

Learning transfer and neuronal plasticity in humans trained in tactile discrimination

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Abstract

Adult humans were unilaterally trained in a tactile discrimination task of sequentially applied multi-finger stimuli. Magnetic source imaging (MSI) was performed before and after the training to evaluate use-dependent neuronal plasticity. All subjects showed fast improvements in performance and complete transfer of the learned task. MSI recordings revealed an unilateral decrease in current dipole strength in the somatosensory system contralateral to the trained hand. Attenuation of sensory evoked fields and a complete learning transfer indicate learning in associative and secondary cortices rather than perceptual plasticity operating on neuronal populations involved in early sensory processing. This findings are discussed with respect to an equivalent animal model and to learning specificity and generalization. © 1997 Elsevier Science Ireland Ltd.

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Perceptual learning and memory appear to be based on neuronal plasticity operating during ontogeny as well as in the adult [8]. Psychophysical learning data obtained from primates and humans demonstrate refinements in discrimination abilities after practice. They further indicate that perceptual and procedural learning is paralleled by neuronal reorganization in the primary sensory and motor cortices [8,10,12,13]. These studies demonstrate that one mechanism of learning-induced neuronal plasticity is an increase in the cortical representation of trained inputs. The purpose of our study was to analyze training induced neuronal plasticity in the human somatosensory system using multi-channel magnetic source imaging (MSI). We used a training paradigm previously applied in an animal model to introduce a comparative study on neuronal learning mechanisms [16].

Ten right-handed subjects (two females, eight males;

mean age 28 ± 6 years) gave informed written consent to participate in this study [11]. The subjects placed their non-dominant hand, serving as experimental hand, on a fixation mold and were stimulated at six glabrous skin sites. The dominant hand served as a control. Tactile stimuli were applied simultaneously to the distal or proximal segments of the fingers II–IV using two bars, A and B (Fig. 1A). Each stimulation train was composed of alternating stimuli delivered by bar A and B (background) and two consecutive stimuli applied by either bar (target) (Fig. 1B). The total number of background stimuli and the site of the target were randomized. The task was to press a button with the other hand within a given time window (hit window) when the subject detected the target. A response was categorized as hit if it occurred within the given time window, and as false positive or miss if it occurred before or after it (Fig. 1B). To assure continuous learning and attention to the stimulus, the hit window was successively shortened from initial 1000 ms down to 800 ms. Discrimination performance was defined in relation to the hit window: relative

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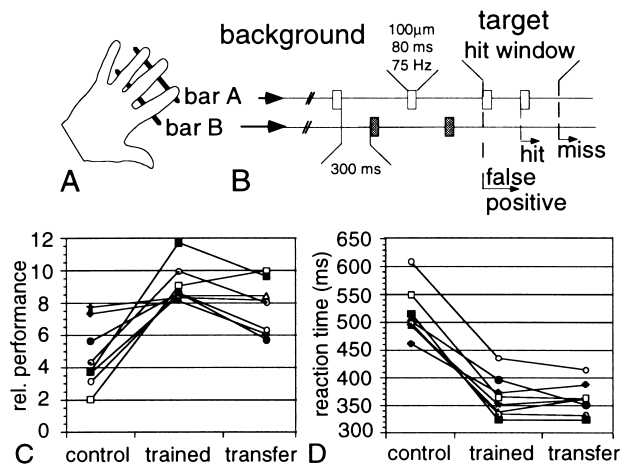


Fig. 1. Training set up and psychophysical learning data. (A) Dorsal view on the left hand with the stimulus configuration used in the tactile discrimination training. (B) Stimulus parameter and schematic drawing of an example of a tactile stimulus sequence. (C,D) Behavioral training data. Each curve and corresponding symbol depict the mean relative performance^a (C) and mean reaction time (D) of each subject for the first training session of the experimental hand (control), the experimental hand at the end of the training (trained), and for the first contralateral hand testing at the end of the training (transfer). Learning transfer is indicated by comparable relative performance rates and reaction times for trained and control hands at the end of unilateral training. ^aRelative performance = (total number of hits)/((total number of trials) × hit window duration (ms)).

performance = (total number of hits)/((total number of trials) × hit window duration (ms)). Subjects performed 100–300 hits/session 3–5 times a week for 3–4 weeks. For within-subject controls, the control hand was trained only at the end of the training in order to avoid any learning at the control side itself. Both hands were retested after a 6 month training break.

MSI was recorded at baseline and following the termination of the behavioral training. Complete data sets were obtained from six behaviorally trained subjects. Three sub-

jects were additionally rescanned 6 months later. Magnetic evoked fields in response to contralateral tactile stimulation were recorded in a magnetically shielded room using a 37-channel SQUID-based biomagnetometer (MAGNES, BTi). Passive stimulation was applied to the distal, middle and proximal segments of finger II, III and V using an air-driven diaphragm. The interstimulus interval ranged from 400 to 500 ms. Each stimulus was repeated 512 times. Data were sampled with a bandwidth of 400 Hz, low-pass filtered (<40 Hz) and analyzed with a single equivalent dipole model. For each evoked magnetic field, a single ECD model (equivalent current dipole/best fitting local sphere) was fitted and the medians of the dipole moment and dipole location were computed from a section of points within a 20 ms time window (11 sampling points) around the maximal root mean square (rms) across the 37 channels within a 30–70 ms time-window are routinely used to localize the primary somatosensory cortex [14]. Later time windows (e.g. 100–200 ms and 300–400 ms) reflecting activity in the secondary somatosensory cortex were not analyzed as they require a different positioning of the sensor array to effectively capture the activity over the parietal operculum [5]. Points were selected following three criteria: rms indicating a signal-to-noise ratio >3; correlation between goodness of the fit and the measured field >0.97; confidence volume of the ECD location <300 mm³ [14]. The dipole localization was determined by coregistering the magnetoencephalography (MEG) data with high resolution magnetic resonance images using standard anatomic landmarks as external fiducial points.

Within 3–4 weeks of training all subjects showed fast, asymptotic learning on the discrimination task. Learning was expressed by significantly improved discrimination accuracy and shortened reaction times for the experimental hand (Fig. 1C,D; Table 1). Two of our subjects were initi-

Table 1
Summary of behavioral and neuronal data

		mean ± SE			
		Group	Baseline	Trained	Recovery
(A) Discrimination training data					
Relative performance	Experimental		4.7 ± 0.7	9.1 ± 0.4*	8.2 ± 1.3
	Control			7.8 ± 0.6	7.7 ± 1.1
Reaction time (ms)	Experimental		5155.5 ± 1.6	364.4 ± 13**	371.6 ± 15.3
	Control			364.8 ± 3.9	377.4 ± 14
(B) MSI data					
Current dipole strength (nA × m)	Experimental		9.7 ± 0.6	6.2 ± 0.2**	[8 ± 0.4]
	Control		8.2 ± 1.2	7.9 ± 1.2	[8.6 ± 1.2]

(A) Discrimination training data. Discrimination accuracy and reaction time were significantly improved over all subjects comparing baseline vs. trained of the experimental hand (**P* < 0.005; ***P* < 0.0001, paired *t*-test). The data obtained from the experimental hand are highlighted in bold. The learning effect was persistent as revealed by high performance rates and short reaction times 6 months without training (recovery). A high discrimination accuracy on the control hand indicates complete transfer of learning (control). (B) MSI data. All subjects showed a significant decrease in the magnitude of the current dipole strength with training recorded contralateral to experimental hand stimulation (control vs. trained; **P* < 0.0001, Wilcoxon signed-rank test). This response attenuation was reversible as indicated by recovery data revealed from three subjects. Recovery data are given in brackets because of the deviating sampling size. Non-significant changes were observed in the data recorded for control hand stimulation.

ally tested at both hands starting at either hand (experimental hand, 6.8 ± 0.5 ; control hand, 7.0 ± 1.0 ; mean \pm SE of relative performance). The question of learning transfer was addressed at the end of the training. The learning was fully transferred to the contralateral hand, as shown by comparable relative performance rates and reaction times for the experimental and control hand when tested at the end of the training (Fig. 1C,D; Table 1). Generalization of the learned task was observed, when testing other 'naive' skin sites with different bar orientation along the three segments of finger II and IV, and testing the dorsum of the trained hand (data not shown). Subjects were retested 6 months after the end of the training. All of them revealed high discrimination accuracy with short reaction times for both hands (Fig. 1C,D; Table 1).

The MSI data obtained from six experimental subjects revealed a significant decrease in the magnitude of the current dipole strength in response to training, but no clear effects on dipole localization and latency of peak responses

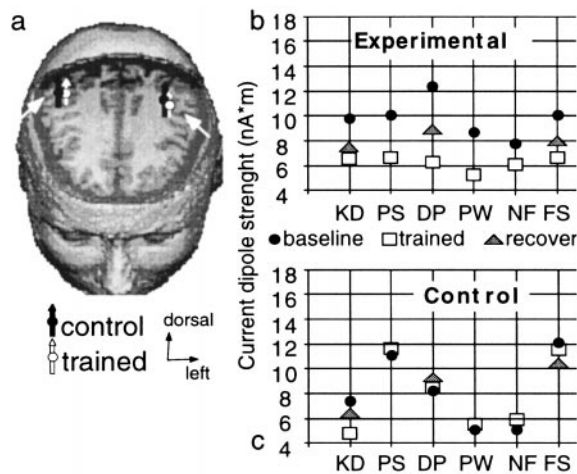


Fig. 2. (a) Mean equivalent current dipole (ECD) localizations superimposed onto a MRI reconstruction of the cortex of a trained subject elicited by experimental (right hemisphere) and control hand stimulation (left hemisphere) under control (black arrows with black dots) and after training (white arrows with white dots). The arrows represent the location and orientation of the ECD vector averaged over nine stimulation sites on the right/left hand. The width of the arrows indicates the mean magnitude of the dipoles for each hand stimulation. Small light grey arrows indicate the localization of the central sulcus. (b) After training all subjects revealed decreased magnitudes of the dipole strength averaged over all tactile stimulation sites on the experimental hand. The mean current dipole magnitude is indicated for each subject as a filled circle for baseline recordings, an open square for trained and a shaded triangle for recovery conditions: KD: 9.7 (0.6), 6.8 (1.9), 7.4 (3.1); PS: 10.0 (0.8), 6.5 (0.7); DP: 12.3 (1.6), 6.2 (0.5), 8.7 (0.7); PW: 8.6 (1.4), 5.3 (1.0); NF: 7.6 (0.9), 6.1 (0.5); FS: 10.0 (0.8), 6.5 (0.7), 7.9 (1.3); mean current dipole strength (\pm SE), ($nA \times m$); for baseline and trained (all subjects), and recovery imaging sessions (subject KD, DP, FS). (c) Mean current dipole magnitude for control hand stimulation revealed invariant mean current dipole strength for all subjects except KD for baseline, trained and recovery imaging sessions: KD: 7.5 (1.0), 9.3 (1.4), 6.4 (2.5); PS: 11.2 (1.6), 11.4 (0.8); DP: 8.2 (0.9), 8.3 (1.0), 9.0 (0.9); PW: 5.1 (1.0), 5.4 (0.6); NF: 5.2 (0.8), 5.9 (1.0); FS: 11.2 (1.6), 11.4 (0.8), 10.3 (1.1); mean current dipole strength (\pm SE), ($nA \times m$), conventions as in (b).

(Fig. 2a). The mean dipole strength obtained in the highly trained state was significantly decreased compared to baseline for experimental hand stimulation (Wilcoxon signed-rank test, $P < 0.0001$) (Fig. 2b, Table 1). Control hand stimulation revealed no significant difference in mean dipole strength between baseline and trained condition (Fig. 2c; Table 1). The decrease in the current dipole strength in the cortical hemisphere contralateral to the trained hand is consistent over all subjects except KD. KD showed a decrease in dipole magnitude even for the control hand, indicating bilateral neuronal changes or, alternatively, individual variability in recordings due to modifications in the state of alertness and motivation during scanning sessions. The data obtained 6 months later suggest that the training effect on the mean current dipole strength is reversible (Fig. 2b; Table 1).

The most dominant effect of the psychophysical data presented here is the complete transfer of the learned task revealed by testing the untrained hand and other 'naive' skin sites. Perceptual learning specificity is widely regarded as an indication of the neurological localization of the learning process. Specific perceptual learning is contributed to early stages whereas unspecific learning and generalization are contributed to neuronal learning mechanisms on higher stages of information processing [4,7]. The issue of learning transfer and learning specificity is highly complex as revealed by controversial findings on nearly identical training paradigms [7,15]. We conclude that learning transfer is also related to the interaction of sensory processing and attention involved [1,2]. Here, strong attentional control may have involved higher stages of cortical information processing in learning and may have generated associative images of the trained paradigm and the training procedure which allowed performance widely independent of local perception.

We report a decrease in the current dipole strength of the sensory evoked magnetic field with perceptual learning. The current dipole strength is hypothesized to be an indicator of the net strength of cortical polarization which reflects the total number of synchronously firing neurons contributing to the stimulus-driven cortical response [17]. Our finding of post training reduced current dipole strength would implicate either a decrease of the neuronal population contributing to the signal evoked by trained hand stimulation or a decrease in temporal or spatial coherence in the evoked neuronal activity. Thus, two hypothetical explanations of our observation arise: (1) that the effect of the highly attended training is to reduce the neuron count involved in the evoked magnetic field in the primary somatosensory cortex; (2) that a larger spatial extent of cortex is involved with consequent paradoxical cancellation of extracranial fields due to a loss of spatial and temporal neuronal coherence, arising from the extended non-planar anatomic organization. Also the larger number of neurons could result in temporally asynchronous firing patterns. Electrophysiological studies on animal models report increased cortical repre-

sentations of trained skin sites [13,16]. Similar effects are reported in a MEG study in longterm string players [3]. Our discrimination training appears simple and short in comparison to learning to play a musical instrument. It required attention directed toward every single stimulus and operated exclusively on the localization of cutaneous inputs. We assume that the nature of learning-related cortical reorganization is dependent on the complexity of the task in terms of sensory-motor and associative/cognitive requirements and on the period of learning [2]. The amount of attention required for correct performance most likely excludes that automatization of the task occurred with training. A dominant top-down control also minimizes the possibility that subcortical levels were involved in behavioral learning, although thalamic structures play a role in general arousal and vigilance [9].

Issues of complexity, duration and attention may also be important to consider when interpreting the observation of increasing neuronal populations representing learned inputs in animal models and the decrease in current dipole strength after that tactile discrimination task in humans reported here [13,16]. In any event, a behavior that results in striking positive representational changes including changes in distributed neuronal discharge coherence in monkeys appears to result in a decrease in current dipole strength in humans. It is possible that there are differences in the way the monkeys and the human subjects progress through the training task, and that this may implement different cortical learning strategies [18]. Alternatively, plasticity phenomenology in monkeys and in humans on the applied training paradigm may be fundamentally different in the two species. Finally, we have to take into consideration that different methodological approaches had been used in the two studies. Plausible explanations of our observation of amplitude attenuation in response to training in humans based on MSI data might include neuronal adaptation to simple tactile stimuli during the MSI-recordings after a period of a complex discrimination training, and increased temporal and local interference of current sources induced in the sensory and motor cortices by the highly attended performance of the task evoked by simple tactile stimulation [6,9].

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