Evidence for training-induced crossmodal reorganization of cortical functions in trumpet players

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The aim of this study was to compare multimodal information processing in the somatosensory and auditory cortices and related multimodal areas in musicians (trumpet players) and non-musicians. Magnetoencephalographic activity (MEG) was recorded in response to five stimulus conditions from 10 professional trumpet players and nine musically untrained control subjects. Somatosensory and auditory stimuli were presented alone or in combination. Our data suggest that musicians, in general, process multisensory stimuli differently to the control group. When stimulating the lip in professional trumpet players, a multimodal interaction (expressed as difference between the multimodal response and the sum of unimodal responses) in the corresponding somatosensory cortex showed a positive peak at 33 ms, which was not found in the control group. Conversely, the control group shows a significant interaction of opposite polarity around 60–80 ms. We suggest that training-induced reorganization in musicians leads to a qualitatively different way to process multisensory information. It favors an early stage of cortical processing, which is modified by the connections between multimodal and auditory neurons from thalamus to primary somatosensory area. *NeuroReport* 14:157–161 © 2003 Lippincott Williams & Wilkins.

Key words: Brain imaging; Crossmodal cortical plasticity; Magnetoencephalography (MEG); Music; Somatosensory and auditory cortex

INTRODUCTION

Cortical reorganization has recently been shown to take place in the auditory [1] and the somatosensory [2] cortex of skilled musicians, respectively. However, musical performance in general is a multimodal task that requires simultaneous perception of several sensory modalities. By means of auditory, visual, and haptic (tactile, proprioception, kinaesthesia) feedback mechanisms, musicians continually adjust their motor program to fit their musical image. For example, trumpet players assess their performance by listening and by monitoring both the position and the pressure of their lips touching the mouthpiece as well as their fingers pressing the valves. Errors in musical performance are detected in the auditory modality conjointly with haptic feedback from the vocal tract, the diaphragm and in particular the lips to recalibrate and refine existing skills [3]. Therefore, the desired outcome of an action is compared with the actual outcome. The recognized discrepancy between intention and actuality is used to modify subsequent movements. Alternatively, a musician compares the mechanical information arriving in the haptic feedback path against a desired haptic response and modifies subsequent manipulations to minimize that difference.

Each single sensory pathway relates to a specific perceptual quality. Cues in one modality can help process information in another. Both behavioral and electrophysiological data have shown that multimodal perception enables us to recognize objects and events faster and with less ambiguity [4,5]. Furthermore, information from different modalities can interact and add new quality of perception that conveys information, not inherent in each single modality [6–8]. Neuroimaging studies have shown that responses in a single modality can be enhanced by inputs from other sensory modalities [9,10].

Crossmodal plasticity was first described in humans that experienced sensory loss in early life. The cortex, deprived from exposure to visual or auditory stimuli, starts to process information of the intact senses, like tactile processing in the occipital cortex in blind individuals [11] or visual processing in the auditory cortex in those who are deaf [12]. Multisensory integration has been defined by Meredith and Stein [13] as the increase of a neuron's responses to a stimulus combination compared with its response to an individual stimulus. Multimodal representations are possibly generated through the convergence of information from different sensory systems onto a common group of neurons. These neurons integrate multimodal signals that occur within a certain time frame for a defined receptive field. When multiple sensory cues are available a synthesis of cross-modal information is performed and the response is modified if stimuli of two or more modalities are presented simultaneously [14,15].

In general, it seems that the perception of crossmodal cues, involving crossmodal plasticity mechanisms, is important for playing a musical instrument. Primary cortices that have been classically thought to respond to one modality might actually be more complex. With regard to this idea we suggest that crossmodal plasticity is involved in the process of sensory signal integration over the merged senses to achieve a superior musical performance.

MATERIALS AND METHODS

Subjects: Ten professional trumpeters (three females, seven males, age 26 ± 2.9 years) participated in the study. Nine non-musicians (three females, six males, 25 ± 3.9 years) served as a control group. All subjects were right handed and had normal hearing according to air- and bone conduction thresholds between 250 and 8000 Hz. The trumpet players had been playing their instrument for an average of 15.3 ± 3 years and reported that they practiced an average of 18.4 ± 8 h/week in the 5 years preceding the study. The study was reviewed by the Ethics Commission of the Medical Faculty of the University of Münster. Informed consent was obtained from each subject after the nature of the study was explained to the subjects in accordance with the principles of the Declaration of Helsinki.

Stimuli: All stimuli were presented contra-laterally to the side of MEG measurement. Unimodal tactile stimuli were applied either to the lateral side of the lower lip or to the tip of the index finger. The auditory stimulus was the trumpet tone B2 (American notation). In the bimodal conditions, the same trumpet tone was presented simultaneously with the tactile stimulation of either the lower lip or the index finger. The intensity of the digitally sampled trumpet tone was 60 dB above individual sensation level. The sound was delivered through echoless plastic tubing and a silicon earpiece to the subject's ear canal. Balloon membranes of 1 cm diameter driven by impulses of compressed air applied the tactile stimuli. Each stimulus occurred 256 times in a pseudo-randomly presented sequence with a stimulus onset asynchrony (SOA) of 1900 ± 200 ms. The randomization was constrained so that the same stimulus or stimulus combination were sequentially repeated no more than twice. The stimulus sequence was split into four blocks of about 10 min duration. After a short break the same procedure was used in a counterbalanced manner, measuring the evoked fields above the other hemisphere.

The neuromagnetic signals were collected from the left and right hemispheres using a 37-channel neuromagnetometer (MAGNES, 4D-Neuroimaging Inc.) in a magnetically and acoustically shielded room. The detection coils of 20 mm diameter and 22 mm distance between the centers of the coils were arranged in a circular concave array with a diameter of 144 mm and a spherical radius of 122 mm. Data epochs of 900 ms duration, including 300 ms pre-stimulus interval, were sampled at a rate of 297.6 Hz after filtering between 0.1 and 100 Hz. During the measurement the subject's body was supported by vacuum cast in a 30° upright position. In order to keep the subject in an alert state, a self-chosen soundless movie was presented during the MEG measurement.

Data analysis: Stimulus-related epochs of the evoked magnetic fields were averaged with respect to the different stimuli. Epochs were rejected when the peak-to-peak field amplitude exceeded 2.5 pT. The averaged data were baseline corrected using the pre-stimulus interval. The magnetic field maxima of the somatosensory responses were identified for all subjects near 20 and 40 ms after stimulus onset for the lip and about 50 ms for the index finger. Magnetic source analysis was performed using the data points around these field maxima. The origins of the cortical sources were estimated based upon a single equivalent current dipole (ECD) model. The field of the ECD was fitted to the measured magnetic field distribution in the time interval with the maximal field power (measured as root mean square across all channels). Dipoles with a goodness of fit $> 95\%$ and a distance of the source to the mid-sagittal plane > 2 cm were accepted as representing the sources of the primary somatosensory evoked field. The obtained source coordinates and orientations were used to form a spatial filter that collapsed the time-series of the 37 MEG sensors into a single waveform of a magnetic dipole moment. This method of source space projection allowed the observation of the time-course of the dipole moment, which is a measure of cortical activation strength over the whole post-stimulus time interval.

For all subjects the arithmetical sum of the unimodal auditory and somatosensory responses was subtracted from the bimodal response using the tone and the tactile stimulus to the lip or the finger, respectively. The resulting interaction waveforms were statistically tested for difference from baseline and were compared between groups. The bootstrap method [16] was applied to the multimodal interaction waveforms in order to estimate the group averages and their 95% confidence limits. The strengths of all waveforms (uni- and bimodal responses, sum of unimodal responses and multimodal interaction) were evaluated by MANOVA to compare the effects of stimulus conditions and two experimental groups.

RESULTS

Figures 1 and 2 show the time-courses of the group averaged cortical source strength waveforms for all stimulus conditions observed from the primary somatosensory finger and lip area, respectively. Responses for each group and each hemisphere are shown separately. The differences between the response to the combined auditory-somatosensory stimulation and the sum of unimodal waveforms are shaded in light gray for a larger multimodal response and in dark gray for a smaller multimodal response.

In general, musicians showed distinctly different brain response patterns compared to the control group. In the unimodal condition the auditory N100 m response was significantly larger in the musicians compared to the control group ($F(1,34) = 5.2$, $p = 0.03$). However, unimodal somatosensory responses did not differ significantly between the groups for the digit (N50: F(1,34) = 0.0034, NS) or for the lower lip (N20: F(1,34) = 1.6, NS; N40: F(1,34) = 0.26, NS).

In both musicians and the control group, the source waveforms obtained from the somatosensory finger area (Fig. 1) showed no significant differences between the combined condition and the sum of responses to the tone and the finger stimuli. Additionally, source waveforms did not show clear differences between the groups. Therefore, there was no crossmodal interaction between the musicians and control group and no significant differences between the groups.

In contrast, source waveforms obtained from the somatosensory lip area (Fig. 2) showed distinctive differences between the responses to the combined lip and tone stimulation and the responses obtained by summating responses from the unimodal lip and tone stimulation. These differences of bimodal interaction waveforms (multimodal response minus the sum of unimodal responses) are even more obvious in Fig. 3. The group mean interaction waveforms are displayed in combination with their bootstrapped 95% confidence limits. Centered around 33 ms the musician's response waveforms show a clear amplitude increase in the multimodal lip and tone condition compared to summed waveforms of responses in both single modalities (F(1,34) = 7.2, $p = 0.011$). The multimodal interaction was more pronounced in the musicians group than in control group, especially in the right hemisphere ($p = 0.012$), and was also more pronounced than the multimodal interaction obtained for the left hemisphere ($p = 0.037$). On the other hand, in the latency interval of 60–80 ms (Fig. 2) the control group showed a noticeable amplitude decease in the multimodal lip and tone response compared to the summed unimodal responses (F(1,34) = 19.1, $p = 0.00011$). A pair-wise t-test proved that there was a larger interaction in the control than in the musicians group for the right ($p = 0.013$) and left ($p = 0.0026$) hemisphere.

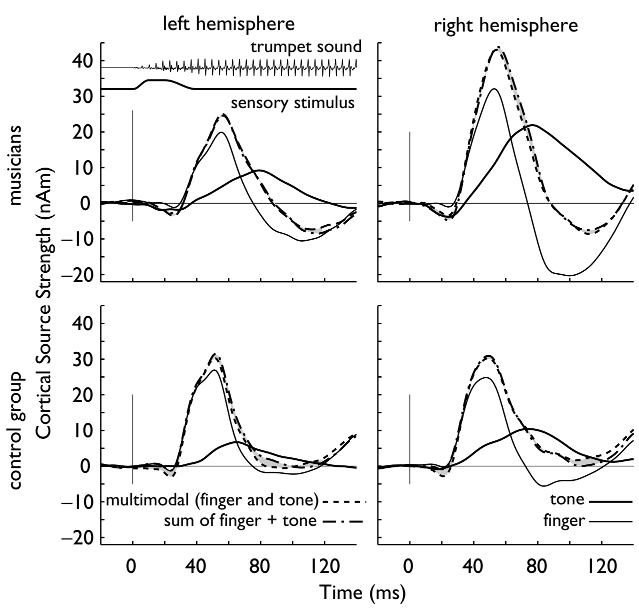

Fig. 1. Group averaged waveforms of cortical source strength (dipole moment in nAm) for musicians (upper row) and control subjects (lower row) obtained from the right and left hemisphere (right and left column) after auditory stimulation (thick solid lines), somatosensory stimulation applied to the index finger (thin solid lines), and multimodal and sum of unimodal stimulations (dashed lines). The sum of responses to separately presented auditory and somatosensory stimuli is shown with dashed-dotted lines. The area between the graphs of this sum and the response to multimodal stimulation is darkly gray shaded if the multimodal response is larger and lightly gray shaded otherwise. The upper left diagram shows the time-course of the auditory and somatosensory stimuli.

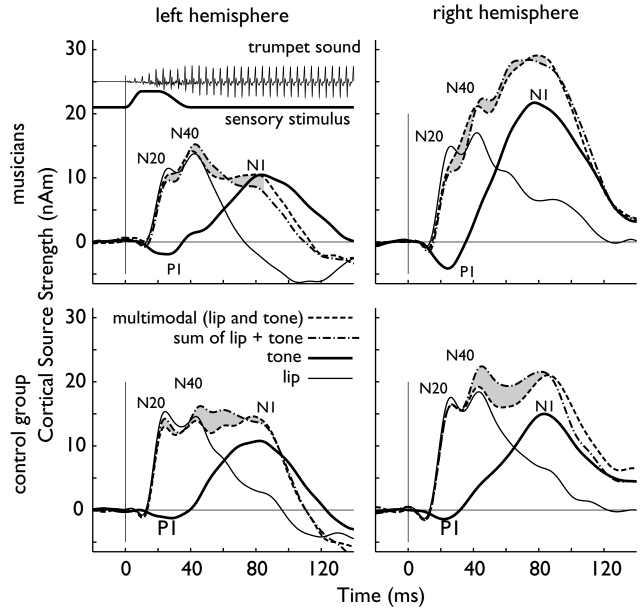

Fig. 2. Group averaged waveforms, as in Fig. 1, for the case of somatosensory stimulus applied to the lip.

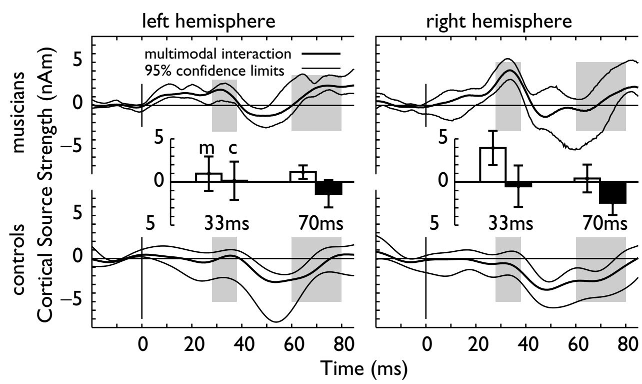

Fig. 3. Group averaged waveforms of multimodal interaction (thick lines), which was calculated as the difference between the multimodal response and the sum of responses to the separately applied auditory and somatosensory lip stimuli. The 95% confidence limits of the mean are shown with thin solid lines. The inserted bar diagram shows the mean interaction in the gray shaded intervals around 33 and 70 ms for the musician group (m, open bars) and the control group (c, filled bars). The error bars denote the 95% confidence limits as the result of a t-statistic.

DISCUSSION

In the present study, musicians and non-musicians show distinctive response patterns characteristically for each group. In line with reports of Pantev *et al.* [1,17] in the unimodal auditory condition the musician's N100 m response was significantly larger compared to the non-musicians. The most important and new result of this study was that auditory-somatosensory interaction effects are also characteristically different between musicians and non-musicians. Comparing responses from combined auditory-somatosensory stimulation with the sum of responses in the unimodal auditory and somatosensory condition showed significant differences between the groups of musicians and non-musicians. In two distinct time intervals the multimodal interaction in the musicians group was superior to that found in the non-musicians group. First, the lip interaction waveform from the musicians showed a positive peak with a maximum around 33 ms, which was missing in the non-musicians group. Second, in the 60–80 ms interval the lip interaction waveform in the non-musicians group showed a clear decrease while the corresponding waveform in musicians group did not decrease. A multimodal interaction in non-musicians at this latency range is in line with recent reports [18]. Foxe *et al.* interpreted the result as multimodal interaction over the central–postcentral brain areas. However the detailed physiological background is still unknown.

Even though the sources of the waveforms were placed in the somatosensory cortex, we have to admit that the spatial selectivity of the source space projection is limited. Consequently, responses originating from the auditory cortex are partially seen in the source waveform obtained from the primary somatosensory cortex. Therefore, we are not able to distinguish whether the recorded response pattern are influenced by nearby multimodal or related areas. Even though, there may be different explanations for the polarity changes of the interaction waves. The early and late bimodal interaction differences seen between the groups of musicians and non-musicians allow several interpretations.

The enhanced interaction at 33 ms found in musicians can be explained by a decreased auditory response, an increased somatosensory response, because both responses are of opposite polarity in this latency range, or an additional multimodal response in the vicinity of the somatosensory cortex. The decrease in the interaction found around 60–80 ms in the control group, which was also reported by Foxe *et al.* [18], can be explained by a decreased auditory or somatosensory response to the combined stimuli, or by an additional multimodal response of negative polarity. However, the results of superior multimodal interaction in musicians compared to the control group in both latency ranges suggest a qualitatively different way of processing multimodal information.

When stimulating the index finger, no significant multimodal interactions were found in both groups. In contrast, the lip shows clear multimodal interaction which differ significantly between the groups. The vocal tract, the diaphragm, and in particular the lips are more intensely engaged in playing the trumpet as compared to the fingers. Therefore, it is most likely that the increased interaction around 33 ms in highly trained professional trumpet players is caused by an increased cortical response of the lip related to multimodal interaction occurring early in sensory processing. A trumpet player can perceive changes in pressure and air flow during register jumps or notes at the mouthpiece. Cook [3] has shown that trumpet players use these haptic cues to determine whether the note is properly settled and stable in the instrument. Because somatosensory and auditory signals are correlated during playing a trumpet, crossmodal competition may give rise to multimodal integration via Hebbian mechanisms. Therefore, the data suggest that musical training causes plastic changes in cortical structures, which lead to an increased multimodal integration that is necessary for musicians to master their instrument.

Recent studies [18,19,20] suggest the involvement of the somatosensory cortex in multi-sensory interaction of even untrained non-musicians. The later multimodal interaction in non-musicians might take place at a more long-range cortico-cortical level, connecting the somatosensory cortex with the auditory cortex and/or related multimodal areas. Direct connections between the auditory and visual cortex have been described in immature cats and hamsters [21,22] and more recently in mature primates [23,24]. On the other hand, early multimodal interactions in trained musicians might take place within the thalamo-cortico-thalamic connections between the thalamus and the somatosensory cortex. Therefore, it seems that auditory projections are acquiring a signal role in activating representations of a somatosensory efferent copy. Animal studies indicate that cortical areas historically thought to be unimodal in response to foreign modalities [25,26] suggest that at least some brain regions use the same code for the representation of a sensory environment by visual, auditory, and somatosensory maps with possible transformation between modalities [27]. Behavioral evidence for this was obtained in formerly deaf patients with a cochlear implant who experienced somatosensory sensations resulting from stimulation through the implant [28]. Animal studies have reported functional reorganization after neonatal redirection of retinal projections to the auditory thalamus, resulting in the development of visually responsive cells and retinotopic maps in the auditory thalamus and related cortical areas [29,30].

Although further studies are necessary for a better understanding of multisensory information processing in humans, our study suggests that musical training leads to remarkable modifications in crossmodal processing. The behaviorally relevant stimulation of somatosensory and auditory modalities in trumpet players and the increased use of these modalities during the intense training schedule combined with high motivational drive in a behaviorally relevant context, are the prerequisites for the development of use-dependent cortical reorganization [31].

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