic ruler taped along the proximal-distal axis of the forearm. The arm was touched at various points next to the ruler, and the subject responded by marking the ruler with a piece of chalk. To measure the EOL in two dimensions on the arm, we had a rubber stamp shop make a large rectangular grid. Each square in the grid was 5 mm on a side. The grid was inked and rolled across the subject's arm to provide coordinates for stimulating and responding. On each trial, a computer program generated a random pair of proximal-distal and transverse coordinates corresponding to the rows and columns on the

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grid. The arm was touched, and the subject responded with the row and column coordinates. In addition to the grid, we also surrounded the arm with wire mesh to provide spatial coordinates for stimulus location and the subjects' responses. These techniques are useful for relatively homogeneous areas of skin, although the experimenter is required to enter the data by hand. For testing an area such as the hand and fingers, where there may be gaps between adjacent sensory surfaces, there is a problem in generating coordinates (points) on the computer that do not fall between fingers.

The method that we currently use in measuring the EOL is a variation of earlier measures, in which a subject is touched at some location on the skin and responds by touching a location on a picture of the skin. In brief, we use a photocopy of the part of the body to be tested—for example, the palm or fingers—and place the photocopy on a digitizing tablet interfaced with a computer. Points to be tested are entered into the computer by the experimenter's touching of locations on the photocopy with the pen from the digitizing tablet. A point on the subject's skin is touched, and the subject uses the pen from the digitizing tablet to touch the tablet. The responses are stored in the computer. Each response is compared with the location of the stimulus, which was previously stored in memory, and the EOL is computed. The results are available for immediate analysis.

METHOD

Apparatus

We considered several kinds of digitizing devices before selecting a digitizing tablet. A digitizing tablet allows us to use a realistic, full-scale, visual representation, generally a photocopy, of the body part to be tested. It has the added virtue of being portable, permitting us to test subjects at locations outside the laboratory.

The laboratory's IBM-compatible microcomputers consist of a PC's Limited 286 and an NEC MultiSpeed EL portable computer. We required a tablet that (1) would readily interface to the laboratory's microcomputers, (2) could be obtained in a size that would accommodate testing of the volar forearm, (3) would not require extensive software development, and (4) would give us some degree of portability. After receiving product specifications from various companies, we purchased a (CalComp, Inc.) digitizing tablet.

The digitizer that we purchased is a 2300-series DrawingBoard (Model 23180), which has an accurate digitizing area of 305 mm × 457 mm (12×18 in.). This digitizing tablet interfaces to a serial port on a microcomputer (RS-232 C standard) and is user programmable. We purchased the standard package, which includes the tablet, documentation, a plug-in power supply/transformer, cabling and connectors, a standard pen (pushbutton and side button), and a four-button cursor. Also included is a disk containing software drivers for the tablet and relevant documentation. Because we expected them to get hard use, an extra pen and plastic overlay were purchased. The warranty period for this product is 5 years. CalComp, Inc. offers an educational discount for their digitizers. We paid $597 for this model. We have also purchased a 305 mm × 305 mm (12×12 in.) tablet (Model 23120) for $297.

The digitizing tablet that we use in the measurement of the EOL may be controlled by software commands coded in assembly language (i.e., device drivers) or in high-level languages such as BASIC, PASCAL, or C. There are also many off-the-shelf software packages that support such digitizers, especially for use in computer-aided design, mapping, and drawing. All of the software we use for communicating with the digitizer is coded by Microsoft QuickBASIC Version 4.5.

The CalComp digitizer parameters are set to point mode, 10 lines/mm resolution, 125 points/sec data rate, and CalComp 2000 ASCII format with the line feed on. Note that these settings are CalComp options and that other digitizers may implement them under different names. In connecting the digitizer to the NEC portable computer, we additionally set the serial communication parameters to 4800 baud, even parity, and 7 data bits/byte. The parity setting and data-bit setting are required by the CalComp 2000 format. For each pen press, the tablet delivers an ASCII string consisting of four x digits, four y digits (corresponding to the x and y coordinates from the tablet), a character representing the pen press, a carriage return, and a line feed. The program stores these data in a string variable and calls a subroutine that parses the data and converts the digits to integer x and y coordinates. On a typical trial, the control program opens the serial port, gets the x and y data from the tablet, closes the serial port, parses the data, and stores the data in memory.

Procedure

We have measured the EOL on the volar surface of the forearm, the palm, and the palmar surface of the fingers. We will describe the procedures we use for testing the EOL on the fingers; however, the procedures can be readily adapted to test other body surfaces. A testing session is begun by making a photocopy of the palmar surface of the subject's hand. (When testing the forearm, we have used a line drawing of the arm.) To provide the experimenter with test locations, the subject's skin is marked with a series of dots. During testing, all five fingers were marked, and any one of the fingers could be stimulated. Typically, more dots are placed on the skin than will be tested, so that the subject cannot simply try and remember where the dots were placed. A second photocopy of the subject's hand is then made. A subset of the dots are numbered on the photocopy, 1 through n on each digit. Figure 1 shows how the dots were placed and numbered on one finger. The photocopy of the hand with the numbered dots is placed on the digitizing tablet. Information about the subject and the testing procedures is entered into the computer. The computer returns a prompt asking how many points are to be entered for D1, that is, Digit 1 (the thumb). We have typically used 10 points on the thumb. After typing in "10," the computer returns the prompt, "D1,1."

Point number 1 on Digit 1 is entered by touching the tablet on the point on the thumb numbered "1" on the photocopy of the hand.

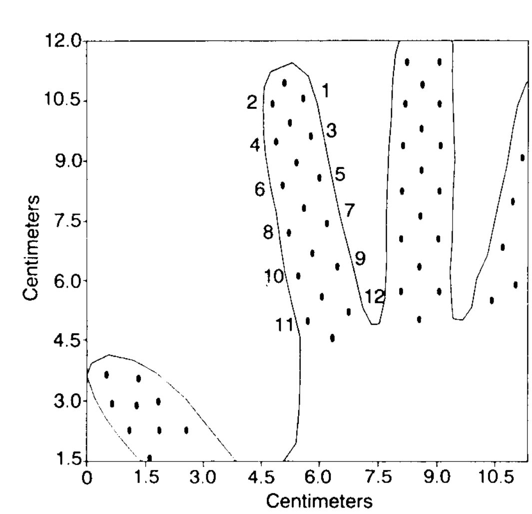

Figure 1. A drawing showing how the points were marked on the fingers and the numbering of the points for Digit 2. As noted, more points were marked on the finger than were numbered or tested.

The x, y coordinates for that point are then stored as D1,1. The computer then asks for point D1,2, and so forth until 10 points have been entered. Next, the points for D2 are entered, and so forth. At the end of this procedure we have stored the x, y coordinates corresponding to all the points that we will test, typically 56 per hand. During a session, all points may be tested without replacement, or a random sample of the points may be tested.

Prior to measuring the EOL, the original photocopy (the copy with no points marked on it) is placed directly over the photocopy with the points on it. We do this so the subject does not try to use the points marked on the photocopy to localize the touch. During testing, the subject is seated directly in front of the digitizing tablet, with the hand to be tested placed slightly to one side, palm side up. A screen is placed so that the subject cannot see his or her hand. The experimenter presses the space bar on the computer keyboard, and the computer responds with "Trial 1" and a randomly selected point such as D2,9. The experimenter touches the designated point on the subject's finger, and the subject touches a point on the photocopy with the digitizing pen to indicate where the point was felt.[1] For the tactual stimulation, we have typically used a nylon monofilament that exerts approximately 4 g of force, although the particular choice of stimulator depends on the nature of the testing. After the subject responds, the computer displays "Trial 2" and the next designated point.

It is also possible to measure the subject's reaction time (RT), a measure that might prove useful as an indicator of the subject's uncertainty in localizing the touch. To measure RT, the program is modified so that after the trial number and stimulus location are displayed, pressing the space bar starts a clock that is stopped when the digitizing pen contacts the tablet. The experimenter presses the space bar at the same time as he or she presents the tactual stimulus to the subject. The RT is stored along with the EOL on each trial. Because this method of determining the RT depends on the experimenter pressing the space bar at the same time as he or she delivers the stimulus, there is some error associated with starting the clock and presenting the stimulus simultaneously; however, for a group of 8 subjects tested on the fingers, the mean RT was 2.7 sec and the error, relative to RTs of this size, is likely to be small.

After the last response is collected, the data are written to an ASCII file that contains a header, the stimulus points, the response points, the reaction time, the calculated error for each point, the average EOL, and the average RT. The standard deviation can also be computed, and large EOLs—that is, large relative to the mean and standard deviation of the responses—can be displayed at this time. This information allows the experimenter to retest locations that show particularly large errors.

To obtain a graphic representation of the collected data, we read the data file into a spreadsheet program. Using the digitizing tablet and the photocopy of the hand, it is also easy to enter and store an individual image of each subject's hand. To do this, we use the digitizing pen to trace the outside edges of the photocopied image. In fact, we enter a series of points (typically about 100-150) and then, when displaying the image, connect adjacent points. To obtain both the image of the hand and a graphic representation takes about 5 min. An example of the type of resulting image is shown in Figure 2. The image makes it possible to display each trial—that is, the location of each stimulus and the corresponding response—or to display a designated subset of the data. For example, we have found it useful to display all trials with EOLs greater than the mean error for that subject. Other ways to sort and display the data might be by all stimuli or all responses that occur within a predefined location on the skin.

For certain experimental studies and certain clinical applications, repeated testing of subjects is required. For most of these studies, it is unnecessary to test precisely the same points on the skin over a period of weeks and months—simply measuring the EOL for a particular region is sufficient—however, for some applications, it is necessary to return to the same locations over time and to determine changes in the EOL at those locations. In one study, we made a plaster cast of each subject's hand. We drilled holes in the cast and used these holes to mark the points on the skin to be tested. For some testing situations, a single template, to be used with all subjects, is useful. The template is constructed with fixed, interhole spacing. Such templates greatly reduce the time needed to mark points on the subject's skin.

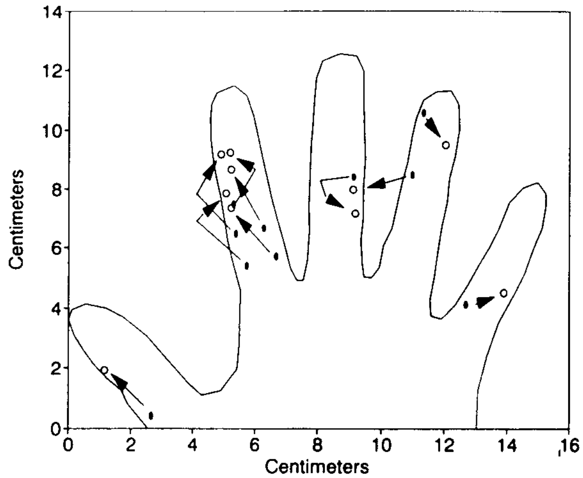

Figure 2. A graphic representation of a typical subject's hand and of 10 of the 56 trials showing the largest EOL. The filled circle represents the stimulus; the open circle represents the response. This subject shows 1 interdigit confusion (D4 to D3) out of 56 trials.

RESULTS AND DISCUSSION

The absolute size of the EOL depends on the method used to measure it (Boring, 1942; Loomis, 1979). Because of the number of differences between the procedures used in previous studies and our procedure, direct comparisons of the size of the EOL determined with various procedures are difficult. It is likely that because subjects are not touching their skin directly, and thus receiving feedback, the EOLs will be larger with the present technique than with those techniques that allow direct contact. The rank ordering of the average EOLs for the areas of the body we have tested are similar to those obtained in previous studies (Weinstein, 1968). The average EOL is approximately 7.5 mm on the fingerpads,[2] 11.6 mm on the palm, and 30.6 mm on the volar forearm. The ratio of the EOL on the distal fingerpad to the medial fingerpad is 1:1.2, and the ratio for the distal to the proximal fingerpad is 1:1.7. These results are consistent with Vierordt's law of mobility, which states that sensitivity increases with mobility (Boring, 1942; Sherrick & Cholewiak, 1986). For our technique, the ratio of the EOL on the distal fingerpad (5.5 mm) to the forearm is 1:5.6. Weber (cited in Boring, 1942) reported a ratio of 1:7.7, and Weinstein (1968) reported a ratio of approximately 1:5.7. Overall, there appears to be a reasonable agreement between the present and earlier techniques with respect to relative sensitivity.

We were also able to compare the EOL measured with the digitizing tablet with that measured by the wire mesh, as described above. Four subjects who responded by pointing to spatial coordinates on the wire mesh showed an average EOL of 31.1 mm. This value resulted from repeated testing of the volar surface of the left forearm. Four different subjects, also tested repeatedly on the left volar forearm, had an EOL of 30.6 mm when tested on the digitizing pad. It appears that these two procedures, pointing to a location above a site on the arm or pointing to a location on a photocopy of the arm, produced comparable results.

We have considered several other ways, in addition to the use of the digitizing tablet, to enter subjects' responses directly into the computer. One way would be to use a drawing of the part of the body to be tested and to present that on a monitor screen. The subject could respond by using a light pen to mark the location on the drawing where the touch was felt. As with the digitizing tablet, the point to be tested would have to be entered in advance. Other ways of inputting responses, such as positioning a cursor by means of a mouse or using a touch sensitive screen, could be examined. A potential disadvantage of these methods is the relatively small size of the screen on most monitors. It is a matter for further investigation whether the ease and accuracy of these methods is adequate for specific uses.

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NOTES

1. The pen produces an audible click that tells the subject a response has been recorded. The pen has an additional button on its side that might be pressed inadvertently. The computer tests whether the data are coming from a pen press or from a side-button press. A side-button press is considered inadvertent, and the subject is asked to press the pen again on that trial.

2. The EOL on the fingerpads was computed by averaging across all fingers and the three interphalangeal areas. Errors in which subjects confused one digit with another were deleted from this analysis.

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