The Brain That Plays Music and Is Changed by It

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ABSTRACT: Playing a musical instrument demands extensive procedural and motor learning that results in plastic reorganization of the human brain. These plastic changes seem to include the rapid unmasking of existing connections and the establishment of new ones. Therefore, both functional and structural changes take place in the brain of instrumentalists as they learn to cope with the demands of their activity. Neuroimaging techniques allow documentation of these plastic changes in the human brain. These plastic changes are fundamental to the accomplishment of skillful playing, but they pose a risk for the development of motor control dysfunctions that may give rise to overuse syndromes and focal, task-specific dystonia.

KEYWORDS: Brain plasticity; Musical training

INTRODUCTION

The most intricately and perfectly coordinated of all voluntary movements in the animal kingdom are those of the human hand and fingers, and perhaps in no other human activity do memory, complex integration, and muscular coordination surpass the achievements of the skilled pianist.

— Homer W. Smith, *From Fish to Philosopher*

Playing a musical instrument requires more than factual knowledge about the musical instrument and the mechanics of how it is played. For example, given complete information about hand position, finger motions, and sequence of keys to push for how long and with what force, I would still be unable to play even the simplest piano sonata. The central nervous system has to acquire and implement a "translation mechanism" to convert knowledge into action. These translation capabilities constitute the skill that enables the pianist to act on memory systems, select the relevant facts, choose the proper response goals, activate the necessary sensorimotor structures, and execute the sonata successfully. We generally think of such a skill as being acquired with practice. The pianist confronted with a new composition, after understanding the task and its demands, develops a cognitive representation of it and ini-

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tiates a first, centrally guided response that results in sensorimotor feedback and movement correction. It seems certain that both sensory and motor aspects have to be exquisitely coordinated. At the beginning, the limbs move slowly, with fluctuating accuracy and speed, and success requires visual, proprioceptive, and auditory feedback. Eventually, each single movement is refined, the different movements chained into the proper sequence with the desired timing, a high probability of stability in the ordered sequence attained, and a fluency of all movement developed. Only then can the pianist shift his or her attentional focus away from the mechanical details of the performance towards the emotional content of the task. We can think of the acquisition of such a skill as the conversion of declarative knowledge (facts) into procedural knowledge (actions, skills).[1–3]

Learning and memory might be considered integral parts of all the operations of any neural circuit, a concept for which Fuster[4] recently made an eloquent and convincing argument. In this view, "perception and action are phenomena of memory and, conversely, memory is an integral part of perceptual and motor processing" (Ref. 4, p. 21). The nervous system comes to be viewed as a dynamic, dialectic organization in which plasticity is an intrinsic property that relates to the acquisition of new memories and skills as an obligatory consequence of perceptions and motor actions. To play an instrument, the nervous system is modified as a consequence of practice to yield the necessary changes in ability. We refer to this experience-dependent modification in neural structure as plasticity. These changes take place both in sensory and motor systems as well as in their interface. The consequence of this notion is that these changes do not necessarily represent behavioral benefits to the subject but might in fact be misguided and functionally deleterious. The development of noninvasive imaging and neurophysiologic techniques enables us to pursue the study of such changes in humans.

LEARNING TO PLAY THE PIANO CHANGES YOUR BRAIN

…the work of a pianist…is inaccessible for the untrained human, as the acquisition of new abilities requires many years of mental and physical practice. In order to fully understand this complicated phenomenon it is necessary to admit, in addition to the strengthening of pre-established organic pathways, the establishment of new ones, through ramification and progressive growth of dendritic arborizations and nervous terminals. …Such a development takes place in response to exercise, while it stops and may be reversed in brain spheres that are not cultivated.

—Santiago Ramón y Cajal, *Textura del Sistema Nervioso del Hombre y de los Vertebrados*

Normal subjects were taught to perform with one hand a five-finger exercise on a piano keyboard connected by a MIDI interface to a computer.[5] Subjects did not play any musical instrument, did not know how to typewrite using all fingers, and held jobs not demanding skillful hand and finger activities. The exercise required pressing a piano key sequentially with thumb (C), index finger (D), middle finger

(E), ring finger (F), little finger (G), ring finger (F), middle finger (E), index finger (D), thumb (C), index finger (D), and so forth. The subjects were instructed to attempt to perform the sequence of finger movements fluently, without pauses and without skipping any key, while paying particular attention to keep the interval between the individual key presses constant and the duration of each key press the same. A metronome gave a tempo of 60 beats per minute, which the subjects were asked to aim for. Subjects performed the exercise under auditory feedback. They were studied on five consecutive days, and each day they had a two-hour practice session followed by a test. The test consisted of the execution of 20 repetitions of the five-finger exercise and was eventually analyzed with the computer for the exact sequence of key presses, the interval between keys, and the duration and velocity of each key press. Following each test the subjects were given feedback about their performance and tips about how to improve. FIGURE 1 illustrates the great improvement in the subjects' playing skill over the course of the five study days. The number of sequence errors and the duration and variability of the intervals between key presses (as marked by the metronome beats) all decreased significantly.

The aim of the experiment was to correlate skill acquisition with changes in motor cortical output. Therefore, before the first practice session on the first day of the experiment, we used focal transcranial magnetic stimulation (TMS) to map the motor cortical areas targeting long finger flexor and extensor muscles bilaterally. Thereafter, this mapping was repeated daily. The baseline maps can be compared with those obtained during the five days. As the subjects' performance improved, the threshold for TMS activation of the finger flexor and extensor muscles decreased steadily; even taking into account this change in threshold, the size of the cortical representation for both muscle groups increased significantly (FIG. 1).[5] However, this increase could be demonstrated only when the cortical mapping studies were conducted following a 20- to 30-minute rest after the practice (and test) session. No such modulation in the cortical output maps was noted when maps were obtained before each daily practice session (FIG. 1).[6]

When a near-perfect level of performance was reached at the end of a week of daily practice, subjects were randomized into two groups (FIG. 2). Group 1 continued daily practice of the same piano exercise during the following four weeks. Group 2 stopped practicing. During the four weeks of follow-up, cortical output maps for finger flexor and extensor muscles were obtained in all subjects on Mondays (before the first practice session of that week in group 1) and on Fridays (at the end of the last practice session for the week in group 1). In the group that continued practicing (group 1), the cortical output maps obtained on Fridays showed an initial plateau and eventually a slow decrease in size despite continued performance improvement (FIG. 2). On the other hand, maps obtained on Mondays before the practice session and after the weekend rest showed a small change from baseline with a tendency to increase in size over the course of the study (FIG. 2). In group 2, who stopped practicing after one week, the maps returned to baseline after the first week of follow-up and remained stable thereafter.

This experiment reveals that acquisition of the necessary motor skills to perform a five-finger movement exercise correctly is associated with reorganization in the cortical motor outputs to the muscles involved in the task. There are two main mechanisms to explain this reorganization: establishment of new connections, or sprouting, and unmasking of previously existing connections. The rapid time course in the

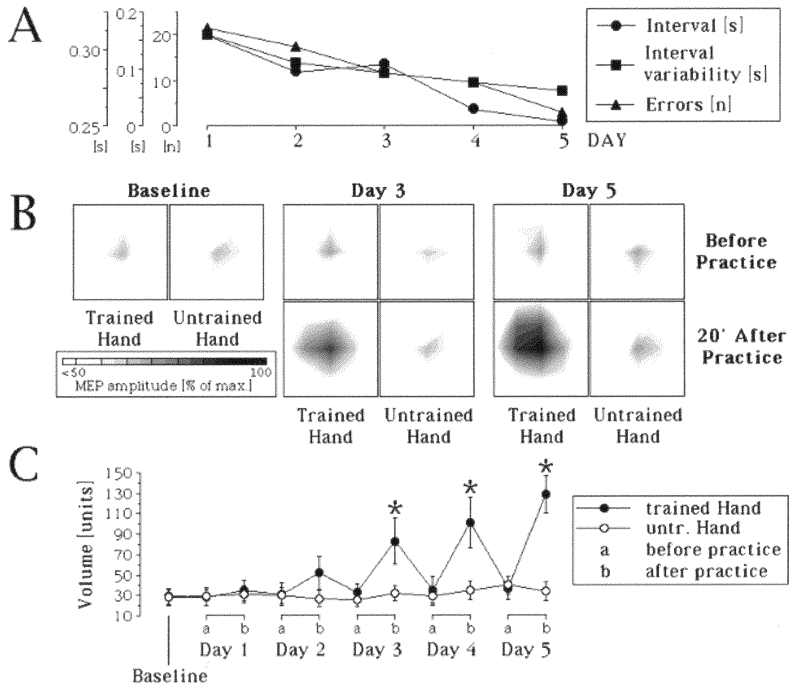

FIGURE 1. (**A**) Behavioral results of the week-long practice of the five-finger exercise on the piano. Interval between key presses, variability of these intervals, and number of errors in 20 repetitions of the exercise all show a highly significant decrease. This documents learning for all subjects studied. (**B**) Cortical output maps for the finger flexors of the trained and untrained hands of a representative subject. (See text and Pascual-Leone *et al.*[5] for details on mapping method.) Note the marked changes of the output maps for the trained hand and the lack of changes for the untrained hand and the maps obtained for either hand before the daily practice sessions. (**C**) Graphic display of mean (± SD) volumes of the cortical output maps for all subjects studied. Note the significant (*star*) changes in cortical output maps for the trained hands after practice sessions on days 3 to 5.

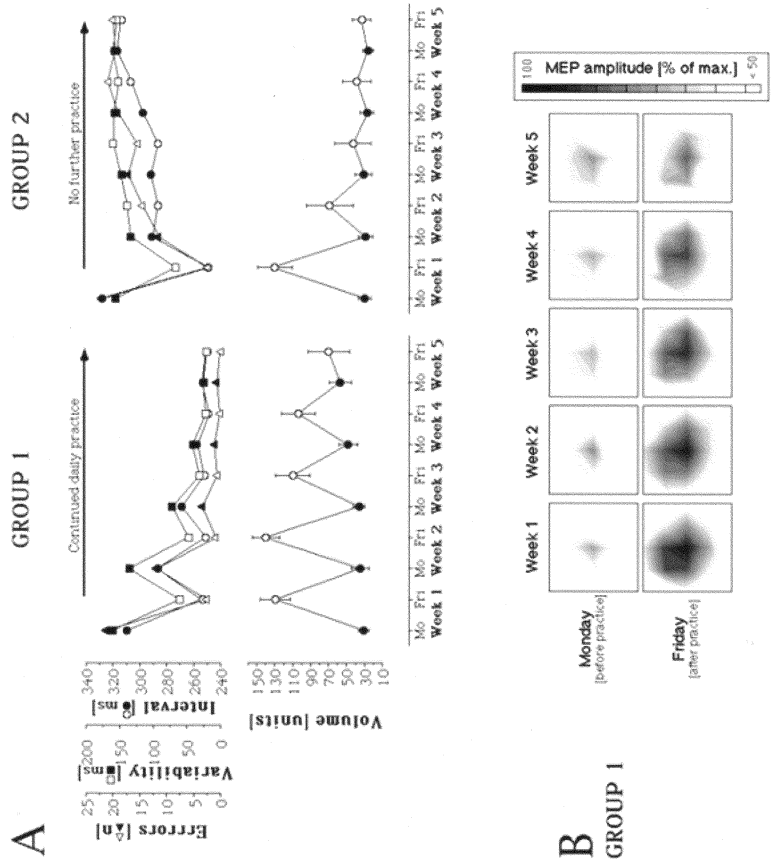

FIGURE 2. (**A**) Behavioral results for subjects in groups 1 (continued practice after 1 week) and 2 (practice limited to 1 week) learning the five-finger exercise on the piano. Interval between key presses, variability of these intervals, and number of errors in 20 repetitions of the exercise are shown. Data from Monday and Friday of each week are shown. (**B**) Cortical output maps for the finger flexors of the trained hand of a representative subject. (See text and Pascual-Leone *et al.*[5] for details on mapping method.) Note the marked changes in the output maps. There appear to be two parallel processes in action, one accounting for the rapid modulation of the maps from Monday to Friday and the other responsible for the slow and more discrete changes in Monday maps over time.[5,6]

initial modulation of the motor outputs, by which a certain region of motor cortex can reversibly increase its influence on a motoneuron pool, is most compatible with the unmasking of previously existing connections.[7–10] Supporting this notion, the initial changes are transient, demonstrable after practice, but return to baseline after a weekend of rest. We suggest that such flexible, short-term modulation represents a first and necessary step, leading to longer-term structural changes in the intracortical and subcortical networks as the skill becomes overlearned and automatic.

It is important to realize that our TMS mapping technique demonstrates a trace or memory of the activation of the motor cortical outputs that took place during the performance of the task rather than the activation during the task itself, as would be the case with neuroimaging studies. Long-term potentiation has been demonstrated in the motor cortex,[11,12] and our results might reveal a similar phenomenon. During the learning of the task, the cortical output maps obtained after task performance show a progressive increase in size, suggesting that skill acquisition is associated with a change in the pattern of activation of the executive structures. These changes are not demonstrable before the task performance, and we might hypothesize that "learning" to activate the cortical outputs appropriately (in this case, activating a progressively larger cortical output map) constitutes the neurophysiological correlate of performance improvement.

As the task becomes overlearned over the course of five weeks, the pattern of cortical activation for optimal task performance might change as other neural structures take a more leading role in task performance. This might result in the decreasing size of the cortical output maps after practice and the increasing size before practice. For example, if basal ganglia play a more important role in driving task performance, the changed activity in the basal ganglia motor circuit might enhance thalamocortical connections. This may account for changes in the cortical motor representation, which would be more stable than that observed during the initial acquisition of a skill. Greenough *et al.*[13] showed that motor training is associated with changes in the dendritic branching patterns of motor and sensory cortical cells involved in the performance of a task. Sprouting may account for plastic changes in such situations, as likely occurred in monkeys deafferented for 10 years,[14] and represent the correlate of long-standing "memories." Neuroimaging studies suggest a similar phenomenon.[15–22] Related changes in the pattern of cortical activation and the resulting modulation of cortical outputs might be induced by changes in the subject's strategy as explicit learning mechanisms are engaged.[23]

Our findings stress the role of the primary motor cortex (M1) in skill acquisition. It is not unreasonable to expect plastic changes in M1 during motor skill learning, because M1 is clearly involved in movement, and its cells have complex patterns of connectivity, including variable influences on multiple muscles within a body part.[24,25] Recent animal studies also illustrate the importance of the M1 in skill learning. For example, increases in excitability of primary motor cortex neurons have been found during conditioning,[26,27] and repeated activation of somatosensory inputs into the motor cortex results in long-term potentiation of motor neurons.[11,12] Even so, at the low stimulus intensities used in our mapping studies, TMS activates cortical cells largely transsynaptically.[28,29] Therefore, the demonstrated modulation in motor cortical outputs might be conditioned by changes in premotor areas projecting to M1, rather than by changes in M1 itself.

IF YOU CANNOT DO IT, AT LEAST THINK ABOUT IT: MENTAL PRACTICE

In the quote reproduced above, Cajal talks about rapid and slower plastic changes in the brain in the context of practice. Our results confirm his intuitions. Furthermore, Cajal writes about physical and *mental* practice. Might the latter result in plastic brain changes similar to those induced by the former?

Mental practice is the imagined rehearsal of a motor act with the specific intent of learning or improving it, without overt movement output. Mental practice can be viewed as a virtual simulation of behavior by which the subject develops and "internally" rehearses a cognitive representation of the motor act. When confronted with a new motor task, the subject must develop a cognitive representation of it and initiate a centrally guided response, which secondarily can be improved using sensorimotor feedback. Mental practice may accelerate the acquisition of a new motor skill by providing a well-suited cognitive model of the demanded motor act in advance of any physical practice.[30, 31]

Mental practice has found wide acceptance in the training of athletes.[32] Musicians also have long recognized the benefit of mental rehearsal. Harold Schoenberg, in his fascinating books on virtuoso intrumentalists,[33,34] provides ample information on this topic. For example, Horowitz is supposed to have practiced mentally before concerts to avoid disturbing his motor skills by the feedback of pianos other than his own Steinway. Rubinstein, eager to enjoy life to its fullest and dedicate as little time to practice as possible, found mental rehearsal the best way to minimize the number of hours spent sitting in front of the piano while maintaining his skill.

Using the same experimental design as described above for the five-finger exercise, we studied subjects who, instead of practicing at the keyboard two hours daily for five days spent time at the keyboard visualizing, rather than executing, the movements.[5] They were told to repeat the movement mentally, as if they were playing, but without moving their fingers. They could rest their fingers on the piano keyboard, but the lack of voluntary movements was monitored using electromyography and video. Such mental practice resulted in a reorganization of the motor outputs to finger flexor and extensor muscles similar to the one observed in the group of subjects who physically practiced the movements and led to similar improvement in their ability to perform the five-finger movement exercise (FIG. 3).

Studies of regional cerebral blood flow (rCBF) suggest that the prefrontal and supplementary motor areas, basal ganglia, and cerebellum are part of the network involved in the mental simulation of motor acts.[35–38] Therefore, mental simulation of movements activates some of the same central neural structures required for the performance of the actual movements. In so doing, mental practice alone seems to be sufficient to promote the modulation of neural circuits involved in the early stages of motor skill learning. This modulation not only results in marked improvement in performance, but also seems to place the subjects at an advantage for further skill learning with minimal physical practice.[5,6] The combination of mental and physical practice leads to greater performance improvement than does physical practice alone, a phenomenon for which our findings provide a physiological explanation.

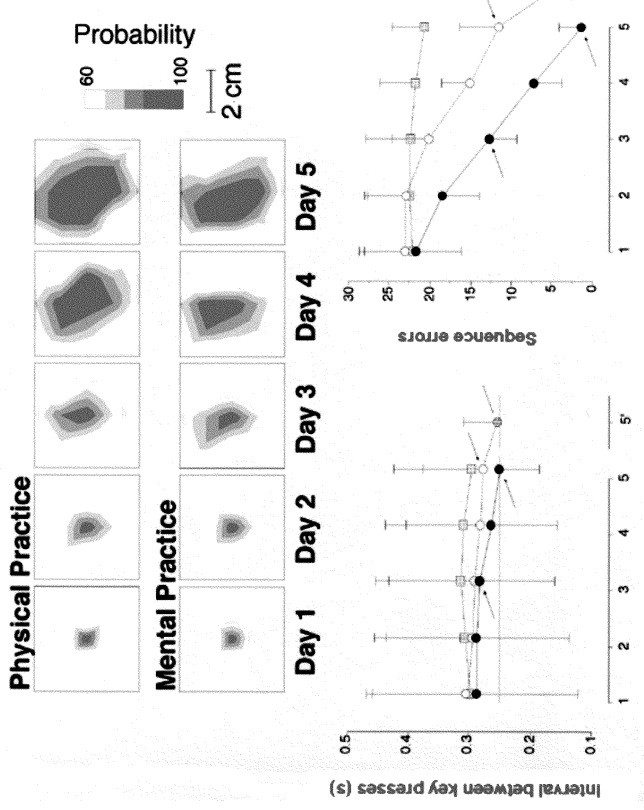

FIGURE 3. (*Top*) Cortical output maps for the finger flexors of the trained hand in a representative subject with physical versus mental practice alone. Modified from Pascual-Leone *et al.*;[5] see also text for details. Note the parity of changes with either form of practice. (*Bottom*) Graphic representation of behavioral data in a group of control subjects (no practice, *squares*) and a group of test subjects performing mental practice (*open circles*) versus physical practice (*filled circles*). Note the behavioral advantage of the physical practice group, but the significant improvement of the mental practice group as compared with controls. The last data point (5′) represents the performance achieved by the mental practice group after 5 minutes of physical practice at the end of day 5. Note the apparent advantage of mental practice, because subjects go from a performance equivalent to day 3 of the physical practice group to matching their day 5 performance with only 5 minutes of practice. Modified from Pascual-Leone *et al.*[5]

THE RISK OF THE CHANGE: SENSORIMOTOR MISMATCH AND TASK-INDUCED DYSTONIA

As we have seen, skill acquisition requires plastic changes in the brain. This plastic reorganization is driven by efferent demand and afferent input. However, a system capable of such flexible reorganization harbors the risk of unwanted change. Increased demand of sensorimotor integration poses such a risk. We can postulate that faulty practice may result in unwanted cortical rearrangement and set the stage for motor control problems such as overuse syndrome and focal, task-specific dystonias. The style of piano playing—for example, the Russian versus the German school—seems to play a critical role in the risk of development of motor control problems. Forceful playing with the fingers bent and executing hammer-like movements is more frequently associated with overuse syndrome and dystonia than is softer playing with extended fingers "caressing" the keys. This stresses the importance of proper, well-guided practice and illustrates the need for greater understanding of the neurobiology underlying music playing to define what proper practice actually is.

Focal hand dystonia in musicians is a strongly task-related movement disorder that can end an instrumentalist's career. Typically, symptoms become manifest only when players execute specific overpracticed skilled exercises on their instrument. Suddenly, a finger moves involuntarily, voluntary motor control is lost, the muscles tense up excessively, and pain develops. Playing is disturbed. For years, focal, task-specific dystonias were thought to be psychiatric in nature. It seemed too bizarre that involuntary muscle contraction might occur when playing a certain passage but not with any other activity or when playing on a certain instrument (organ) but not another (pianoforte). We now know that dystonias are neurologic involuntary movements due to disturbances in motor programs.[39] What, however, is their underlying pathophysiology?

We examined five guitarists with functional magnetic resonance imaging (fMRI) during dystonic symptom provocation by means of an adapted guitar inside the magnet.[40] As reference, we used the activation pattern obtained in the same subjects during other hand movements and in matched guitar players without dystonia during execution of the same guitar playing exercises. A 1.5-Tesla system equipped with echo-speed gradients and single-shot echoplanar imaging (EPI) software was used. Data acquisition was centered on the cortical motor system encompassed in eight contiguous slices.

Dystonic musicians compared in both control situations showed significantly greater activation of the contralateral primary sensorimotor cortex, which contrasted with conspicuous bilateral underactivation of premotor areas (FIG. 4). Our results agree with studies of other types of dystonia in that they show abnormal recruitment of cortical areas involved in the control of voluntary movement. They do suggest, however, that rather than being hypoactive in idiopathic dystonic patients, the primary sensorimotor cortex may be overactive when tested during full expression of the task-induced movement disorder.

Although the primary manifestation of dystonia is abnormal motor function, evidence is increasing for a dysfunction of sensory processing that may be an associated or contributing factor.[39,41–43,46,47] In fact, dedifferentiation of the normally independent sensory representations of multiple digits may be a causative element

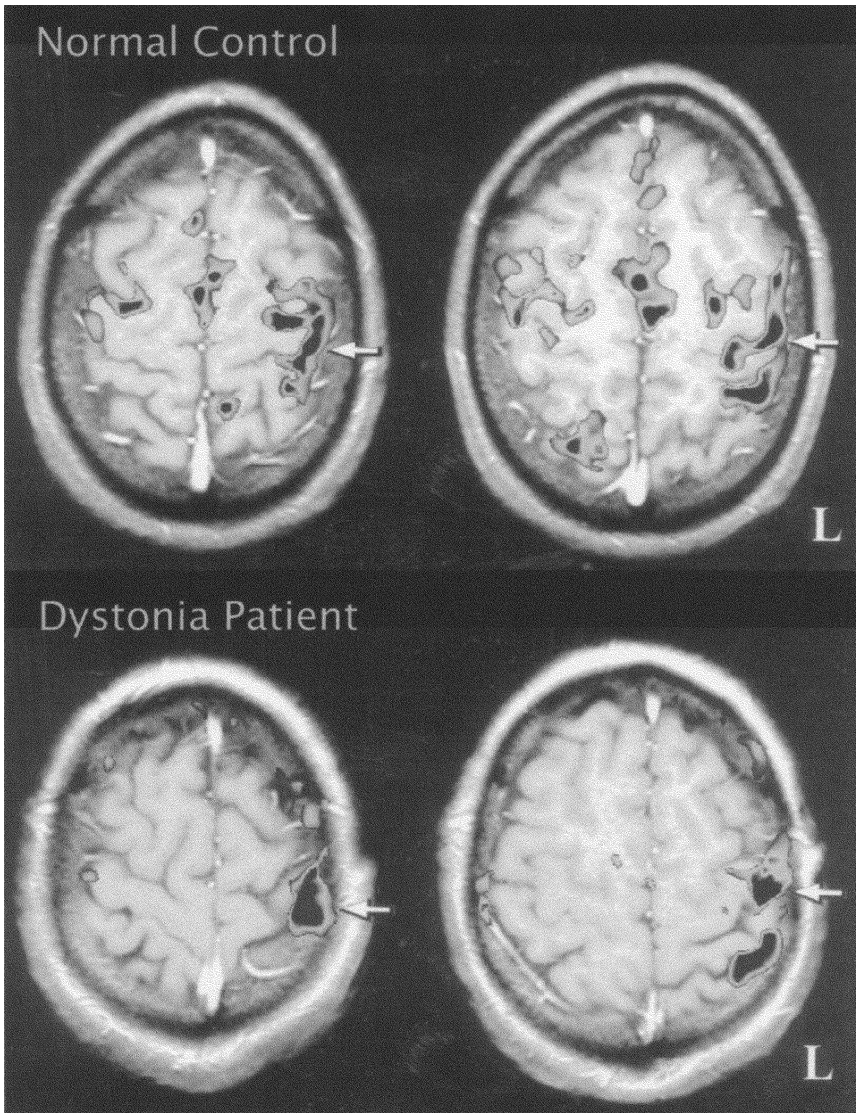

FIGURE 4. See Plate 20 in color section. The BOLD fMRI images of a normal and dystonic guitar player executing right hand arpeggios in the scanner are displayed. Note the greater activation of the sensorimotor cortex (*arrows*) and the lack of activation of premotor and supplementary motor cortices in the dystonic patient. Modified from Pujol *et al.*[40]

in the etiology of dystonia.[44,45] For example, in musicians, extensive practice of coordinated hand postures in which various digits function as a unit, such as arpeggios, could eventually induce changes in the sensory representation of the hand with blurring of the segregation of different digits. This might be the case particularly when

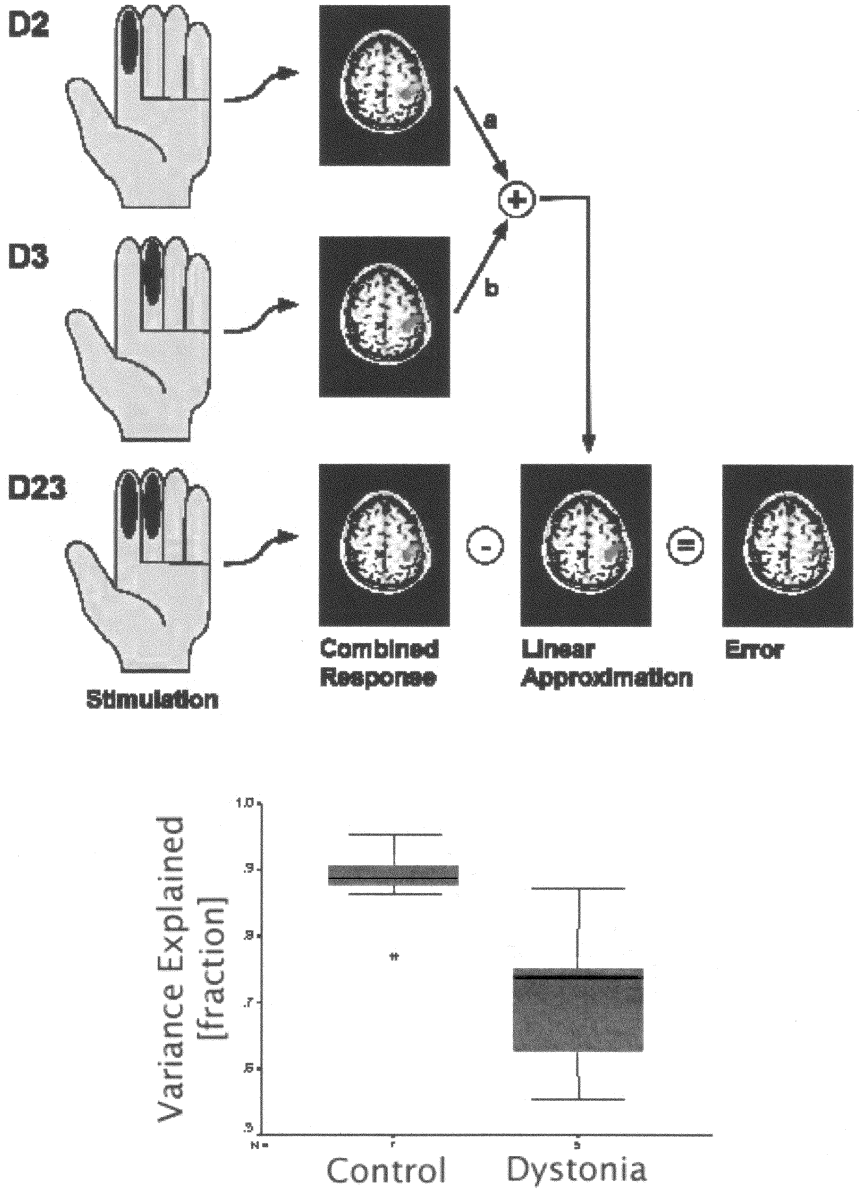

FIGURE 5. See Plate 21 in color section. (*Top*) Schematic representation of the experimental design and representative fMRI data in one subject. Sensory stimulation was applied to the index (D2) or middle (D3) finger alone or to both fingers at the same time (D23) while the fMRI BOLD signal was recorded. A linear approximation of the fMRI signal associated with combined stimulation of D2 and D3 was calculated and substracted from the measured signal, giving rise to the "error" of "variance." (*Bottom*) Variance results in graphic form for all control subjects and patients with dystonia. Modified from Sanger *et al.*[46,47]

small repeated traumas are added, as in forceful, "hammer-finger" piano playing. Disorganization and consequent confusion of sensory inputs could potentially lead to poorly differentiated control of motor representations and be the mechanisms underlying the risk of faulty motor control in some instrumentalists.

Sanger *et al*.[46,47] investigated whether evidence from fMRI supports abnormal receptive fields in primary somatosensory cortex that span more than a single finger surface. We developed a new technique for investigating overlap of sensory cortical receptive fields (FIG. 5) and hypothesized that the combined metabolic demands of two spatially separated populations of cells, when activated simultaneously, would be approximated by the sum of the metabolic demands of each population individually. Therefore, if the populations of cells activated by the second and third digits in normal subjects are distinct, we expect that the task-related component of the blood oxygenation level–dependent (BOLD) signal obtained by simultaneous activation of the two digits will be a linear combination of the task-related BOLD signals when each finger is activated individually. Conversely, if there is overlap of the receptive fields so that the same sensory populations respond to two different fingers, we do not necessarily expect linearity, because the metabolic demands of a single population stimulated by two different fingers may be determined by a complex function of the stimulus strength.

BOLD contrast was measured with fMRI during tactile stimulation of the index finger, the middle finger, or both simultaneously in five patients with focal dystonia and seven control subjects. In the control subjects, a linear combination of activation patterns for individual finger stimulation predicts an average of 88% of the variance in the pattern of activity for combined stimulation. In patients with dystonia, the linear combination predicted only 70% of the combined stimulation pattern ($p = 0.008$; FIG. 6). Therefore, our results suggest that in patients with dystonia, the same region of sensory cortex may respond to tactile stimuli on more than one finger. Disorganization of sensory representations appears to be part of the pathophysiology of focal dystonia and may contribute to motor abnormalities. Hence, emphasis needs to be placed in the sensory as well as on the motor aspects of skill acquisition and practice in musicians. Perhaps all instrumentalists should learn Braille to enhance the functional segregation of individual fingers and minimize the risk of dystonia.

CONCLUSION

Tools are now available to study the neurophysiological correlates of skill learning in humans. The motor cortex plays an important role in motor skill learning, but so does the sensory cortex. The sensorimotor cortex changes as a consequence of skill acquisition. These plastic changes, which probably include functional and structural components, place the subjects at great advantage for skillful task performance, but harbor the risk of the development of motor control disorders. The results of our studies may be useful in understanding not only the physiology of skill acquisitions, but also the pathophysiology of movement disorders in skilled performers. Further work along these lines may lead to helpful insight into the appropriate teaching/learning technique for fine motor skills.

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