ELSEVIER

Neuropsychologia 44 (2006) 711–717

NEUROPSYCHOLOGIA

www.elsevier.com/locate/neuropsychologia

Learning by doing versus learning by thinking: An fMRI study of motor and mental training

Lars Nyberg [a,*], Johan Eriksson [a], Anne Larsson [b], Petter Marklund [a]

[a] *Department of Psychology, Umeå University, S-901 87 Umeå, Sweden*
[b] *Department of Radiation Sciences, Umeå University, Umeå Sweden*

Received 30 June 2004; received in revised form 16 August 2005; accepted 16 August 2005
Available online 7 October 2005

Abstract

Previous studies have documented that motor training improves performance on motor skill tasks and related this to altered functional brain activity in cerebellum, striatum, and frontal motor cortical areas. Mental training can also improve the performance on motor tasks, but the neural basis of such facilitation is unclear. The purpose of the present study was to identify neural correlates of training-related changes on a finger-tapping task. Subjects were scanned twice, 1 week apart, with fMRI while they performed two finger-tapping sequences with the left hand. In-between scans, they practiced daily on one of the sequences. Half of the participants received motor training and the other half received mental training (motor imagery). Both training procedures led to significant increases in tapping performance. This was seen for both the trained and the untrained sequence (non-specific effect), although the gain was larger for the trained sequence (sequence-specific effect). The non-specific training effect corresponded to a reduction in the number of activated areas from an extensive set of brain regions prior to training to mainly motor cortex and cerebellum after training. The sequence-specific training effect involved the supplementary motor area and the cerebellum for motor training and visual association cortex for mental training. We conclude that gains following motor and mental training are based on distinct neuroplastic changes in the brain.

Keywords: fMRI; Motor skill learning; Mental training; Cerebellum; SMA; Imagery

1. Introduction

Learning by doing may be the most effective way of learning a new motor skill but it is not the only way. Controlled studies have demonstrated that mental practice leads to improved performance on tests of motor skill (e.g., Feltz & Landers, 1983). The neural bases for such improvements are not well understood. Motor learning has been shown to be associated with training-related changes in several brain regions, notably cerebellum, striatum, and frontal motor cortical areas (e.g., Doyon, Penhune, & Ungerleider, 2003). A recent study of mental-training induced strength gains included EMG and EEG recordings (Ranganathan, Siemionow, Liu, Sahgal, & Yue, 2004). It was found that strength gains following mental training were related to elevated cortical EEG potentials, but the EMG indicated that the resulting signal did not go down to the muscle level. Based on these observations, Ranganathan et al. proposed that the training affected higher-order motor cortical regions, such as supplementary motor and prefrontal regions. In turn, these areas can influence primary motor areas, and there is some evidence that mental training actually can affect primary motor cortex (e.g., Pascual-Leone et al., 1995).

The purpose of the present study was to identify neural correlates of training-related changes on a finger-tapping task. Our procedure was patterned after a previous study of motor training (Karni et al., 1995). During the first of two fMRI session the participants performed finger tapping according to two different novel sequences. A second identical fMRI session followed after 1 week. In the time in-between sessions, the participants received daily training on one of the sequences. Half went through a motor-training program, whereas the other half received mental training. The mental training involved visualization (motor imagery). For both groups we evaluated gains in tapping performance after compared to before training for *both* the trained and

* Corresponding author. Tel.: +46 907 866 429; fax: +46 907 866 695.
E-mail address: lars.nyberg@psy.umu.se (L. Nyberg).

0028-3932/$ – see front matter
doi:10.1016/j.neuropsychologia.2005.08.006

untrained sequence (*non-specific training effect*). In addition, and of main concern, we evaluated *sequence-specific training effects* by contrasting the trained and untrained sequences after completion of the training program.

2. Materials and methods

2.1. Subjects

Sixteen young, neurologically healthy subjects participated in the study. They were between 24 and 37 years old. All participants were right handed by self report and had normal or corrected to normal vision. They were randomly divided into one of two groups; *motor* (four women and four men, mean age = 29.9) or *mental* (three women and five men, mean age = 29.9). The study was approved by the ethical committee at the University Hospital of Northern Sweden and all participants gave informed consent prior to participation.

2.2. Procedure

The first part of the study consisted of the initial fMRI-session. Prior to scanning, the subjects were instructed that the left index to little fingers were numbered from 1 to 4 and that they were to perform finger tapping sequences as fast and accurate as possible according to visually presented sequences. They were also told that when series of "x x x x x" were presented they should rest and lie still. In the scanner two different sequences (A = 4 1 3 2 4; B = 4 2 3 1 4) were presented in a blocked fashion intermixed with blocks of x's (block length = 30 s; block order = A-X–B-X, repeated three times per subject).

After the first scanning session, the participants received four daily sessions of individual training on one of the sequences. In each group (motor and mental), half of the subjects practiced on sequence A and the other half on sequence B. In the motor group, training consisted of tapping the left-hand fingers on a table in front of the subject according to the specified sequence (the sequence was written on a paper that was placed on the table). To prevent visual feedback the hand was concealed with a cardboard box. The subjects tapped for 90 s, rested for 60 s, and then tapped again. They tapped a total of four times (6 min) per session (a total of 16 times or 24 min across sessions). The mental group followed exactly the same training program with the exception that they were instructed to visualize that they performed the finger-tapping sequence. To prevent actual finger movements they had their left and right hand fingers crossed, visible on the table.

One week after the first scanning session the subjects were again placed in the scanner and they performed an identical run as during the first fMRI session. Importantly, at the time of the second session, they had practiced on one of the two sequences that were presented and performed.

2.3. MRI methods

Scanning was conducted on a Philips Intera 1.5 T system (Philips Medical Systems, Netherlands), equipped for echo-planar imaging (EPI). Blood-oxygen level-dependent contrast images were acquired using a T2*-weighted single-shot gradient echo EPI sequence with the following parameters: echo time: 50 ms, repetition time: 3000 ms, flip angle: 90°, field of view: 22 × 22 cm, matrix size: 64 × 64 and slice thickness: 4.4 mm. Thirty-three transaxial slices positioned to include the whole brain volume were acquired every 3.0 s. Five "dummy scans" were run before the image acquisition started to avoid signals resulting from progressive saturation.

The finger tapping sequences were presented visually on a semi-transparent screen at the end of the scanner bore, which the subject could view via a mirror mounted on the head coil. Cushions inside the head coil were used to reduce head movement, and headphones (Silent Scan™ SS-3100, Avotec, FL, USA) were used to dampen the scanner noise.

The finger tapping task was executed with a four-button response pad (Lumitouch reply system, Lightwave Medical Industries, Canada). The response pad was connected to a computer running the program E-prime (Psychology Software Tools, PA, USA) which registered the responses.

A program was written in Matlab (Mathworks Inc., MA, USA) to count the number of correct sequences performed by each participant, where a correct sequence was defined as a complete motor replicate of the visually presented sequence (e.g., 4 1 3 2 4).

2.4. Statistical analyses

The fMRI images were transferred to a PC and converted to Analyze format using the program *MRIcro* (Rorden & Brett, 2000). The data was then pre-processed and analysed using SPM2 (*Wellcome Department of Cognitive Neurology, London, UK*) implemented in Matlab 6.5.1 (Mathworks Inc., MA, USA). The pre-processing steps were: slice timing correction, realignment with respect to the first image volume in the series, unwarping to reduce residual movement related variance, normalisation to an EPI template in the Montreal Neurological Institute (MNI) space, and smoothing with an isotropic 8.0 mm Gaussian filter kernel. Single-subject statistical contrasts were then set up using the general linear model. The blocks of finger tapping and rest were modelled as fixed response (box-car) waveforms convolved with the hemodynamic response function (HRF). Statistical parametric maps (SPMs) were generated using *t*-statistics to identify regions activated according to the model for individual subjects, and random effects analyses were then used to reveal results for the whole group.

Finger tapping performance was analyzed as a series of planned comparisons (one-tailed within-subjects *t*-tests). To test for non-specific training effects, tapping performance after training was contrasted with tapping performance before training for both the trained and untrained sequences in each group. To test for sequence-specific training effects, tapping performance after training was contrasted for the trained versus untrained sequence. Two outliers with very few performed sequences were identified in the motor group for the untrained sequence after training, possibly signalling a registration failure. These were removed from the analyses (if they had been included this would have served to magnify the training effect in the motor group, i.e., an effect in the expected direction).

3. Results

3.1. Finger tapping

On average, the participants performed 26.7 correct sequences before training (range = 24–28). The proportion correctly performed sequences was 88% of the total number of performed sequences. The mean increase in finger tapping performance after training is shown in Fig. 1. At this session, the proportion correctly performed sequences was 90% of the total number of performed sequences. Thus, the vast majority of performed sequences before as well as after training were correct and only a minority represented incorrect responses. In both

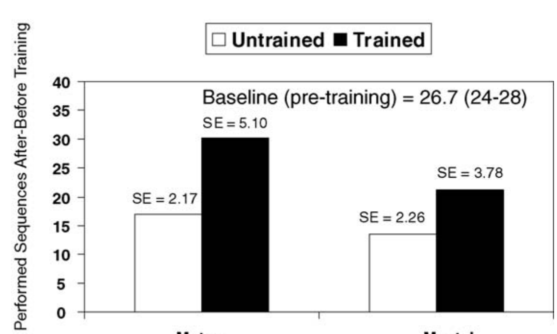

Fig. 1. Mean increases in finger-tapping performance as a function of sequence and group. S.E. = standard error of the mean increase.