First publ. in: Electroencephalography and Clinical Neurophysiology / Supplement, 49 (1999), pp. 292-298

Development of cortical reorganization in the somatosensory cortex of adult Braille students

Annette Sterr*, Matthias Müller, Thomas Elbert, Brigitte Rockstroh and Edward Taub[1]

Department of Psychology, University of Konstanz, D-78457, Konstanz (Germany)

Introduction

Braille reading is a behaviorally relevant task, often carried out several hours a day. In blind Braille readers, reorganization of the motor cortex has been demonstrated using transcranial magnetic stimulation (TMS). For instance, the cortical representation of the finger muscles involved in the reading process encompasses an expanded area in the motor cortex [1–3]. Furthermore, in a single-subject pilot study with a normal sighted person, Rockstroh and coworkers [4] demonstrated that the organization of the primary somatosensory cortex, presumably area 3b, could be changed by Braille training. From these results it can be concluded that Braille reading is a potent behavioral task capable of inducing cortical reorganization, and can therefore serve as a model in investigating use-dependent adaptation of somatosensory cortical representation and related perceptual changes. This task may also be used to study the time-course of cortical adaptation to new demands. This was the major aim of the pilot experiment on blind Braille students described below.

In a previous study [5] we examined cortical reorganization of the primary somatosensory cortex and related perceptual changes in experienced Braille readers, using magnetic source imaging. Tactile evoked magnetic fields were recorded in order to map the hand representation; Semmes-Weinstein-Monofilaments were employed to investigate sensory thresholds for passive touch. Two groups participated in the study: (1) experienced three-finger readers, who employed D2, D3 and D4 of both hands respectively for reading and (2) experienced one-finger readers, who used the index finger to read. Compared to sighted control subjects, we observed a substantial enlargement in the size of the hand representation in the three-finger readers, but not in one-finger readers.

However, in one-finger readers, there was a substantial increase in the dipole strength of the reading D2 compared to the non-reading D2 (18.7 ± 7.0 nAm versus 9.2 ± 1.6 nAm; $t = 2.7$, $P < 0.05$), suggesting that there was an expansion of the reading D2. Furthermore, in one-finger readers, the sensory threshold of the reading finger was lower than the respective finger of the sighted controls ($t = -2.3$, $P < 0.05$). These results demonstrate that the altered organization of the finger representations in the cortex is dependent

---

* *Correspondence to*: Dr. Annette Sterr, Department of Psychology, University of Konstanz, D-78457 Konstanz (Germany).

[1] Present address: Department of Psychology, University of Alabama at Birmingham, Birmingham, AL 35294 (USA).

on how the fingers are employed in the reading process, suggesting use-dependent and use-specific adaptation of the cortical organization.

Braille students learn to read the tactile characters with the dominant index finger. The above results of experienced one-finger Braille readers served, therefore, as the basis for the investigation of the time-course of cortical adaptation in Braille students. The aim of this pilot study was to explore the somatotopy of the cortical digital representations and the perceptual capacity in blind people who had lost sight recently and started to learn the tactile script. Analogous to our previous study we employed magnetic source imaging to map alterations of the cortical hand representation and Semmes-Weinstein-Monofilaments to describe the sensitivity of the fingertips. The literature on the time-course of cortical reorganization suggests that input-dependent changes in humans can be non-invasively detected within weeks after the experimental intervention [4,6]. These stimulation-dependent changes progressively develop over months up to years [7–9]. We therefore expected the cortical representation of Braille students to reflect a transitional state between sighted Braille-naive persons and experienced blind one-finger Braille readers. The hypothesis was that an increased dipole moment would be found for the reading finger in Braille students. To test this hypothesis, comparisons between reading hand and non-reading hand were calculated for the students. In addition, the data on Braille students were compared to the experienced one-finger readers and the sighted controls tested in the above mentioned study.

Methods

Subjects

All subjects were right-hand dominant. The protocol was approved by the institution's review board and subjects gave informed consent after hearing a description of the study. Subjects participated on a voluntary basis and received financial compensation. Five persons (mean age 38.4 ± 8.6 years) who had become blind 3–12 months prior to the investigation participated in the study. The blind subjects had lost sight through diseases affecting the peripheral components of the visual system (Table 1), and were screened for exclusion of further neurological problems.

At the time of data recording, subjects attended the rehabilitation program for blind adults at the San Diego Center for the Blind and Visual Impaired, San Diego, CA. In this program participants were trained once a week in e.g. cooking, mobility and Braille-reading. Braille was taught on an individual basis for 45 min per session. Additionally, the students were asked to practice Braille at home daily. All participants were in the process of learning to read and write the letters of the alphabet. The individual reading performance (defined as number of letters known in Braille), the learning period, the number of professional Braille-sessions and the amount of practice at home (self-rating) are listed below (Table 2). The Braille-students were instructed to use the dominant (right) index finger for reading.

Five experienced one-finger readers (mean age 50.0 ± 7 years) and five sighted Braille-naive participants (mean age 35 ± 7 years) served as control

TABLE 1
CAUSES OF BLINDNESS, RESIDUAL VISION AND DURATION OF BLINDNESS IN BRAILLE STUDENTS

ID	Cause of blindness	Residual vision	Duration (months)
BE	Glaucoma	Left eye light perception; right eye: rudimentary color and movement perception	12
DW	Retinopathy due to hypertonia	Light perception	3
JA	Detachment of retinae	Light perception	12
LP	Retinopathy due to diabetes	Left eye full blind; right eye rudimentary movement perception	12
SA	Optic nerve transsection	Full blind	10

TABLE 2
DESCRIPTION OF INDIVIDUAL READING PERFORMANCE

ID	Letter	Learning period	Professional sessions	Training at home
BE	A-D	2 weeks	2	90 min at 3–4 days per week
DW	A-G	5 weeks[a]	4	20 min once or twice per day
JA	A-G	12 weeks[b]	2	30–45 min per day
LP	A-I	20 weeks[c]	10	10–20 min at 4–5 days per week
SA	A-Z	12 weeks	10	Daily 15-60 min

[a] Jumbobraille.
[b] Before JA came to the blind school he tried to learn Braille by himself.
[c] Vacation and disease caused longer breaks, during which the subject did not visit blind school.

groups (data from these subjects have been reported in part in [5]). Two of these persons were congenitally blind and had read Braille since age 6. Another two one-finger readers suffered from visual impairment due to progressive retinal disease and became entirely blind at ages 20 and 23, while a fifth subject became blind as a result of optic nerve transection at age 30. At the time of the experiment, the latter subjects had been reading Braille for 25, 35 and 16 years, respectively.

Stimuli

Stimulation consisted of light superficial pressure applied by means of a pneumatic stimulator using a standard, non-painful stimulation intensity (see [10] for more details). Tactile stimulation was delivered to the mid-volar aspect of the distal phalanx of left and right D1, D2, D5. At each site, 512 stimuli were delivered at a rate of 2.2 Hz. Stimulation site sequence was varied according to a fixed irregular order across subjects.

MEG recording

Magnetic fields were recorded in a magnetically shielded room using a 37-channel magnetometer (Magnes, BTi,) with a sampling rate of 297.6 Hz. The sensor array was positioned over the hemisphere contralateral to the side of stimulation (centered at C3 or C4) and evoked magnetic fields were obtained by on-line averaging.

Sensory testing

After the MEG recording, the sensory thresholds of the fingertips were determined using a von Frey-type aesthesiometer (Semmes-Weinstein-Monofilaments, model 16010, Lafayette Instruments Co). Participants were instructed to indicate verbally when the touch was felt. Stimulation consisted of pressing a von Frey hair gently against the skin until it just began to bend. A stimulus of a given strength was applied to the mid-volar surface of the distal phalanx of each of the digits of one of the hands in random order. Sighted subjects were required to keep eyes closed. Each hand was tested separately; thresholds for each finger were determined twice by the method of limits, using stimulus series of increasing and decreasing strengths. Counterbalancing was used for direction of stimulus series both within and between subjects and for order of hand tested first.

Data analysis

The averaged evoked magnetic field data were digitally filtered using a second order bandpass filter (3–30 Hz). Within the range of 30–70 ms after stimulus onset, a first major peak was identified in each of the evoked waveforms. For each evoked magnetic field, a single equivalent current dipole (ECD) model (best individually fitting local sphere) was fitted and the dipole moment (Q, in nAm) and the dipole location for the peak in the signal power (root mean square across channels, RMS) were computed, if the following requirements were met: (1) a signal to noise ratio >4, (2) a goodness of fit of the ECD-model to the measured field >0.95, and (3) a minimal confidence volume of the ECD location $<300\ \text{mm}^3$. The Euclidean distance and the distance in the three separate dimensions were calculated between the centers of cortical responsivity to tactile stimulation of each of the digits (D1-D2, D1-D5 and D2-D5).

Sensory thresholds were defined as the weakest stimulus strength the subject could feel on each finger in each testing sequence (increasing and decreasing stimulus strength). For every finger, the mean threshold of ascending and descending stimulation sequence was calculated (the thresholds never differed more than one stimulus strength).

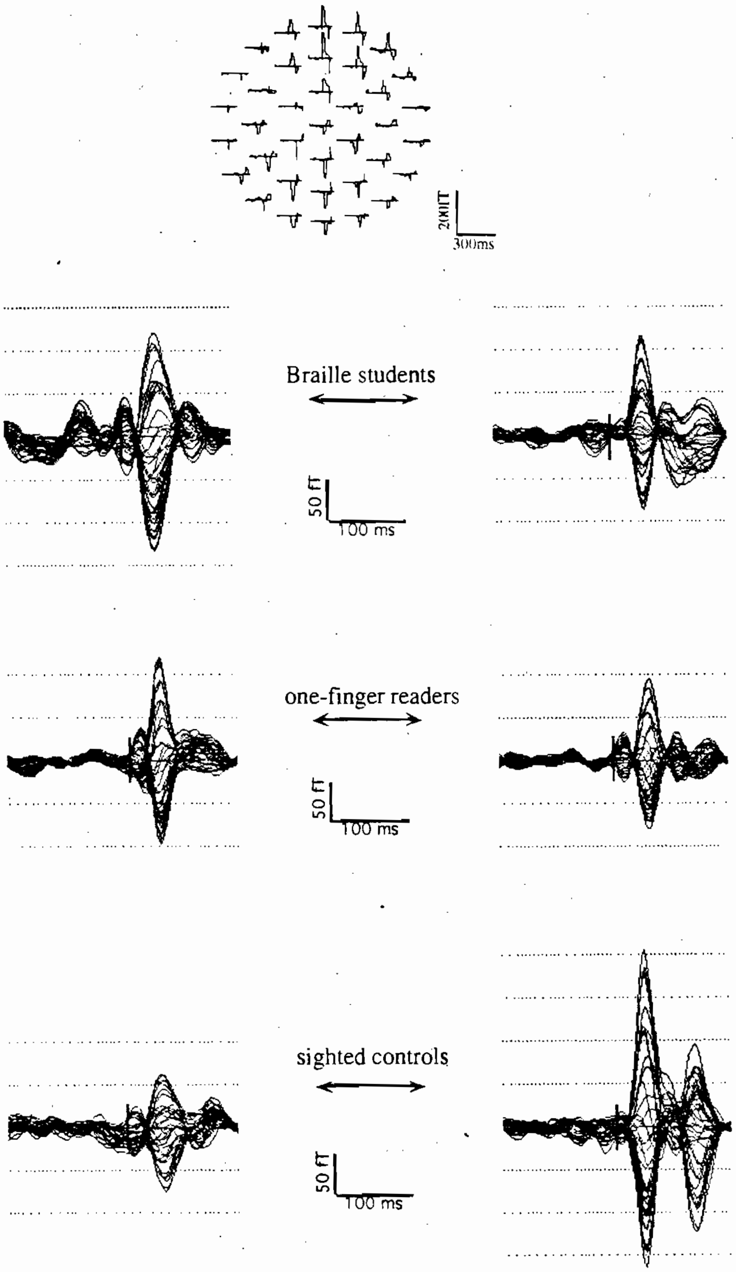

Fig. 1. Set of individual waveforms indicating the magnetically evoked responses for stimulation of the right index finger of two members of each group: Braille students, one-finger blind Braille readers and sighted controls.

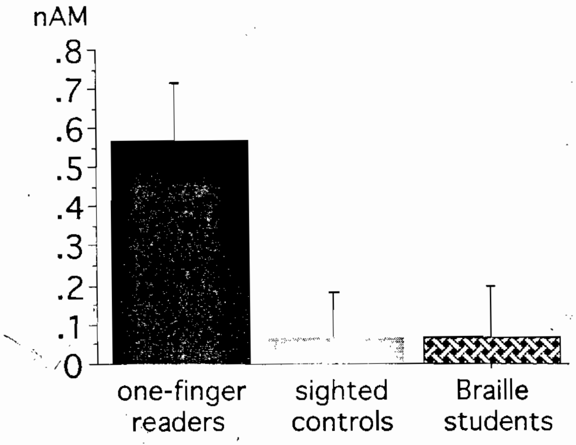

Fig. 2. Laterality coefficient and standard deviation of the dipole strength of the index fingers, plotted for one-finger readers, sighted controls and Braille students.

Statistical analysis

The latency of the maximal RMS-activity, RMS-amplitude, dipole moment, Euclidean distances and distances along the *x*, *y* and *z*-dimension between the respective fingers as well as the sensory thresholds were used as dependent variables. For group comparisons, three-way ANOVAs were calculated for each parameter. For the within-comparisons, two-way repeated measurement ANOVAS were employed. T tests were used for mean comparisons.

Results

Braille students, experienced one-finger readers and sighted controls: between-groups comparison

Waveforms of evoked magnetic fields of Braille-students showed no obvious differences in comparison to sighted controls and experienced one-finger readers. For demonstration purposes, the average magnetic response after stimulation of the right index finger is given for two members of all three groups (Fig. 1).

No significant group differences were found for the latency, the RMS-amplitude, the Euclidean distances and x, y, z-distances. The laterality coefficient of the dipole strength Q of the reading D2 compared to the non-reading D2 (right D2 versus left D2 in sighted controls)

$$\left(\frac{2\left(Q_{\text{reading}} - Q_{\text{non-reading}}\right)}{Q_{\text{reading}} + Q_{\text{non-reading}}}\right)$$

revealed a significant group effect ($F(2, 12) = 4.9$, $P < 0.05$), indicating dominance of the reading finger in experienced one-finger readers compared to the right D2 in sighted controls (mean difference 0.507, critical difference 0.406; $P < 0.05$) and to Braille students (mean difference 0.505, critical difference 0.406; $P < 0.05$, Fisher's protected least significant difference, respectively, Fig. 2). In all Braille students, the sensory thresholds were slightly lower than in sighted controls, but this result was also insignificant.

Reading versus non-reading hand: within-group comparison in Braille students

For the right hand (which is used for reading), the dipole moment of the index finger (reading finger (RD2)) was significantly larger than the dipole moment of the thumb (RD1: $t = -3.01$, $P < 0.05$) and the fifth finger (RD5: $t = 2.78$, $P < 0.05$; paired t test two tail, respectively). For the left hand, the dipole moments of the reading fingers did not differ significantly. The dipole moments of the left and the right index finger were not significantly different from one another. Group mean values of the dipole moments are listed in Table 3.

Comparable results were obtained for the maximal RMS amplitude. There was an enlarged RMS amplitude for the right index finger compared to the right D1 and the right D5, but the difference did not achieve significance (D1/D2: $t = -2.31$,

TABLE 3
MEAN DIPOLE MOMENTS AND STANDARD DEVIATIONS FOR FINGERS IN BRAILLE STUDENTS

	D1 (nAm)	D2 (nAm)	D5 (nAm)
Reading hand	8.9 ± 3.1	11.9 ± 2.4	8.0 ± 0.9
Non reading hand	10.4 ± 4.6	11.4 ± 3.5	9.3 ± 2.2

$P < 0.09$; D2/D5: $t = 2.47$, $P < 0.07$, paired t test two tail). The fingers of the non-reading hand had lower sensory thresholds than the fingers of the reading hand ($F(1,4) = 25.1$, $P < 0.001$). Sensory mislocalizations were not observed in Braille students. The somatotopic order of digital representation was observed in all but one Braille student. For the Euclidean difference and the expansion along the x, y and z-axis, no significant differences between the reading and the non-reading hand were found.

Conclusion

The aim of the present study was to investigate whether reorganization of the somatosensory cortex can be observed in blind Braille students that had started practicing Braille for only a relatively short period. These persons use, in particular, their reading finger more and might therefore demonstrate changes in the cortical representations of the fingers. Compared to sighted controls there is evidence that the cortical organization of the Braille students starts to adapt to the new task of Braille reading. We found a significant increase of the dipole moment for the reading finger compared to the thumb and little finger of the same hand. It is generally believed [11], that the larger the dipole moment, the larger the cell population that was activated by the tactile stimulation. It would therefore appear that the increased dipole moment of the reading finger indicates an enlarged cell population representing the reading finger. Similarly, results from our laboratory indicate that in professional string players, the representation of the fingers that engage in fingering the strings are enlarged [10].

The finding in Braille students may be interpreted as evidence of the beginning of use-dependent adaptation of digital representation in adult blind persons who were just beginning to learn Braille. This interpretation also fits well with the results we have obtained with experienced Braille readers. One-finger readers are characterized by a significantly enlarged dipole moment of the reading finger while the total area representing the hand in the cortex seems not to be enlarged (as opposed to that in experienced three-finger Braille readers). In addition, the present study confirms the results reported by other laboratories that Braille reading alters the sensorimotor organization of the cortex within short periods [3,4]. We therefore conclude that the cortical reorganization in Braille students reflects a transitional state. In agreement with animal experiments [7,9,12] and studies in humans [8] which demonstrate progressive cortical adaptation for months after deafferentation, it may be assumed that the adaptation of the cortical representation of the reading finger in Braille students continues as long as the subject keeps practicing the tactile reading. Further investigation in longitudinal studies is needed to see whether and how the changes in cortical reorganization proceed.

Acknowledgements

Part of this work was carried out at the Scripps Clinic and Research Foundation, La Jolla, CA. It was supported by Biomagnetic Technologies Inc., a grant from the Deutsche Forschungsgemeinschaft to T.E. and a grant to E.T. from the Rehabilitation Research Service of the Veterans Administration (B95-975R). We are grateful to the staff members of the San Diego Center for the Blind and the Braille Institute La Jolla, for referring participants. We further want to thank Patti Quint, Lacey Kurelowech and Joslyne Foley for technical assistance and Dipl. Psych. Lisa Green for editorial assistance.

References

[1] Pascual-Leone, A. and Torres, F. Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. *Brain*, 1993, 1160: 39–52.

[2] Pascual-Leone, A., Cammarota, A., Wassermann, E.M., Brasil-Neto, J.P., Cohen, L.G. and Hallett, M. Modulation of motor cortical outputs to the reading hand of Braille readers. *Ann. Neurol.*, 1993, 34: 33–37.

[3] Pascual-Leone, A., Wassermann, E.M., Sadato, N. and Hallett, M. The role of reading activity on the modulation of motor cortical outputs to the reading hand in Braille readers. *Ann. Neurol.*, 1995, 38: 910–915.

[4] Rockstroh, B., Vanni, S., Elbert, T. and Hari, R. Extensive somatosensory stimulation alters somatosensory evoked fields. In: C. Aide, Y. Okada, G. Stroink, S. Swithenby and C. Wood (Eds.), *Advances in Biomag-*

netism Research: Biomag96 International Conference. Springer, New York, 1998.

[5] Sterr, A., Müller, M.M., Elbert, T., Rockstroh, B., Pantev, C. and Taub, E. Changed perception in Braille-readers. *Nature*, 1998, 381: 134–135

[6] Mogilner, A., Grossman, J.A.I., Ribary, U., Joliot, M., Volkmann, J., Rapaport, D., Beasley, R.W. and Llinas, R.R. Somatosensory cortical plasticity in adult humans revealed by magnetoencephalography. *Proc. Natl. Acad. Sci. USA,* 1993, 90: 3593–3597.

[7] Kelahan, A.M.and Doetsch, G.S. Time-dependent changes in the functional organization of somatosensory cerebral cortex following digit amputation. *Somatosens. Res.*, 1984, 2: 49–81.

[8] Pascual-Leone, A., Peris, M., Tormos, J.M. and Catalá, M.D. Reorganization of human cortical output maps following traumatic forearm amputation. *NeuroReport*, 1996, 13(2): 2068–2070.

[9] Churchill, J.P., Muja, N., Myers, W.A., Besheer, J. and Garraghty, P.E. Somatotopic consolidation: a third phase of reorganization after peripheral nerve injury in adult squirrel monkeys. *Exp. Brain Res.*, 1998, 118: 189–196.

[10] Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B. and Taub, E. Increased use of the left hand in string players associated with increased cortical representation of the fingers. *Science*, 1995, 220: 21–23.

[11] Elbert, T., Flor, H., Birbaumer, N., Knecht, S., Hampson, S., Larbig, W. and Taub, E. Extensive reorganization of the somatosensory cortex in adult humans after nervous system injury. *NeuroReport*, 1994, 5: 2593–2597.

[12] Cusick, C.G., Wall Jr., J.T., J.H.W. and Wiley, R.G. Temporal progression of cortical reorganization following nerve injury. *Brain Res.*, 1990, 537: 355–358.