Objective Measurement of Tactile Mislocalization

Christoph Braun*, Jennifer Ladda, Michaela Burkhardt, Katja Wiech, Hubert Preissl, and Larry E. Roberts

***Abstract*—Stimulating the skin with intensities close to the sensory threshold causes erroneous localization of the site of stimulation. Previous studies using manual methods for applying faint tactile stimuli have shown that localization errors obey a somatotopic principle in which tactile stimuli are preferentially mislocalized to sites adjacent to the stimulated skin region. However, manual testing of mislocalization is time consuming and only partially objective because results depend on the skills of the tester. To improve the testing procedure, an automated apparatus was developed. The procedure adjusted stimulus intensity adaptively during testing to remain near the individual subject's sensory threshold, so that mislocalizations occurred often enough to assess somatotopic organization. The new method was applied to 12 healthy subjects. In each subject, the five digits of the right hand were stimulated singly in random order. Localization errors were distributed preferentially to fingers close to the stimulated finger rather than to distant fingers. The profile of mislocalization differed significantly from that expected on the basis of response bias or guessing behavior. The present results replicate previous findings obtained for manual testing with improved sensitivity and indicate that the new technique is a useful tool for the study of somatosensory processing on a perceptual level.**

***Index Terms*—Instrumentation, mislocalization, perception, psychophysics, sensory threshold, somatosensory system.**

I. Introduction

DETECTION and localization of tactile stimuli are the main functions of the somatosensory system. The ability to correctly localize tactile stimuli depends, first, on stimulus parameters such as the intensity, texture, and geometry of the stimulus. Temporal characteristics of the stimulation are also relevant; e.g., vibratory stimuli and stimuli moving across the hand are more easily perceived and localized than static stimuli applied to the skin [1]. Second, localization accuracy depends on the site of stimulation. In humans, the lowest perception and localization thresholds for tactile stimuli are found at the lips and the finger tips [2]–[4]. As inferred by two-point discrimination procedures, spatial resolution is also best in these regions [3]. Detection and localization are also modulated by the attentional state of the subject. Focusing attention on the site of stimulus application yields improved perception, discrimination, and localization thresholds compared with unattended stimulation [5]–[7]. Finally, sensory performance can be altered by learning. For example, discrimination of small changes in the frequency of tactile stimulation is improved by practice at tasks that involve processing of tactile stimulus frequency under conditions of attention [8], [9]. Furthermore, changes in the two-point discrimination threshold after intensive tactile experience [10] and synchronous stimulation of nearby skin regions have been reported [11]–[13].

Additional information about features of the somatosensory system can be obtained by studying errors in tactile localization. Localization errors occur when subjects report stimulation at one skin site although the stimulus was applied to a different skin site. When healthy subjects are stimulated by faint tactile stimuli such as "von Frey hairs" or "Semmes-Weinstein monofilaments" [14]–[16], localization errors reveal a systematic pattern. Schweizer *et al.* [17], [18] applied von Frey hairs at intensities close to the sensory threshold to a target finger chosen randomly on one hand, and then they required a localization judgment. Mislocalizations were preferentially assigned to fingers neighbored to the stimulated finger compared to distant fingers. Localization performance was also altered by learning. Localization errors with respect to a target finger shifted toward distant compared with proximal fingers after perceptual training in which distant and target fingers were stimulated simultaneously [18].

The topographical relationship between tactile stimulation and mislocalization suggests that localization errors reflect the functional organization of the primary somatosensory cortex. Physiological studies of somatosensory interactions in animals suggest that sensory input to primary somatosensory cortex is not only a point-to-point projection from a circumscribed skin region to a focal area of the cortex, but also it involves interactions between the center of the cortical representation and the surrounding cortical representations of adjoining skin regions [19]. If it is assumed that surrounding areas are inhibited less by near-threshold than by supra-threshold stimulation of a skin site, then localization errors (which are more likely to occur under conditions of near-threshold than supra-threshold stimulation) might be explained by an enhanced role for neighboring cortical representation areas when stimulation is weak. Although this model is tentative and needs concise experimental proof, it

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can explain mislocalization effects in subjects with both normal and reorganized primary somatosensory cortex [18], [20]–[23]. For example, in patients suffering from amputation of a hand, it has been shown that the former hand representation in primary somatosensory cortex receives input from a nearby representation of the face. Correspondingly, faint tactile stimulation of the face using a cotton swab elicits mislocalization of the face stimuli to the amputated limb referred to as phantom sensations [24]–[26]. Input from adjoining cortical regions seems likely to be involved in localization errors of this type, although the precise relationship of functional reorganization in the primary somatosensory cortex to phantom sensations is debated and interactions occurring at other levels of the somatosensory projection pathway may contribute [27], [28].

Previous studies of localization have stimulated the selected target finger manually by placing a filament on the skin at near-threshold intensity and then calling for a localization judgment. Although the study of mislocalization seems to be a promising tool for assessing somatosensory interactions, manual estimation of the mislocalization profile has some problems. First, it is only possible within certain limits to manually place filaments in the same way on each trial. Varying the angle and the speed of positioning, the filament might alter stimulus perception. It is also difficult to avoid movement across the skin inducing vibratory sensation as the filament crosses ridges in the fingerprint. Because different testers develop different techniques for placing the filament, it is essential that individual subjects be evaluated by the same experimenter when repeated measurements are required. Alternatively, if several experimenters are involved, intensive training on the placement of filaments must be given to control stimulus conditions. Second, thresholds may change during the measurement due to variations in attention and sensory learning. If during the course of an experiment localization accuracy increases because of learning, then the probability of mislocalization decreases, and the influence of somatotopic organization becomes difficult to detect. On the contrary, if concentration on the localization task fades during the experiment, thresholds increase and the effects of near- or sub-threshold information processing can be obscured by guessing. To overcome these problems, it is desirable to track the localization threshold during the measurement and adjust stimulus intensity accordingly [29]. However, adaptive procedures of this type are difficult to implement in manual testing because of the need for continuous adjustment of stimulus intensity. Finally, manual assessment of localization errors is time consuming. Automation of the procedure would shorten trial duration and allow more measurements to be taken, thus reducing measurement error in the estimation of the mislocalization profile.

In this paper, we describe an automated apparatus designed to overcome the limitations of manual testing. Localization errors detected by the apparatus were determined for stimuli applied to the fingers of the right hand of 12 healthy subjects and compared with the distribution of errors expected on the basis of guessing behavior. Furthermore, the results obtained by the automated procedure were compared with the results of a manual testing strategy [18].

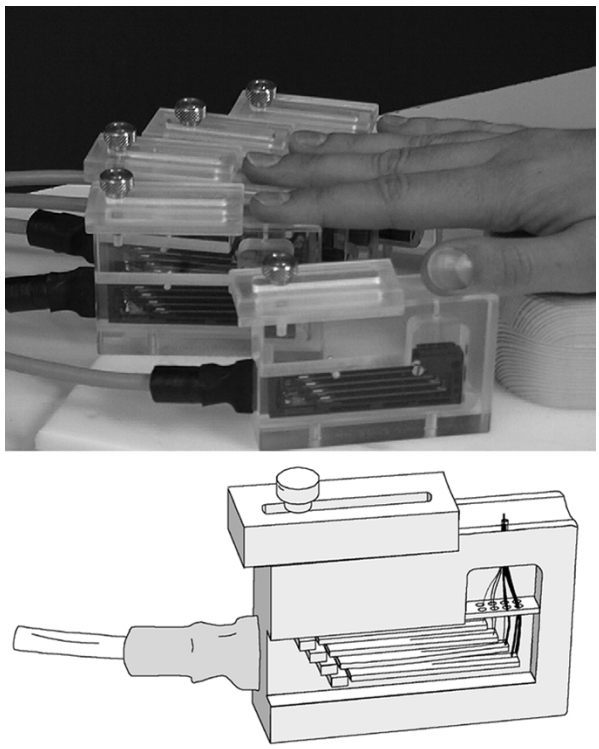

Fig. 1. Photograph and sketch of stimulation device. Fingers are placed on a support. Filaments of different thickness are protruded by piezoelectric crystals.

II. Material and Methods

Eight women and four men (aged 23–38 years, $\mathrm{m}\pm\mathrm{sd}$: 25.4 ± 4.8 years, all right-handed and reporting good health) participated in the study after having given written informed consent. The apparatus (Fig. 1) consisted of a hand support on which subjects placed their right hand palm down. A stimulation unit was located beneath each finger. Stimulation units were based on commercially available display elements for Braille letters (metec AG, Stuttgart, Germany) employed for blind computer users. Single Braille elements consist of eight rods arranged in a 2×4 matrix that can be protruded individually by the activation of piezocrystals. When activated, the rods form a tactile pattern that codes for alphanumerical characters. In our experiment, the Braille element was modified such that seven of the eight rods were replaced by filaments of different thickness. The different filaments generated forces $(\mathrm{m} \pm \mathrm{sd})$ of $0.32 \pm 0.08, 0.85 \pm 0.39, 1.15 \pm 0.26$, $2.27 \pm 0.42, 1.75 \pm 0.58, 4.03 \pm 1.09$, and 5.47 ± 0.86 mN. Filaments were glued onto the piezocrystals. The free ends of all filaments were fed through a single hole in the finger mold. The length of filaments was such that they could not be felt when the piezocrystal was in its resting position. Depending on the activation of a single crystal, either no filament or a distinct filament was moved toward the skin. The hole in the finger mold ensured that all filaments stimulated a defined location at an individual finger. Like "von Frey hairs" and "Semmes-Weinstein filaments," each filament produced a certain force on the skin. By loosening a fixation screw, the position and orientation of the stimulus device could be altered to accommodate different hand sizes (Fig. 1). As the activation of a single rod produced a click, at the eighth position, no filament was mounted serving as an acoustic sham stimulus. In each trial,

TABLE I
EXAMPLE FOR NORMALIZATION OF MISLOCALIZATIONS

$f(i\,\vert\,k)$		Response i						$\tilde{f}(i\,\vert\,k)$	response i					
stimulation		d1	d2	d3	d4	d5	Sum		d1	d2	d3	d4	d5	Sum
k	d1	26	7	6	4	3	20	d1		4.9	4.2	2.8	2.1	14
	d2	1	32	4	4	2	11	d2	1.3		5.1	5.1	2.5	14
	d3	2	5	23	2	3	12	d3	2.3	5.8		2.3	3.5	14
	d4	1	3	4	25	2	10	d4	1.4	4.2	5.6		2.8	14
	d5	2	6	2	7	25	17	d5	1.6	4.9	1.6	5.8		14
	Sum						70	Sum						70

only one finger of the right hand was stimulated. To avoid any acoustic cues that might inform subjects about the finger being stimulated, the acoustic sham stimulus was applied at all non-tactilely stimulated fingers. Stimuli were delivered for 1 s.

After each stimulus, subjects indicated the site of stimulation by clicking with a computer mouse on one digit of a hand scheme displayed on a computer screen. The computer mouse was operated with the left hand. An interval of 4 s was allowed for responding. If the selected finger on the screen was correct, it turned green, and if not, it turned red. If no stimulus was perceived, subjects were asked to indicate their best guess. Responses were stored on a computer for off-line analysis of the localization responses. Feedback was given to increase the motivation of the subjects.

Fingers were stimulated in pseudo-random order such that by the end of the session all fingers had been stimulated approximately the same number of times. Stimulus intensity at each finger was adjusted to be close to the localization threshold determined by the method of limits. Beginning with the thickest filament, which was correctly localized by all subjects, filaments one grade thinner were applied until a localization error occurred. When a localization error occurred, a filament one grade thicker was chosen until a correct response was made. This procedure was continued throughout testing and resulted in maintenance of finger-specific stimulation intensities that were close to the localization thresholds of each finger. The stimulation procedure was repeated until at least ten mislocalizations were obtained for each stimulated finger. On average, each finger was stimulated about 40.5 ± 15.9 times in a single run that lasted about 15 min.

III. DATA ANALYSIS

Data analysis was performed in accordance with the studies of Schweizer *et al.* [17], [18], in which tactile mislocalizations were measured using a manual testing method. Due to the randomized presentation of stimuli at the different fingers, the number of mislocalizations obtained was not equal for all fingers and, therefore, could not be compared directly. Therefore, in a first step of the data analysis, the frequency of mislocalizations was normalized for each finger. The normalization was done for each subject such that the number of mislocalizations was equal for every stimulated finger and that the overall number of mislocalizations was maintained. The normalized number of mislocalization $\tilde{f}(i\,|\,k)$ for a stimulus presented at finger k and attributed to finger i was obtained by weighting the absolute number of mislocalizations $f(i\,|\,k)$ according to

$$\tilde{f}(i\,|\,k) = \frac{1}{5}\frac{f(i\,|\,k)F_{\mathrm{tot}}}{F(k)} \tag{1}$$

where $F(k) = \sum_{i\neq k, i=1}^{5} f(i\,|\,k)$ was the number of mislocalizations for stimulation of finger k and $F_{\mathrm{tot}} = \sum_{k=1}^{5}\sum_{i\neq k, i=1}^{5} f(i\,|\,k)$ equaled the total number of localization errors across all fingers.

An example of normalization for a representative subject is given in Table I.

A second step of the analysis determined whether localization errors were more likely to be reported for some nonstimulated fingers than for others. Analogous to the studies of Schweizer *et al.* [17], [18], five separate analyses of variance (ANOVAs) were conducted, one for each stimulated finger, comparing localization errors across the unstimulated digits using the repeated-measure factor "FINGER" with four levels (all fingers except the stimulated one). Subsequent *post-hoc* tests revealed which erroneously named fingers were selected above or below chance level. To account for violations of the sphericity assumption of variances, the Greenhouse-Geisser correction was applied.

A third step of the analysis tested whether neighborhood was a factor in mislocalization. To test this hypothesis, mislocalizations were summed according to the degree of neighborhood with respect to the stimulated finger giving a distribution φ_j, with j being the first, second, third, or fourth neighbor. If d1 was stimulated, d2 was considered the first, d3 the second, d4 the third, and d5 the fourth neighbor. Likewise, for stimulation of d2, both d1 and d3 were first neighbors, d4 was second, and d5 was the third neighbor (see Table II for a complete set of neighborhood definitions). As in total there were eight first neighbors, six second neighbors, four third neighbors, and two

TABLE II
DEFINITION OF NEIGHBORHOOD RELATION

	Response				
stimulation	d1	d2	d3	d4	d5
D1		first	second	third	fourth
D2	first		first	second	Third
D3	second	first		first	second
D4	third	second	first		first
D5	fourth	third	second	first	

fourth neighbors, the frequency of mislocalizations can be expected to differ among the neighborhoods even in the case of random selection. To prepare the data for assessment of neighborhood effects, mislocalization frequencies were first normalized by dividing them by neighborhood frequency n_j ($n_{\text{first}} = 8, n_{\text{second}} = 6, n_{\text{third}} = 4$, and $n_{\text{fourth}} = 2$; Table II)

$$\tilde{\varphi}_j = \frac{1}{n_j}\varphi_j. \tag{2}$$

The transformed data were then subjected to a one factorial ANOVA involving the repeated measurement factor NEIGHBORHOOD with four levels (first, second, third, and fourth neighbor). *Post-hoc* tests determined which neighborhood effects deviated significantly from chance. Again, the Greenhouse-Geisser correction was applied.

Two subsequent analyses determined whether the mislocalization profile could be differentiated from profiles expected on the basis of guessing behavior by the subject. For this purpose, normalized mislocalization profiles were summed across subjects. The resulting profile was compared with a chance distribution using a G-test [30]. In a first test, the chance distribution was based on the assumption that subjects randomly selected a finger on the localization test. As most fingers are first neighbors and progressively fewer fingers are second, third, and fourth neighbors (see Table II), a chance distribution was calculated using (3)–(6) with $f_{d1} = f_{d2} = f_{d3} = f_{d4} = f_{d5} = (1/5)\sum_{i=1}^{5}\tilde{f}(i)$, and with the total number of mislocalizations being the same as for the observed frequencies. In a second test, it was considered that guessing behavior might be affected by a bias in naming specific fingers more frequently than others. For example, it might be supposed that subjects selected middle fingers of the hand more frequently as their response due to uncertainty. To infer any bias in response selection, frequencies for naming individual fingers $f_{di} = \tilde{f}(i)$ were calculated by summing individual responses, regardless of which finger was stimulated. Consecutively, a chance profile of mislocalizations due to the degree of neighborhood $\hat{\varphi}_j$ was delineated.

$$\hat{\varphi}_{\text{first}} = \frac{1}{4}f_{d1} + \frac{1}{2}f_{d2} + \frac{1}{2}f_{d3} + \frac{1}{2}f_{d4} + \frac{1}{4}f_{d5} \tag{3}$$

$$\hat{\varphi}_{\text{second}} = \frac{1}{4}f_{d1} + \frac{1}{4}f_{d2} + \frac{1}{2}f_{d3} + \frac{1}{4}f_{d4} + \frac{1}{4}f_{d5} \tag{4}$$

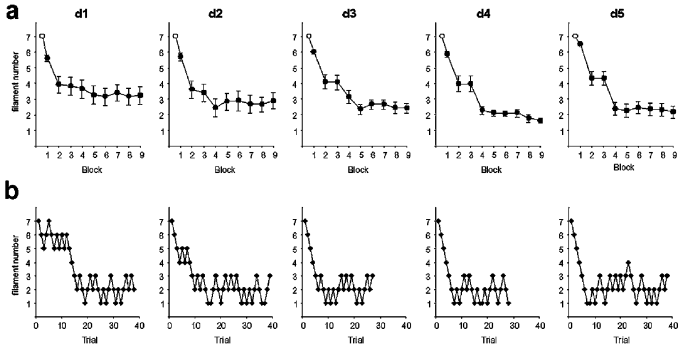

Fig. 2. (a) Average stimulus intensity (number of "von Frey hair," ordinate; number 1 refers to the weakest stimulus and number 7 to the strongest stimulus) applied during blocks of trials at the fingers of the right hand (d1: thumb—d5: little finger). Each block consisted of 20 subsequent trials, during which the specified finger was stimulated in a random series of finger stimulations. Starting intensity was always 7 (open circle). (b) The course of stimulus intensities applied to the five fingers in a single subject. Intensity decreased smoothly to threshold followed by brief increases, particularly for d5. Changes of threshold may be caused by shifts of attention. A decrease in threshold might also be the consequence of sensory learning occurring with stimulus repetition. Small movements of the finger affecting stimulus location could also explain fluctuations in threshold.

$$\hat{\varphi}_{\text{thrird}} = \frac{1}{4}f_{d1} + \frac{1}{4}f_{d2} + \frac{1}{4}f_{d4} + \frac{1}{4}f_{d5} \tag{5}$$

$$\hat{\varphi}_{\text{forth}} = \frac{1}{4}f_{d1} + \frac{1}{4}f_{d5}. \tag{6}$$

To test whether the observed profile differed from the hypothetical distribution, a G-test for goodness of fit [30] was applied. The test value

$$G = 2\sum_{j=1}^{4}\varphi_j \ln\left(\frac{\varphi_j}{\hat{\varphi}_j}\right) \tag{7}$$

was tested by a χ^2-distribution with 3 degrees of freedom.

In a final step of the analysis, the profile obtained for automated testing was compared with the results of manual testing published in Schweizer *et al.* [18]. To this end, profiles relating misolcalizations to the degree of neighborhood were normalized such that the total number of mislocalizations was identical for each method. Profiles were then compared by a two factorial ANOVA with the between factor METHOD (levels: automated and manual) and the within factors NEIGHBORHOOD. Again, the Greenhouse-Geisser Correction was applied.

IV. RESULTS

On average, $168.3 \pm 6.3(\text{m} \pm \text{se})$ stimuli were delivered per subject. The average number of mislocalizations was 70.5 ± 0.6, which corresponds to an error rate of 42%. Changes in stimulus intensity over test blocks averaged across subjects are depicted for all five stimulated fingers in Fig. 2(a). Beginning with intensity 7 (corresponding to the strongest filament), intensity decreased with subsequent stimulations of a particular finger until the localization threshold was reached. The results for a single representative subject are shown in Fig. 2(b). Stimulus intensity typically decreased toward threshold followed by short-lived increases after localization failures.

The profile of mislocalizations after stimulation is shown for the group as a whole in Fig. 3, separately for each stimulated

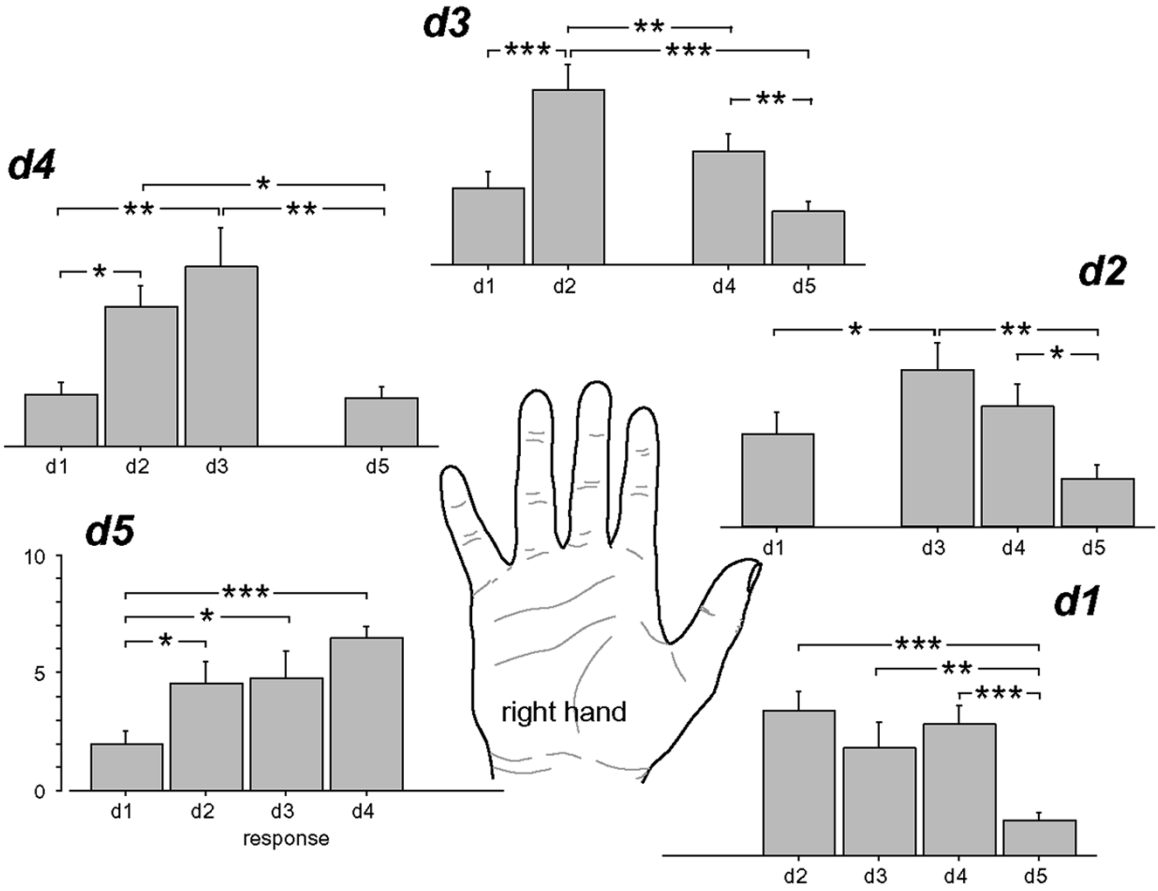

Fig. 3. Mislocalization profiles for stimulation of different fingers. Individual digits from thumb to little finger are labeled by "d1" to "d5". Depending on the level of significance, differences are marked by one to three asterisks $(*\colon 0.01 < \mathrm{p} \leq 0.05; **\colon 0.001 < \mathrm{p} \leq 0.01; ***\colon \mathrm{p} \leq 0.001)$.

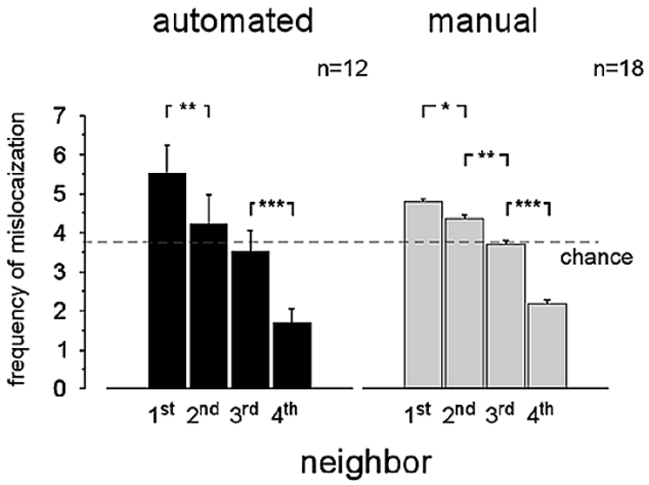

Fig. 4. Mean frequency of mislocalization as a function of the degree of neighborhood, normalized for neighborhood frequency. Random guessing corresponds to the horizontal dashed line. Data of the automated approach (left panel) are compared with manual testing (right panel). The negative slope in the mislocalization profile is more pronounced for the automated than for the manual procedure. To infer significant differences between mislocalization frequencies, contrast analyses were calculated for adjacent degrees of neighborhood. The significance level is indicated by one to three asterisks $(*\colon 0.01 < \mathrm{p} \leq 0.05; **\colon 0.001 < \mathrm{p} \leq 0.01; ***\colon \mathrm{p} \leq 0.001)$.

finger. To infer whether mislocalizations were assigned equally to all nonstimulated fingers, five ANOVA's were calculated, one for each stimulated finger, including the repeated measurement factor FINGER with four levels according to the number of fingers to which a stimulus could be mislocalized. For all ANOVA's, the factor FINGER was significant, which indicated that individual fingers were not chosen equally frequently (stimulation of d1: $\mathrm{F}(3,33) = 11.14, \mathrm{p} = 0.0001, \varepsilon = 0.82$; d2: $\mathrm{F}(3,33) = 5.70, \mathrm{p} = 0.0105, \varepsilon = 0.66$; d3: $\mathrm{F}(3,33) = 15.46, \mathrm{p} = 0.0001, \varepsilon = 0.69$; d4: $\mathrm{F}(3,33) = 9.50, \mathrm{p} = 0.0017, \varepsilon = 0.60$; d5: $\mathrm{F}(3,33) = 7.73, \mathrm{p} = 0.0029, \varepsilon = 0.67$). The results of paired comparisons are depicted in Fig. 3.

Inspection of Fig. 3 suggests that mislocalizations were more likely to occur for fingers neighboring the stimulated finger than for more distant fingers. To evaluate this effect, mislocalization responses were reordered according to their proximity to the stimulated finger and are presented in Fig. 4. ANOVA revealed an effect of neighborhood $(\mathrm{F}(3,33) = 29.64, \mathrm{p} = 0.0001, \varepsilon = 0.78)$. Contrasts summarized in Fig. 4 (left panel) indicate that the number of mislocalizations attributed to the first neighbor was larger compared with all other neighbors and that the frequency of mislocalizations attributed to the fourth neighbor was the lowest of the group.

Two subsequent analyses compared the observed distribution of mislocalizations with respect to neighborhood with chance distributions calculated in two ways. The results are presented in Fig. 5. First, the chance distribution that is expected if subjects were simply guessing without a bias among fingers [inset a), Fig. 5] was calculated. The expected distribution (expected unbiased selection, Fig. 5) is not rectangular because first

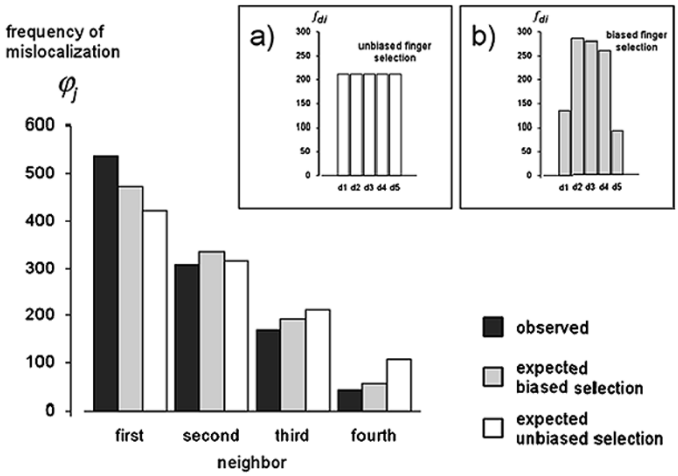

Fig. 5. Pooled frequencies of mislocalizations observed across subjects for different degrees of neighborhood (black bars) φ_j. Results are compared with profiles that can be expected if naming of stimulus locations occurs on the basis of guessing $\hat{\varphi}_j$ (see text). White bars depict the chance distribution that arises by equally frequent random selection among the five fingers [unbiased selection, inset a)]. If guessing is influenced by a bias in naming different fingers regardless of which finger was stimulated, a biased distribution of mislocalizations f_{di} is obtained [gray bars, biased selection, inset b)]. Although the biased distribution resembles the observed distribution more closely than the distribution based on unbiased guessing, both distributions differ significantly from the observed profile.

neighbors are more common than second neighbors, and so on (see Table II). The observed mislocalization profile was found to differ significantly from the distribution expected from unbiased guessing $(\mathrm{G}(3) = 88.51, \mathrm{p} < 0.0001)$. The second analysis took into account possible response bias in localization behavior. The grand average of response choices across all subjects revealed a bias toward the middle fingers of the hand in finger naming [d1: 134 times, d2: 286, d3: 281, d4: 261 and d5: 92 times; inset b), Fig. 5]. Calculating an expected distribution of mislocalization from these frequencies (expected biased selection, Fig. 5) and comparing the expected frequencies with the observed profile of mislocalizations yielded a significant difference between both profiles $(\mathrm{G}(3) = 10.29, \mathrm{p} = 0.016)$. These tests indicate that the observed profile of mislocalization is not adequately explained by guessing, with or without response bias. There seems to be a systematic tendency in attributing mislocalized tactile stimuli preferentially to sites adjacent to the stimulated regions than to more distant regions.

A final analysis compared mislocalization profiles obtained by automated and manual testing. Data for manual testing were taken from Schweizer *et al.* [17] and are shown in Fig. 4 (right panel). An ANOVA including the two methods revealed an effect of neighborhood reflecting the above-mentioned results and previous findings $(\mathrm{F}(3, 84) = 99.71, \mathrm{p} < 0.0001, \varepsilon = 0.949)$. Additionally, a significant interaction between the two methods and the degree of neighborhood was obtained $(\mathrm{F}(3, 84) = 4.87, \mathrm{p} = 0.004, \varepsilon = 0.949)$. This interaction indicated that the effect of higher frequencies of mislocalizations to the nearest finger neighbor and lower frequencies to the more distant finger was stronger for automated than for manual testing (Fig. 4). Hence, although both manual and automated procedures detected neighborhood effects, the automated procedure did so without involvement of the experimenter and with greater sensitivity.

V. Discussion

Faint tactile stimuli applied to a finger with intensities close to the perception threshold are mislocalized to other digits [31], [32]. The phenomenon of mislocalization has also been reported for toes [33], [34]. However, systematic studies of mislocalization have not been undertaken until recently [17], [18]. In these studies (which employed stimulation of the digits), it has been shown that the pattern of mislocalizations is not adequately explained by guessing behavior on the part of the subject. Mislocalization profiles also deviated from those expected from possible biases in the *a priori* probability of response choices. Instead, the observed pattern of mislocalization corresponded to the somatotopic representation of the digits in the primary somatosensory cortex [35]. Localization errors were more probable for fingers adjoining the stimulated finger in the somatotopic representation than for fingers more distant to the target digit.

A possible limitation of these findings, however, is that studies reporting them used manual testing procedures. Because these procedures require manual placement of stimuli on the digit, a contribution of unintended experimenter bias cannot be fully discounted. Reliable application of tactile stimuli with spatial precision, constant speed, and positioning angle, and without sliding the filament across the skin, requires extensive training. Sliding of filaments placed on the skin is potentially a severe problem, because sensitivity for stimuli moving across the skin is much higher than for stimuli presented at a fixed location. These concerns raise the possibility that results may be corrupted when tactile stimuli are inadvertently moved during manual application. Manual testing of mislocalization is also time consuming and requires that the subject's attention be maintained for at least 30 min when one hand is tested.

To overcome these shortcomings of the manual approach, an automated testing device that can deliver faint tactile stimuli was developed and examined in this study. The new method was faster than the manual procedure, which allowed estimation of the mislocalization profile of one hand in about 10 to 15 min. Furthermore, automation assured that the stimuli were applied in exactly the same way on each trial. Using this method, we replicated our previous findings showing localization errors increasing as a function of increasing proximity to the stimulated digit (neighborhood). The obtained mislocalization profiles deviated significantly from profiles expected on the basis of guessing behavior with and without a response bias that was detected by summing all responses of incorrect stimuli. The response bias showed a clear tendency for preferring the central fingers.

If tactile stimuli are too faint to elicit any neuronal processing, mislocalizations would be identical to guessing. Only if stimulus intensities are applied that are close to the threshold it is assured that mislocalizations occur and that systematic deviations from guessing can be expected. To this end, the intensity of stimulation in the current procedure was adapted under computer control during testing, such that correct localizations yielded a weaker stimulus that was more difficult to localize and incorrect responses a stronger stimulus. This strategy is realized in a manual testing procedure only with considerable effort and is more susceptible to error than when thresholds are adjusted

by a computer. The automated method revealed a sharper gradient of mislocalization with respect to neighborhood than did the manual method, which indicates not only that the new device uncovered the mislocalization profile, but also that it did so with greater sensitivity than with manual testing. This method may, therefore, provide improved insight into the nature and relevance of plastic changes in the functional organization of the somatosensory cortex for tactile perception and stimulus processing.

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