

# Tactile spatial resolution in blind Braille readers

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**Article abstract**—*Objective:* To determine if blind people have heightened tactile spatial acuity. *Background:* Recently, studies using magnetic source imaging and somatosensory evoked potentials have shown that the cortical representation of the reading fingers of blind Braille readers is expanded compared to that of fingers of sighted subjects. Furthermore, the visual cortex is activated during certain tactile tasks in blind subjects but not sighted subjects. The authors hypothesized that the expanded cortical representation of fingers used in Braille reading may reflect an enhanced fidelity in the neural transmission of spatial details of a stimulus. If so, the quantitative limit of spatial acuity would be superior in blind people. *Methods:* The authors employed a grating orientation discrimination task in which threshold performance is accounted for by the spatial resolution limits of the neural image evoked by a stimulus. The authors quantified the psychophysical limits of spatial acuity at the middle and index fingers of 15 blind Braille readers and 15 sighted control subjects. *Results:* The mean grating orientation threshold was significantly ( $p = 0.03$ ) lower in the blind group (1.04 mm) compared to the sighted group (1.46 mm). The self-reported dominant reading finger in blind subjects had a mean grating orientation threshold of 0.80 mm, which was significantly better than other fingers tested. Thresholds at non-Braille reading fingers in blind subjects averaged 1.12 mm, which were also superior to sighted subjects' performances. *Conclusion:* Superior tactile spatial acuity in blind Braille readers may represent an adaptive, behavioral correlate of cortical plasticity. **Key words:** Touch—Blindness—Discrimination learning—Form perception.

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Do blind people develop superior capacities in their remaining senses compared with sighted persons? If so, is the nature of the sensory signal (neural representation of sensory stimuli) the same in both blind and sighted persons, but do blind persons simply pay more attention to it?

The neural representation of nonvisual sensory stimuli is different in blind people. Stimulation at the reading finger of blind Braille readers results in expanded areas of scalp-recorded somatosensory evoked potentials<sup>1</sup> and cortical magnetic responses.<sup>2</sup> Furthermore, tactual or auditory stimuli activate the visual cortex in blind subjects.<sup>3–6</sup> The plasticity observed within the somatosensory as well as across sensory modalities (cross-modal changes) has been suggested to represent an adaptive change in neural processing enabling a compensatory improvement in the capacities of the remaining senses. However, previous behavioral studies have not demonstrated uniform differences in blind subjects for a great variety of tasks. In fact, blind Braille readers misidentify

which finger is being touched and this has been suggested to possibly be a maladaptive result of cortical reorganization.<sup>2</sup>

We hypothesized that the proposed neural network remodeling (modal and cross-modal) in blind Braille readers<sup>1–6</sup> represents an example of compensatory, adaptive change<sup>6</sup> with a behavioral correlate in enhanced tactile spatial acuity. As it is problematic to compare naïve sighted individuals and proficient Braille readers in a Braille identification task, we chose to compare performance in another task novel for both groups yet similar to Braille in that performance is specifically dependent upon resolving the spatial neural profile. Unlike the two-point discrimination task, which is subject to spurious, non-spatial cues,<sup>7</sup> a grating orientation task<sup>8</sup> (GOT) provides a reliable, quantitative measure of spatial acuity. Based on the hypothesis that the increased area of cortical representation observed in blind subjects provides a finer grain of spatial information about surface details of a stimulus, we predicted a behavioral

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**See also page 2203**

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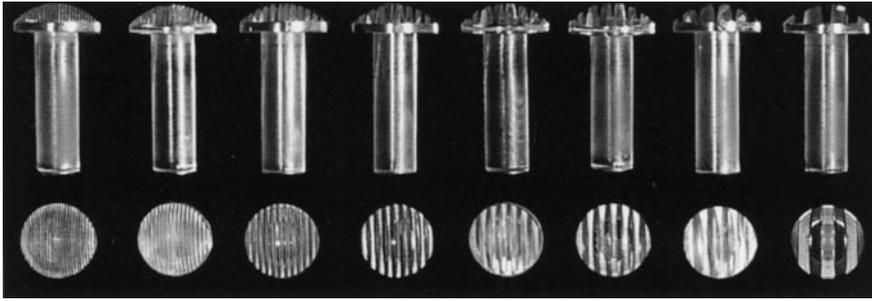


Figure 1. Johnson–Van Boven–Phillips Domes. A set of eight different plastic gratings used for assessing tactile spatial resolution. Dome gratings have equidistant bar and groove widths measuring 0.35, 0.50, 0.75, 1.00, 1.25, 1.50, 2.00, and 3.00 mm. Photograph displays gratings at approximately 58% of actual size.

gain in tactile spatial resolution. Preliminary findings of this study have been reported previously.<sup>9</sup>

**Methods.** *Subjects.* Fifteen blind subjects and 15 sighted control subjects were studied. Exclusion criteria for both groups included history of neurologic disorders known to impair somatosensory function; trauma to the hands or their innervation; calluses at the test sites; and known cognitive or psychiatric impairments, including dyslexia. The blind group consisted of six men and nine women, with a mean age of 42 years (range 25 to 55 years), whose onset of blindness had occurred before age 6. The causes for blindness included retrolental fibroplasia ( $n = 7$ ), retinitis pigmentosa ( $n = 6$ ), and retinoblastoma ( $n = 2$ ). None of the blind subjects had any residual light perception. The subjects began reading Braille at a median age of 6 years (range 4 to 14 years). Braille reading averaged 1.7 hours per day (range 30 minutes to 6 hours).

The sighted controls were age- and gender-matched to the Braille-reading blind subjects; none was familiar with Braille. All had (corrected or uncorrected) 20/20 vision and a normal neurologic and medical examination. The study protocol was approved by the Beth Israel-Deaconess Human Studies Institutional Review Board and all subjects gave informed consent.

*Study design.* Each subject participated in a GOT testing session lasting approximately 45 minutes. Afterwards, subjects were queried regarding self-perceived overall handedness (global self-assessment) and administered a modified Edinburgh Handedness Inventory questionnaire.<sup>10</sup> Blind subjects were asked which fingers they used for Braille reading and which finger(s), if any, served a dominant role in Braille character identification (dominant finger).

The GOT was administered according to the method described previously.<sup>11</sup> A set of eight hemispherical plastic domes with gratings cut into their surfaces, resulting in parallel bars and grooves of equal widths at each dome, were used (JVP Domes, Stoelting Co., Wood Dale, IL [figure 1]).

Subjects were seated in a quiet room, instructed in the task, blindfolded if sighted, and then tested. The test sites were the distal pads of the middle and index fingers of both hands. The hand was placed comfortably in a supinated position and the finger was immobilized using adhesive tape applied to the nail. Gratings were applied manually by an experimenter with moderate force judged to be comfortable by the subjects. As behavioral performance in spatial resolution is relatively insensitive to the force of application<sup>12</sup> and the spatial response profile and receptive field size of the afferent population responsible for performance is relatively independent of the skin indentation depth for complex surfaces,<sup>13</sup> manual application

(resulting in approximately 2 mm of skin displacement) was used.

For each trial, the grating was applied perpendicularly to the surface of the distal pad with the bars and grooves aligned in one of two orthogonal directions (i.e., along or perpendicular to the long axis of the finger) and held for about 1.5 seconds. Subjects were required to identify the stimulus orientation (two-alternative forced choice paradigm) verbally before the stimulus was removed. Careful attention was given to inspect visually and reject any trials in which movement between the skin and grating occurred. Such movement (which rarely occurred) introduces an undesirable temporal cue for performance.<sup>8</sup> Blocks of 20 trials for each grating were administered. The orientation for each trial was selected from a random number table.

*Data analysis.* The grating orientation threshold was determined by interpolating between groove widths spanning 75% correct responses (unless performance was at 75% correct response rate for a particular grating). Performance at this level is midway between chance and perfect performance and is a standard psychophysical threshold criterion.<sup>11</sup> The initial grating selected for testing was one that was easily resolved by a subject (yielding a high percent correct response level). Thereafter, gratings were presented in a descending groove width order until performance approached chance performance (50% correct responses). The order of finger testing was randomized for each subject. Analyses of variance (ANOVAs) with repeated measures or two-tailed *t*-tests were used to compare the blind and sighted groups for all dependent variables. Post hoc comparisons were made using pairwise *t*-tests with the Bonferroni correction. Correlation analyses were performed with Pearson correlation coefficients. Kappa coefficient was used to analyze the degree of agreement between preferred sites of sensory and motor performance. The analysis was conducted using SAS (SAS Institute Inc., Cary, NC).

**Results.** *Blind group versus sighted group performance.* The means for individual finger thresholds and for those of the four fingers combined are depicted in figure 2. Blind subjects had a lower mean threshold of 1.04 mm (SD = 0.19) compared to 1.46 mm (SD = 0.46) for the sighted group ( $F = 10.78$ ,  $df = 1,28$ ,  $p = 0.003$ ). There was a significant group  $\times$  finger interaction ( $F = 3.03$ ;  $df = 3,84$ ;  $p = 0.034$ ), indicating that the extent of the difference in thresholds between the two groups was not the same across fingertips. There was not a significant finger effect ( $F = 2.02$ ;  $df = 3,84$ ;  $p = 0.118$ ). Post hoc comparisons revealed that blind subjects also performed significantly better at each individual finger tested compared to sighted subjects (right index finger,  $t = -7.28$ ,  $df = 84$ ,  $p < 0.001$ ;

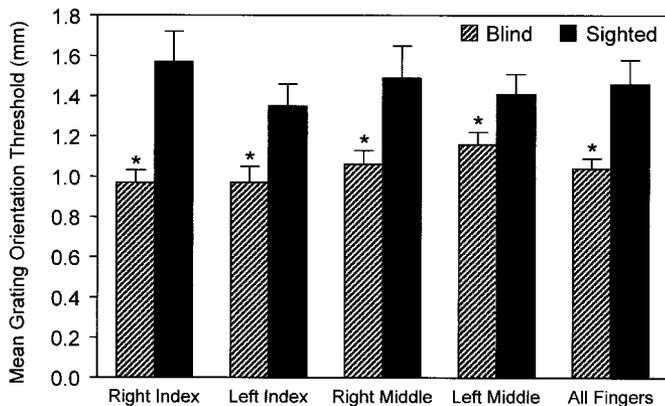


Figure 2. Grating orientation thresholds for blind and sighted subjects at four individual fingers and four fingers combined. The ordinate represents grating orientation threshold, expressed as the groove (or bar) width required for 75% correct responses. Error bars represent SE. \* $p \leq 0.003$ .

left index finger,  $t = -4.63$ ,  $df = 84$ ,  $p < 0.001$ ; right middle finger,  $t = -5.31$ ,  $df = 84$ ,  $p < 0.001$ ; left middle finger,  $t = -3.08$ ,  $df = 84$ ,  $p = 0.003$ ). The blind group's mean threshold at fingers not reportedly used in Braille reading was also significantly lower than the mean threshold for all fingers tested in the sighted group (figure 3; two-tailed  $t$  test,  $t = -2.64$ ,  $df = 19.6$ ,  $p = 0.02$ ).

**Blind subjects: performance at finger dominant for sensory processing.** Thirteen of 15 blind subjects reported a single dominant finger in the identification of Braille characters (six subjects indicated the right index finger, five indicated the left index finger, and two indicated the right middle finger). The two remaining blind subjects reported using both index fingers equally for Braille character identification. Data from the 13 blind subjects who reported a single dominant finger were further analyzed for within-subject differences in performance at each finger tested. Figure 4 illustrates the mean spatial acuity threshold at

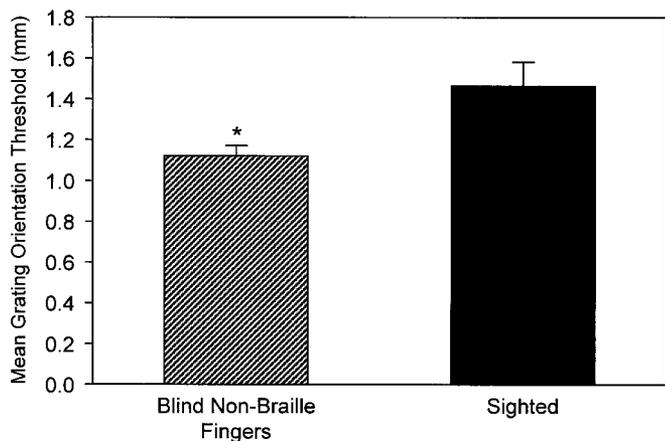


Figure 3. Grating orientation thresholds for blind and sighted subjects. The mean threshold for blind subjects was derived from thresholds at all fingers tested and judged, by subjects, as not being used for Braille character identification. The mean threshold for sighted subjects represents all fingers tested. Error bars represent SE. \* $p = 0.02$ .

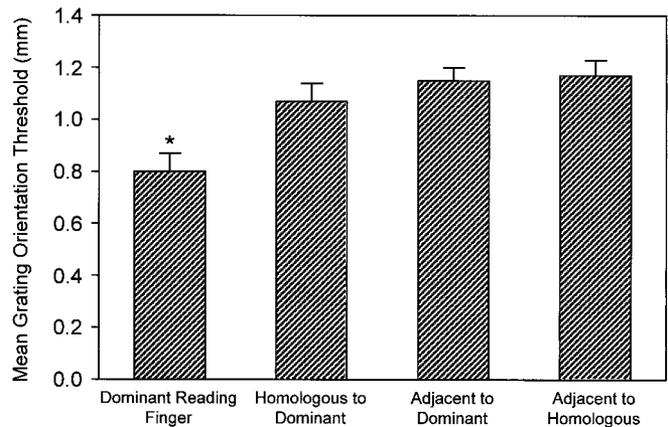


Figure 4. Grating orientation thresholds for four finger-tips in 13 blind subjects who report using a single dominant finger for Braille character identification. Error bars represent SE. \* $p < 0.0016$ .

the dominant finger, the homologous finger in the opposite hand, the finger adjacent to the dominant finger, and its homologous finger in the opposite hand. A repeated measures ANOVA revealed a significant effect of location (finger) on threshold ( $F = 15.8$ ,  $df = 3,36$ ,  $p < 0.001$ ). Post hoc analysis by six pairwise comparisons (two-tailed  $t$ -tests for contrasts) with Bonferroni correction showed that the mean threshold at the dominant finger (0.80 mm, SD 0.27) was significantly lower than that at each of the other three fingers tested ( $p < 0.0016$ ,  $\alpha = 0.01 \div 6$ ). Thresholds at the remaining three fingers were not significantly different from each other (smallest  $p = 0.12$ ).

When comparing blind subjects' performance at the self-reported dominant finger to that finger at which threshold was lowest, we found that nine out of 13 subjects had their lowest spatial acuity threshold at their dominant finger (binomial test,  $p < 0.001$ , probability of correspondence = 0.25). The remaining four subjects had a negligibly lower threshold (0.04 mm or less) at a nondominant finger. For the two subjects who reported both index fingers as their dominant fingers, one of these index fingers was the site of the lowest threshold of all fingers tested, whereas the threshold at the other dominant finger was comparable to thresholds at the remaining fingers.

**Preferred sites for motor versus sensory performance.** Self-reported motor handedness in blind subjects did not correspond closely to the hand with the preferred dominant fingertip for sensory discrimination. Nine of the 15 blind subjects reported themselves to be right-handed (motor), two were left-handed, and four considered themselves ambidextrous. Seven blind subjects reported a "sensory-dominant" finger in a hand that did not correspond to the hand they preferred in their own global assessment in motor handedness ( $\kappa = 0.222$ ,  $p = 0.35$ ). This disagreement in seven cases was changed to five cases when we categorized subjects' handedness according to their modified Edinburgh Handedness Inventory scores (rather than their own global assessment).

For the sighted group, 14 of 15 subjects were right-handed by both self-reported global handedness and scores on a modified Edinburgh Handedness Inventory. However, no significant differences were observed between sensory thresholds for any of the fingers tested in the sighted

group (repeated measures ANOVA for location [finger] effect,  $F = 2.21$ ,  $df = 3,42$ ,  $p = 0.10$ ) nor was laterality evident.

*Laterality assessment in tactile spatial acuity.* No significant laterality in somatosensory performance was found for either the blind group or the sighted group. Specifically, the mean threshold for fingers in the right hand was not significantly different from that of the fingers of the left hand for either sighted subjects (ANOVA,  $F = 2.66$ ,  $df = 1,14$ ,  $p = 0.13$ ) or blind subjects (ANOVA,  $F = 0.88$ ,  $df = 1,14$ ,  $p = 0.36$ ).

*Other results.* For the blind group, neither an age effect ( $r = 0.13$ ,  $p = 0.64$ ) nor hours per day of Braille reading (greater than or less than 1.5 hours per day [two-tailed  $t$ -test,  $t = 1.03$ ,  $df = 11$ ,  $p = 0.33$ ]) nor number of years of Braille reading ( $r = -0.17$ ,  $p = 0.57$ ) was found to relate significantly to thresholds at the dominant finger in this small sample.

Although this study was not designed to assess a gender effect on spatial acuity, a post hoc analysis indicated that blind women (mean threshold = 0.96 mm, SD = 0.14) performed better than blind men (1.17 mm, SD = 0.19; two-tailed  $t$ -test,  $t = -2.44$ ,  $df = 13$ ,  $p = 0.03$ ). No gender difference was observed for the sighted group (two-tailed  $t$ -test,  $t = 0.36$ ,  $df = 13$ ,  $p = 0.72$ ). The sighted group in our study had thresholds slightly higher than subjects at a comparable age tested at another laboratory<sup>14,21</sup> but an ANOVA revealed no significant difference in thresholds between these studies ( $F = 1.742$ ,  $df = 2,50$ ,  $p = 0.19$ ).

**Discussion.** This study has demonstrated that the capacity for spatial resolution at the fingertips is superior in early blind Braille readers compared to sighted subjects. We propose that blind subjects' performance in the GOT is a result of long-term spatial learning which, in turn, is reflected by an expanded area of cortical representation of the fingertip.<sup>1,2</sup> The differential performance gain in the GOT at the preferred finger for Braille identification suggests that Braille reading experience confers a heightened capacity for spatial resolution, particularly at the trained site (relatively location-specific).

*Tactile performance in blind people: review of the literature.* Most previous studies have not shown uniform differences in tactile sensory thresholds between blind and sighted persons.<sup>15</sup> No significant differences in thresholds have been found for vibratory detection,<sup>16</sup> length discrimination or gap detection,<sup>17</sup> or threshold detection of electrical pulses.<sup>1</sup>

Also, comparisons in light touch detection (von Frey-type nylon monofilaments) have not revealed a significant difference in mean thresholds for blind subjects compared with sighted persons.<sup>1,2,15,16,18,19</sup> Post hoc comparisons<sup>2</sup> of individual fingers have yielded mixed results. Compared to sighted subjects, blind subjects who read Braille with multiple fingers had lower tactile thresholds at two of their three reading fingers and at a single nonreading finger. Blind subjects who read Braille with only a single finger had lower thresholds compared to sighted subjects at their reading finger as well as at a nonreading finger.

Most studies of conventional two-point discrimination<sup>1,16,17,19</sup> have not found blind persons to be superior in this task. These results are not incongruous with ours, as thresholds in the two-point discrimination task are not a measure of the limit of spatial resolution and thresholds vary considerably both within and between subjects.<sup>7</sup> A previous comparison of blind subjects' performance in two different forms of the two-point discrimination task yielded mixed results.<sup>17</sup> No significant difference in performance between blind subjects (mean threshold = 1.01 mm) and sighted subjects (mean threshold = 1.21 mm) in the conventional two-point discrimination task was observed. For a technique that yielded much larger thresholds, the mean threshold for a single finger tested in blind subjects (1.94 mm) was significantly lower ( $p = 0.02$ ,  $t$ -test) than sighted subjects (2.31 mm). In a separate study<sup>19</sup> of two-point discrimination thresholds, mean thresholds for three fingers tested in blind (1.63 mm) and sighted subjects (1.66 mm) were not significantly different, although a 0.1 mm lower threshold in the blind group at the right index finger ( $p < 0.05$ ) was noted in a post hoc analysis. The design and varied methods of the two-point discrimination test provide a variety of nonspatial neural cues for performance.<sup>7</sup> For example, nonsimultaneous skin contact of two points provides a temporal cue for discrimination from a single point. Furthermore, it has been recently shown<sup>20</sup> that a single point evokes higher firing rates in primary afferents than do two points presented simultaneously.

One study<sup>17</sup> reported that blind persons can apparently better identify a pair of narrowly separated points pressed onto the finger when placed orthogonal but not longitudinal to the long axis of the finger. The same study also reported that blind subjects are also able to better detect a change in orientation from longitudinally positioned points when presentations are paired with orthogonally positioned points. The neural basis for these data is unknown, although localization of the stimulus may play a role in performance. However, it has been shown recently that blind multifinger Braille readers mislocalize more than sighted subjects when touched with von Frey-type nylon filaments.<sup>2</sup>

A recent study<sup>21</sup> reported that early-onset (<5 years) but not late-onset blind Braille readers can detect a significantly finer offset in the alignment of a row of three embossed dots compared to sighted subjects at initial (task-naïve) testing. However, no difference in performance was noted by the third test session a few days later. No significant differences in the ability to discriminate actively scanned gratings differing in ridge width or in grating orientation were reported. Subjects were not asked which finger(s) were used for Braille character identification nor was the dominant finger specifically tested. Furthermore, within the blind group only, men performed worse in the GOT than women (in agreement with our results) and a greater proportion of blind men were included in the study. These differences in

study design and subjects may have contributed to the varying results compared to our study.

In a study<sup>22</sup> of tactile letter recognition and gap detection task at the fingertip using the Optacon stimulator (a device in which the stimuli are an array of pins activated by way of piezoelectrically driven pulse-taps [Tele Sensory Co., Mountainview, CA]) naïve blind Braille readers perform better than naïve sighted subjects in both tasks. These findings and our results corroborate the notion that blind Braille readers' spatial perceptual abilities are superior to sighted subjects and also suggest that learning can transfer across tasks with a shared neural basis for performance (see reference 3).<sup>29</sup> We propose that spatial learning transfers across tasks in which performance mutually depends on spatial information processing. However, a direct comparison of the Optacon study with our data is problematic, as the Optacon has been shown to engage selectively the rapidly adapting and pacinian afferents,<sup>24</sup> and not the slowly adapting afferent population which is responsible for the limits of tactile spatial resolution.

*Peripheral neural mechanisms of tactile spatial resolution.* Recognition of form (e.g., Braille patterns, gratings, embossed letters) is dependent upon appreciation of the spatial structure of the neural response.<sup>12,25</sup> Performance at the spatial resolution limit of pattern recognition at the fingertip is accounted for by the spatial response profiles of the slowly adapting type 1 (SA1) afferent fiber system in monkeys<sup>25</sup> and humans.<sup>26</sup> Braille characters and other patterns are represented in a spatial pattern of activity across the population of the SA1 afferents (similar to pixels that together constitute an image) in an image nearly identical to actual stimuli (i.e., in an isomorphic fashion).<sup>26,27</sup> The density of the component elements of this peripheral neural representation (the mean center-to-center spacing between afferent receptive field centers at the finger) corresponds closely to the behavioral mean thresholds for spatial resolution (about 0.9 mm) and to the theoretical spatial resolution limit established by this element spacing.<sup>12</sup> Furthermore, the spatial response properties of individual fibers to gratings indicate that only the SA1 population is sensitive to spatial details at or below the human perceptual limit of grating resolution.<sup>25</sup> GOT thresholds have been carefully characterized<sup>8,11,12</sup> and are believed to measure the human ability to resolve the spatial modulation of the afferent discharge. This position is supported by several lines of evidence. First, the neurophysiologic and psychophysical data referred to above strongly support this assertion. Second, GOT performance closely relates with that of a more complex stimulus (embossed letter) that can only be performed based on spatial cues.<sup>12</sup> Third, after peripheral nerve injury, human subjects recover normal sensory capacity in tasks that can be performed based on nonspatial cues long before recovery in GOT and dense reinnervation occurs.<sup>11</sup>

*Spatial pattern representation at the primary somatosensory cortex.* Tactile spatial resolution is believed to depend upon the dense isomorphic peripheral representation of spatial details of a stimulus, which is relayed to the initial stages of cortical processing (area 3b and 1). The spatial details of embossed letters pressed onto the skin in monkeys are preserved spatially in the population response of SA cortical neurons at the level of the primary somatosensory cortex.<sup>27</sup> The area of cortical representation is greatest<sup>28</sup> for body parts with the greatest density of peripheral innervation<sup>29</sup> as spatial information has been preserved at the cortical level. Indeed, the "homunculus"<sup>28</sup> for both the primary somatosensory and motor cortices demonstrates a disproportionate allotment of cortex devoted to body parts specialized in discriminative touch<sup>30</sup> and fine motor control. Furthermore, normative neurophysiologic studies in monkeys have found that the larger the area of cortical representation for a body part, the smaller the individual receptive-field sizes of the relevant cortical neurons<sup>31</sup> (Inverse rule) which presumably provides a finer grain of spatial information available for tactile discrimination.

Behaviorally relevant tactile stimulation can alter the receptive-field sizes of cortical cells and the extent of the area of cortical representation of the engaged skin site.<sup>32-34</sup> Monkeys trained to maintain fingertip contact at a regulated pressure with a rotating disk develop smaller cutaneous receptive fields (area of skin which upon contact activates a neuron) at the primary somatosensory cortex.<sup>32</sup> Sharper cortical tuning of spatial information provided by the peripheral afferent population may facilitate improved spatial acuity or finesse in sensorimotor integration. Furthermore, when monkeys attend to and identify tactile patterns applied to the fingertip, the magnitude and temporal nature of neuronal activity at both the primary and secondary somatosensory cortices are greatly modified.<sup>35</sup> Top-down instruction from higher cortical centers with explicit knowledge of the goals of a task or subcortical influences (e.g., nucleus basalis of Meynert) may drive the observed cortical remodeling to enhance selectively the neural feature (e.g., spatial) which enables improved performance.<sup>36</sup> Hence, the cortical representation of skin surfaces is contributed to by both peripheral mechanisms as well as behaviorally driven central synaptic changes (the central convergent pathways, the cortical network, or both).

The expanded cortical representation of the fingertips in humans trained to read Braille<sup>1,2</sup> or play a musical string instrument<sup>37</sup> may represent the functional development of a finer spatial sampling rate of the peripheral input for individual cortical neurons. Presently, we do not have data on the cortical representation of the fingertips in our subjects, but further studies may enable a direct investigation for a quantitative correlation between the degree of spatial acuity and the area of cortical representation.

*Tactile spatial resolution in blind Braille readers.* Our data suggest that blind Braille readers have

developed heightened abilities in tactile spatial acuity. Furthermore, performance tended to be best at the finger dominantly used for Braille character identification. We believe these data are consistent with a reverse hierarchy model of cortical learning.<sup>38</sup> This model suggests that difficult tasks (e.g., testing to the limits of spatial acuity) are learned at “an early cortical site of plasticity where receptive fields retain fine selectivity along basic spatial dimensions,”<sup>38</sup> and this may account for specificity (e.g. location/finger position) in learning.

Previous studies<sup>39-41</sup> also support the notion of long-term learning to be relatively position-specific and not easily transferable to other sites/fingers (but short-term practice effects appear to generalize across skin location<sup>23,42</sup>). For example, although error rates in bimanual Braille readers are very low with either hand, subjects read faster at the index finger of their preferred reading hand.<sup>40</sup> Another study<sup>41</sup> showed that blind subjects who preferred using their right hand to read Braille were better at detecting accents over Braille characters with their right hand compared to their left hand.

Site-dependent performance is likely attributable to sensory training and not motor handedness. In our study, we did not find a significant correspondence for the hand preferred for motor tasks and the hand (finger) preferred for tactile discrimination. Our results are in agreement with a previous study,<sup>40</sup> which found that in 38 blind, strongly right-handed subjects, 16 preferred and read Braille faster with their left hand, and 17 preferred to read with their right hand (five had no preference). Nearly all (14/15) of our sighted subjects were right-handers and no laterality in tactile performance was evident. An extensive review of the literature for sighted subjects<sup>43</sup> and a recent study of sighted subjects in GOT performance<sup>44</sup> also did not find any robust laterality in spatial tactile performance in humans, yet most are right-handed. Hence, motor handedness has not been found to be associated with a corresponding laterality in somatosensory performance in spatial tasks. This dissociation between global handedness reports or Edinburgh Inventories and sensory performance is not surprising, as these motor surveys do not screen specifically for tasks whose performance is highly dependent on fine spatial acuity (e.g., Braille reading). Also, motor activity (i.e., active exploration) per se does not improve sensory performance in tactile pattern recognition.<sup>45</sup>

In our study, blind subjects' mean performance at fingers reportedly not used in Braille reading was intermediate to performance at their dominant finger and to that of sighted subjects. It is possible that spatial learning at Braille reading fingers partially generalizes to untrained skin locations. However, blindness likely drives attention to nonvisual stimuli (including fine surface details at all fingertips) so individuals can explore their environment safely and effectively. For example, the so called “obstacle sense” of blind persons—the ability to navigate with-

out colliding into objects—has been appreciated for hundreds of years.<sup>15</sup> Originally attributed to “facial vision” (air currents or eddies set up by the obstacle and detected by facial skin), the ability to sense obstacles up to meters away was later actually found to be due to auditory cues.<sup>46</sup> We do not know whether blind persons naïve to Braille have spatial resolution capacities equal to those trained in Braille reading, but we suspect this would not be so as it appears that in our subjects long-term spatial learning has occurred best at fingertips trained in Braille reading.

It is unclear whether sighted subjects could, with training, eventually perform as well as blind subjects in the GOT. Sighted subjects trained for months in Optacon letter recognition can become nearly as proficient as blind subjects trained with the Optacon.<sup>22</sup> Thematically, the obstacle sense is not unique to blind persons, but that with training and attention, sighted subjects who are blindfolded can improve their ability to avoid obstacles.<sup>46</sup>

Our proposal that the tactile spatial resolution capacity of blind persons is represented by cortical plasticity is reminiscent of Tilney's proposal in 1929.<sup>18</sup> His sensory testing results for Helen Keller suggested that she had superior abilities in stereognosis but her capacities in the so-called primary submodalities of somatic sensation (touch, pain, temperature, and vibration sense) were similar to those of sighted persons. He then reviewed the postmortem examination of a blind and deaf-mute person in whom the occipital and temporal lobes were small, and contrasted with well-developed parietal lobes “particularly for the hand and face.” He suggested that “functional demands” induce cortical neural connections and that “such connections are made only when called for by needed communications.”<sup>18</sup>

The reorganization that occurs at the primary somatosensory cortex following the acquisition of tactual skills may constitute the cortical site of learning.<sup>47</sup> Whether the nature or fidelity of the tactual percept is further modified by tactile activation of the occipital cortex<sup>3-5</sup> is unclear though its activation appears to be functionally relevant for certain tactile tasks in blind<sup>4</sup> and sighted subjects.<sup>48</sup>

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