Remodeling of somotasensory hand representations following cerebral lesions in humans

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There is evidence of reorganization of somatotopic maps following cortical lesions in mammals such as monkeys, raccoons and rats. However, there has been a striking lack of research on somatosensory plasticity following cerebral damage in adult humans. We describe two individuals with left hemisphere damage who misperceive the locations of tactile stimuli whose presence or absence they can readily detect. We find that the mislocalizations preserve the relative topography of pre-lesion experiences, resulting in shifted and compressed representations of the hand surfaces. These results not only provide evidence for systematic remodeling of somatotopic maps in humans, they also reveal that the systematic changes in cortical topography that have been documented using electrophysiological methods may give rise to similarly systematic changes in somatosensory perception itself. *NeuroReport* 13:207–211 © 2002 Lippincott Williams & Wilkins.

Key words: Cortical plasticity; Cortical reorganization; Neuroplasticity; Somatosensory maps; Somatosensory plasticity

INTRODUCTION

The functional plasticity of primary somatosensory cortex is revealed by the systematic reorganization of cortical somatosensory maps that has been reported following manipulations that modify peripheral sensory inputs, such as amputation/deafferentation [1,2], surgical syndactyly [3], skin translocation [4] and enrichment or differential use [5]. Most of the work on somatosensory plasticity has involved non-human mammals and has primarily made use of electrophysiological methods of receptive field mapping. However, there have also been a number of more recent studies examining the consequences of peripheral manipulations in humans making use of both behavioral and neuroimaging methodologies in investigating the consequences of amputation/deafferentation [6–10], surgical correction of syndactyly [11] and enrichment/differential use [12,13].

Compared to the considerable number of studies examining the consequences of peripheral manipulations, there have been relatively few studies that have considered the plasticity of somatosensory maps subsequent to injury of the adult cortex itself. Furthermore, although there have been a small number of animal studies investigating this subject, there has been a striking dearth of human research on this topic. Existing findings from animal studies show that systematic changes in cortical topography and neuronal receptive fields are observed subsequent to cortical damage in monkeys [14,15], raccoons [16] and rats [17]. Specifically, this work has revealed that cortical neurons both adjacent to, and at some distance from, the lesioned areas respond to stimulation of skin regions that were previously represented by neurons in the damaged area. These changes have been observed within days or weeks [14,16] and even hours [17] of the focal cortical injury. However, the very few existing studies of adult-onset cortical injury in humans do not provide clear evidence of systematic somatosensory reorganization [18,19]. Research with lesions in human adults would not only provide the opportunity to examine the characteristics of plasticity subsequent to cortical damage in humans, it would also provide a unique opportunity to examine how the topography-preserving neuronal changes observed in the animal research are experienced. Thus, while previous animal work has documented neuronal changes, it has not investigated the manner in which these changes affect perception. By examining the behavioral and phenomenological consequences of human cortical lesions we can determine if, among other things, neuronal reorganization leads to systematic changes in the perceived location and/or quality of tactile stimuli.

We report here on an investigation carried out with two individuals who suffered left hemisphere strokes. We first document their ability to accurately detect the presence or absence of light tactile stimuli delivered to the contralesional hand. We then present the results of an experimental investigation of their ability to localize the tactile stimuli. We find clear evidence of systematic changes in their

perception of location. Strikingly, these changes preserve the topography of the pre-lesion sensations. The results provide, for the first time, evidence of the remodeling of somatosensory representational topography subsequent to cerebral lesions in adult humans.

MATERIALS AND METHODS

The investigation was carried out with two right-handed male subjects (RSB and AKH) who were 4 years and 1.5 years post-stroke, respectively. RSB was a 58-year-old toxicology researcher with a PhD and AKH was a 35-year-old social worker with a Master's degree. No imaging data were available for AKH and it was known only that he had suffered a left hemisphere stroke to the region of the middle cerebral artery. For RSB, MRI revealed an extensive left parietal lesion extending rostrally from the post-central gyrus and caudally to the angular gyrus (Fig. 1) affecting, among other things, what is traditionally considered to be the hand area of SI as well as SII. An examination of the rostral edge of the lesion reveals that the superior rostral edge impinges upon the post-central sulcus and that the lesion advances in an anterior direction into the post-central gyrus at its inferior rostral edge. There are some signs of left frontal atrophy but all subcortical structures appear to be intact. Research with RSB and AKH was carried out in compliance with relevant laws and institutional guidelines and was approved by the Institutional Review Board of the Johns Hopkins University (Homewood Campus).
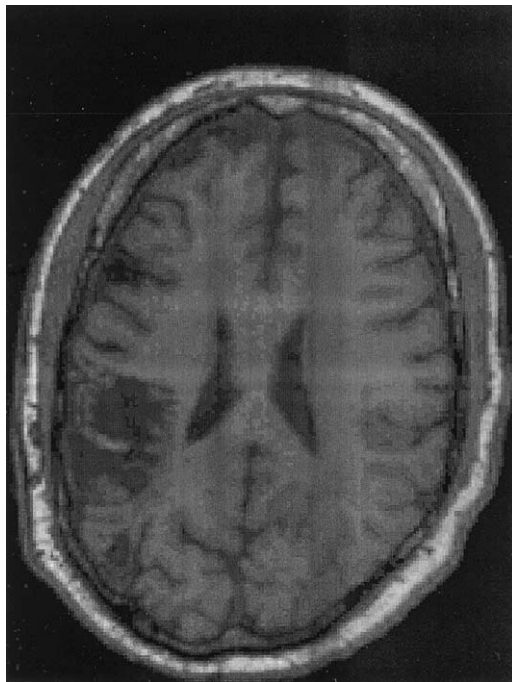

Fig. I. MRI scan for RSB. A horizontal slice from close to the inferior edge of the lesion reveals its rostral extension into the precentral gyrus and its caudal extension into the angular gyrus. The right of the image corresponds to the right hemisphere.

Both individuals reported that they had suffered sensory loss and motoric difficulties in the period immediately following their strokes, but by the time of the investigation neither subject complained of motor difficulties or of loss of somatosensation; nor did they exhibit tactile neglect or extinction. However, both did report sporadic tingling sensations in their hands and forearms and, on occasion, stimulation presented to the ipsilesional hand produced bilateral sensations. Standard neurological testing with RSB revealed mild loss of discrimination bilaterally in hands and feet and some difficulties in finger proprioception in the contralesional fingers. Both men experienced mild/moderate difficulties in written and spoken language production and numerical processing, but their language comprehension and other cognitive abilities were excellent.

The eight neurologically intact control volunteers who participated in this investigation were all males (seven right-handed, one left-handed) with an average age of 42 (range 26–61) years and education levels ranging from 2 years of graduate study to PhD.

First, preliminary testing was carried out to assess each subject's ability to detect the presence or absence of a light touch to either, neither or both hands. For this testing, the subject placed both hands flat on the table with fingers spread at a comfortable distance from one another. The subject closed his eyes and light, brief tap was delivered either to one hand, both hands or neither hand. The subject responded verbally with the terms right, left, both or neither (RSB: $n = 216$ per hand; AKH: $n = 45$ per hand).

The primary empirical investigation consisted of the evaluation of the subjects' perceptions of the locations of the stimuli. Subjects were tested as follows. On each trial, the hand to be stimulated was placed flat on the table, with fingers spread at a comfortable distance from one another. The subject closed his eyes and a light, brief tap was delivered in pseudo-random order to one of the 22 locations on either the dorsal or ventral surface of the hand, as indicated in Fig. 2. Stimulation was presented blocked by surface. Immediately after stimulation, the subject opened his eyes and pointed to the location of sensation with the contralateral hand. The localization judgment was recorded by the experimenter on a line drawing of the subject's hand (some sessions were also videotaped to confirm the accuracy of the recording method). For each target location, the subject's localization judgments were later encoded in x and y coordinates using a grid with the origin of the grid centered on the actual target location for each trial and with the y-axis aligned with the long axis of the finger. In this way, responses were encoded in terms of displacement distance (in mm) from the target along x and y axes. The inter-finger separation that was present at testing was removed from the displacement measurements in order to eliminate the possibility that averaged localizations would be situated in inter-finger space. Each of the 22 points was evaluated the following number of times for each subject. right dorsal: AKH 17, RSB 13; right ventral: AKH 12, RSB 16; left dorsal: AKH 11, RSB 8; left ventral: AKH 9, RSB 9. This yielded a total of 1012 data points for RSB and 1078 for AKH.

These data were used to derive mean displacement values and mean localization judgments. Mean displacement
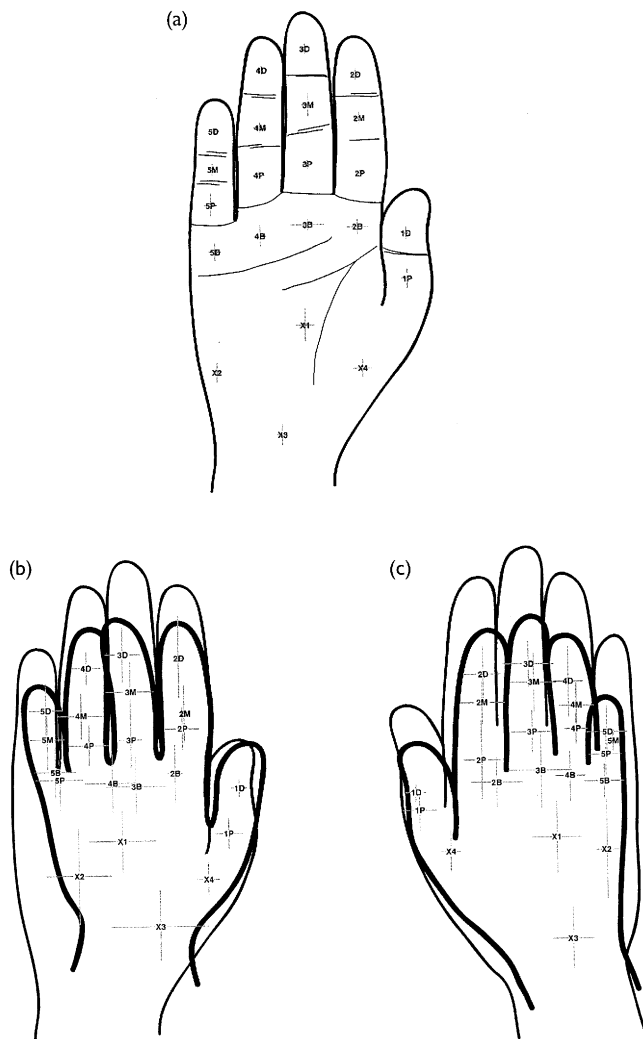
(a)

Table I. Mean displacement of localization judgments (absolute values in mm) along x and y axes, averaged across 22 target locations for each surface.

	RSB	AKH	Controls (range)
Left dorsal			
x	2	3	1–3
y	4	4	1–4
Left ventral			
x	2	3	0.5–2
y	4	6	1–3
Right dorsal			
x	6	13	1–2
y	17	31	1–5
Right ventral			
x	7	8	0–2
y	15	18	1–3

Left = ipsilesional, right = contralesional.

(b)

(c)

Fig. 2. (a) Stimulation points. The palmar surface of a right hand, marking the 22 stimulation locations used in all testing. Numbers 1–5 correspond to each of the digits; D = distal, M = medial, P = proximal, B = basal, X = palmar. Cross-hairs indicate 1 s.d. in the localization judgments of control subjects along x and y axes. (b,c) RSB's mean localization judgments. Mean x and y values of all localization judgments are plotted for ventral and dorsal surfaces. Cross-hairs indicate 1 standard deviation in the judgments. To facilitate an overall evaluation of the location of the points relative to one another, outlines of hands have been drawn around the mean localization judgment locations, approximately preserving the subject's actual finger sizes and shapes. (b) Ventral surface of RSB's contralesional right hand, (c) dorsal surface of RSB's contralesional right hand.

values were calculated by averaging the absolute displacement values along each axis for all responses on a specific hand and surface. Mean localization judgments were determined by plotting the mean x and y values of all localization judgments for each of the 22 target location on an outline of the subjects' hands.

Control data for localization judgments to contralesional stimuli are provided by the subjects' responses to stimulation of their ipsilesional hands, as well as by the responses of eight neurologically intact controls.

RESULTS

Detection accuracy: Detection accuracy was very good: RSB never failed to detect a stimulus delivered to the ipsilesional left hand and failed on only 3% of trials on the contralesional right hand AKH never failed to detect a stimulus to either hand.

Localization judgments: Table 1 reports the mean absolute displacement values (averaged across the 22 stimulus locations) for dorsal and ventral surfaces of both hands for RSB and AKH as well as for the control subjects. These data reveal that RSB and AKH's displacements from contralesional target locations were markedly greater than the displacements of control subjects, while their displacement values for ipsilesional targets were generally within normal range. Specifically, contralesional displacement values on x and y dimensions were 12–26 s.d. from the control means for both RSB and AKH. In contrast, ipsilesional displacement values were all within the control range, except for the y-axis values on the ventral surfaces, where RSB and AKH's mean displacement values were, respectively, 1 and 3 mm outside the range of control subjects. In addition, for both RSB and AKH, displacement values were markedly greater for contra-versus ipsilesional hands, for both x and y-axis values, on both dorsal and ventral surfaces (the eight paired t-tests on the 22 target locations all yielded $p < 0.00001$).

Significantly, the difference between localization accuracy for contralesional and ipsilesional hands indicates that the localization difficulties can be specifically attributed to the neurological insult suffered by these individuals.

While the results reported in Table 1 clearly indicate significant misperceptions of the locations of contralesional stimuli whose presence/absence is readily detected, they do not reveal if there is any systematicity in these misjudgments. The systematic nature of the errors can be seen in Fig. 2 and Fig. 3, which depict the mean localization judgments for each of the 22 locations on the dorsal and ventral surfaces for RSB and AKH's contralesional hands. Hand-shaped outlines have been drawn around the localization positions to facilitate an overall evaluation of the displacements.
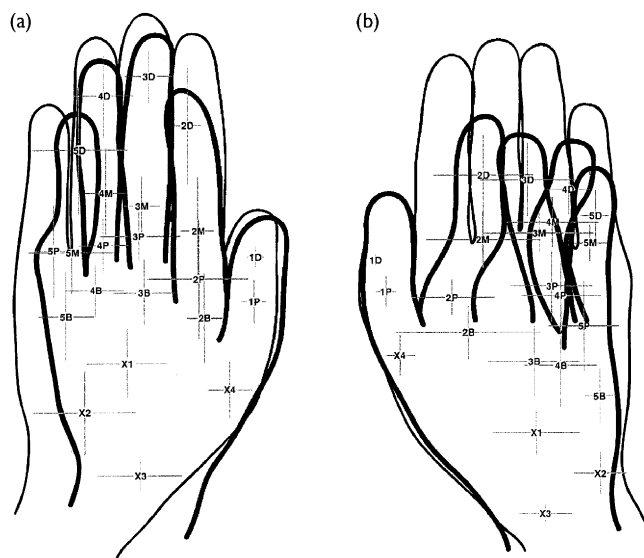
Fig. 3. AKH's mean localization judgments (as in Fig. 2). **(a)** Ventral surface of AKH's contralesional right hand, **(b)** dorsal surface of AKH's contralesional right hand.

The localization judgments clearly indicate systematic changes in the perceived locations of the stimuli. Specifically, the results reveal a striking downward shift in localization judgments; for RSB this is particularly evident for the distal and medial segments of both dorsal and ventral surfaces; for AKH all finger segments on the dorsal surface exhibit a downward shift while on the ventral surface the downward shift is seen primarily with the medial and the basal locations. RSB additionally exhibits an overall compression of the hand representations resulting from the combination of the downward shift of the distal points along with an upward shift of the palmar points and an inward shift of points along the outer edge of the hand. AKH's judgments have considerably more error in the x dimension than do RSB's. The x-axis error is such that stimuli delivered to dorsal digits 2 and 3 as well as to ventral digit 5 are typically experienced on adjacent digits; furthermore, stimuli delivered to the medial and proximal segments on dorsal digits 3 and 4 are virtually indistinguishable. Despite these distortions along the x-dimension, the relative positions along the y dimension are well maintained.

In summary, the data clearly indicate that cerebral damage in humans may result in shifted and compressed perceptual representations that preserve the relative locations of the stimuli. In addition, the data indicate a generally similar systematic reorganization of sensory experiences for both ventral and dorsal hand surfaces.

DISCUSSION

This work reveals that cerebral damage in adult humans can result in a dissociation between the detection and the localization of tactile stimuli, such that stimuli that are readily detected may be significantly mislocalized. Furthermore, the data indicate that the post-lesion mislocalizations

may preserve the relative locations of the pre-lesion topography, resulting in systematically shifted and distorted somatosensory experiences.

These findings suggest that somatosensory representations may have been reorganized within a reduced representational space. Inputs are not merely redirected to intact neural tissue, instead there has been a more general reorganization within the available neural substrate. This is consistent with the neurophysiological findings of animal research reviewed in the introduction indicating that the remodeling of somatosensory neural substrates subsequent to focal cortical lesions generally preserves the original neural topography. In addition, the results from AKH indicating overlapping representational surfaces for ventral digits 4 and 5 and dorsal digits 3 and 4 are consistent with the multi-digit receptive fields that have been observed subsequent to cortical lesions in animals [20]. Finally, the similarity between the results obtained for the dorsal and ventral surfaces constitutes an important contribution to the scarce literature (from either human or animal studies) regarding the plasticity of the dorsal (hairy surface) of the hands. The degree to which the particular changes we have documented are observed in other neurologically injured individuals will, presumably, depend on specific details of lesion locus and extent.

Although the results provide clear evidence of systematic somatosensory remodeling, they do not elucidate the specific mechanisms underlying the observed changes and are generally consistent with various mechanisms that have been proposed: sprouting of new connections [21,22], unmasking of subthreshold or inhibited connections [23], or dynamic reweighting of connectivity [24,25]. Additionally, although RSB's MRI scans reveal that damage is restricted specifically to cortical tissue within the parietal lobe, given the large size of the lesion it is not possible to localize the observed changes to particular areas within damaged or spared parietal cortex. Finally, we have not undertaken a systematic examination of the subjects' discrimination capacities and thresholds. Although both subjects exhibited very good detection accuracy for the stimuli we employed, one would expect that a reduction in representational space should result in the broadening of receptive fields and concomitant decrements in sensitivity.

CONCLUSIONS

The finding of highly organized mislocalizations of tactile stimuli in two adults who have suffered left hemisphere strokes constitutes evidence for the systematic reorganization of somatasensory substrates in response to cortical damage and provides information regarding the experience and perception that may accompany the neural plasticity that has been documented in both humans and other mammals. In these ways, this work adds significantly to the growing body of neurophysiological findings of significant and systematic neural plasticity in the reorganization of somatosensory substrates in response to cerebral damage.

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