Practice and perfect: length of training and structural brain changes in experienced typists

Gianna C. Cannonieri[a], Leonardo Bonilha[b], Paula T. Fernandes[a], Fernando Cendes[a] and Li M. Li[a]

[a]Laboratory of Neuroimaging, Department of Neurology, State University of Campinas, Campinas, São Paulo, Brazil and [b]Departments of Neuropsychiatry and Communication Sciences and Disorders, University of South Carolina, South Carolina, USA

Correspondence to Dr Li M. Li, MD, PhD, Department of Neurology, State University of Campinas, Campinas-SP-Brazil, 13083-970-PO Box 6111
Tel/fax: + 55 19 3521 7292; e-mail: limin@fcm.unicamp.br

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Motor training results in performance improvement. It is not yet fully understood the extent to which functional improvement is reflected in changes in brain structure. To investigate the presence and degree of structural brain plasticity induced by long-term bimanual motor activity, we studied 17 right-handed professional typists with average duration of typing practice of 11 years. Using optimized voxel-based morphometry, we correlated the duration of practice and grey matter volume. Regions of interest were applied using 116 previously segmented predefined brain sites. We found a significant positive regression between grey matter volume and duration of practice in brain regions related to the programming of motor tasks. Long-term bimanual training may increase grey matter volume in the brains of professional typists. *NeuroReport* 18:1063–1066 © 2007 Lippincott Williams & Wilkins.

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Introduction

Motor learning is defined as the acquisition or modification of a trained motor skill, resulting in improvement performance and the need for less attention to execute the action. Motor learning is probably associated with functional adaptation of motor pathways in the brain, as demonstrated by functional studies showing that motor brain areas exhibit different patterns of activation during motor learning [1].

Besides the functional adaptation of the brain motor circuitry, current evidence from animal studies suggests that the practice of a motor action is also reflected in macroscopic changes in motor-related structures. Studies on adult animals revealed structural modifications induced by motor practice [2,3], possibly related to increases in the number of synapses, the number of glial cells and/or the number of capillaries per neuron [2].

In humans, similar evidence comes from structural MRI studies on professional musicians (keyboard players), which demonstrated significant larger white and grey matter volumes in brain areas related to motor and music tasks [4,5]. In addition, evidence from functional studies [6–8] also showed that motor practice might induce different cortical activation in the brain.

Findings from skilled musicians, however, lead to very important questions: are brain alterations really a consequence of prolonged practice, or, instead, could they be due to an innate predisposition for music? Schlaug *et al.* [9], in a longitudinal study with children undergoing musical training, showed brain changes after prolonged (4 years follow-up) training. Although there is evidence that morphometric brain changes [10] occur after motor training in adults also, it remains unclear whether the amount of cortical alteration is related to the duration of training.

In this study we investigated the brain structure of professional typists, aiming to evaluate changes that could be a reflection of the time devoted to the practice of typing. A positive correlation between training duration in years and grey matter volume in training-associated brain structures would provide additional evidence for the hypothesis that the structural alterations are the result of a prolonged training. Like keyboard musicians, professional typists perform sequential bimanual motor activity of the fingers. Complex motor skills used in both situations involve striking a series of keys in a specific order, requiring a high degree of bimanual finger coordination. Typists, however, do not need as many other nonmotor skills as professional musicians, minimizing the factors related to genetic predisposition. Moreover, typists typically do not begin motor learning practice early in life.

Methods

Participants

Seventeen professional typists (six men, mean age=40 years, SD=7, ranging from 27 to 58 years) were studied. The mean age of professional typewriting activity was 11 years (SD=5), ranging from 5 to 20 years. All typists were right-handed according to the Edinburgh Handedness Inventory [11] and had become professional typists after the age of 20 years. Written informed consent was obtained from all participants in accordance with the guidelines of the ethics committee from our institution.

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Imaging

We aimed to quantify grey matter volume in a voxel-wise fashion using optimized voxel-based morphometry of high-resolution T1-weighted MR images.

All subjects were submitted to MR scanning on the same Elscint Prestige 2-Tesla scanner (Haifa, Israel) using a spoiled gradient-echo sequence (TR=22 ms, TE=9 ms, flip angle=35°, matrix=256 × 220), yielding volumetric T1-weighted images with 1 mm isotropic voxels.

Image preprocessing

DICOM images were transformed into ANALYZE format using MRIcro Software (Chris Rorden, *www.mricro.com*) [12] and skull-stripped using the brain extraction tool built within MRIcro. The voxel-based morphometry optimized analysis was performed using modified routines present in the SPM2 software package (Wellcome Department of Cognitive Neurology, *www.fil.ion.ucl.ac.uk*) [13]. For normalization and segmentation routines, we employed an in-house-developed template constructed from T1 images from 96 controls, who were scanned in the same scanner, using the same volumetric T1 protocol. From the in-house template, we also extracted prior images corresponding to grey and white matter probabilistic segmented maps, which were used during segmentation routines applied to images from the typists. We decided to use an in-house template, instead of the standard T1 template from SPM2, for three reasons: first, differences in contrast can exist if images are acquired by different scanners, therefore the standard SPM2 template could have different grey and white matter contrasts than the images from our scanner; second, each scanner is unique in terms of nonuniformities in image intensity and inhomogeneities in the B0 field; and third, we would like to account in our template for the demographics of our population. Prior images and the template were convolved with an isotropic Gaussian kernel of 8 mm and were used for optimizing the nonlinear normalization of raw skull-stripped images.

Spatial normalization was performed using 16 nonlinear interactions, medium regularization and a 25-mm cutoff. Images underwent segmentation of grey matter, that is, the estimation of the probability that each voxel is grey matter, using SPM2's built-in routines. The segmented images were modulated [14], to preserve the information about the original quantity of grey matter while ensuring a good spatial alignment between patients and controls. Finally, the images were convolved with an isotropic Gaussian kernel of 10 mm to minimize gyral interindividual variability. This smoothing creates images that are more normally distributed and permit voxel-wise analysis.

Statistical analysis

After normalization, segmentation, modulation and smoothing, data were statistically analyzed. We aimed to investigate a possible regression between grey matter volume and the time of training, defined as years in which participants worked as typists. We expected that occasional changes in grey matter volume would be subtle, therefore the dataset was analyzed using regions of interest (ROIs). We used 116 previously defined anatomic obtained from the automatic anatomical labeling (AAL) ROI library (*www.cyceron.fr/freeware/*) covering the whole brain. We used the software package MARSBAR (http://marsbar.sourceforge.net) [15] to extract the mean grey matter volume from each ROI and to investigate, as a first pass, ROIs that would exhibit a trend toward correlation with typing, that is, were significant without Bonferroni correction for multiple comparisons. ROIs that exhibited a trend toward a significant positive correlation with time of typing, were exported to the software package SPSS (*www.spss.com*). Under SPSS, bivariate correlation coefficients were calculated and ROIs that correlated with type as a typist with a probability of $P<0.05$ were considered significant.

Results

ROI analyses showed that the grey matter volume was positively linearly correlated with time of typing training in six regions: left medial inferior cerebellar hemisphere (Fig. 1a, Pearson correlation=0.4, P=0.038, Fig. 1c Pearson=0.49, P=0.024), right medial inferior cerebellar hemisphere (Pearson=0.48, P=0.027, Fig. 1b), right medial orbital region (Pearson=0.47, P=0.028, Fig. 1d), right paracentral lobule (Pearson=0.48, P=0.024, Fig. 1e) and the right temporal pole (Pearson=0.43, P=0.042, Fig. 1f).

Discussion

Our results suggest a positive regression between duration of typing practice and grey matter volume in brain areas commonly related to bimanual motor activities, such as supplementary motor area, prefrontal cortex and cerebellum. These findings confirm the hypothesis that training induces structural changes in the brain, which possibly represent the neural substrate of increased performance induced by practice. Moreover, our results indicate that the longer the training, the bigger are the volume of cortices in brain areas related to the execution of the motor task.

The brain regions that were correlated with time of practice observed in our study are in keeping with results from studies that had evaluated the function of areas involved in motor activities. The prefrontal cortex has been associated with motor learning and planning of specific actions regarding maintenance of attention [16]. Paralimbic areas [17], including the orbitofrontal cortex and the temporal pole, have been correlated in functional studies with working memory.

The supplementary motor area (Fig. 1e) is fundamental for programming, executing and controlling bimanual sequential finger movements. Studies in animals [18] and in humans [19] have demonstrated the important role they play in the execution of bimanual and sequential activities.

Interestingly, positive correlation between typing duration and volume of grey matter was found in the right hemisphere of the brain. We expected these alterations to be bilateral as typing is a bimanual activity. Two hypotheses might explain these findings. The first is based on functional studies that revealed greater activity in the right brain hemisphere during nonmirror bimanual finger activities [20] and that lesions in the right supplementary motor area produced mirror movements [18,21] during bimanual coordination activities. These works suggest that the circuits in the right hemisphere may be responsible for nonmirror transformation of motor programs.

Typists perform nonmirror bimanual sequential finger movements that demand greater activity of the right hemisphere to overcome the tendency to mirror the activity

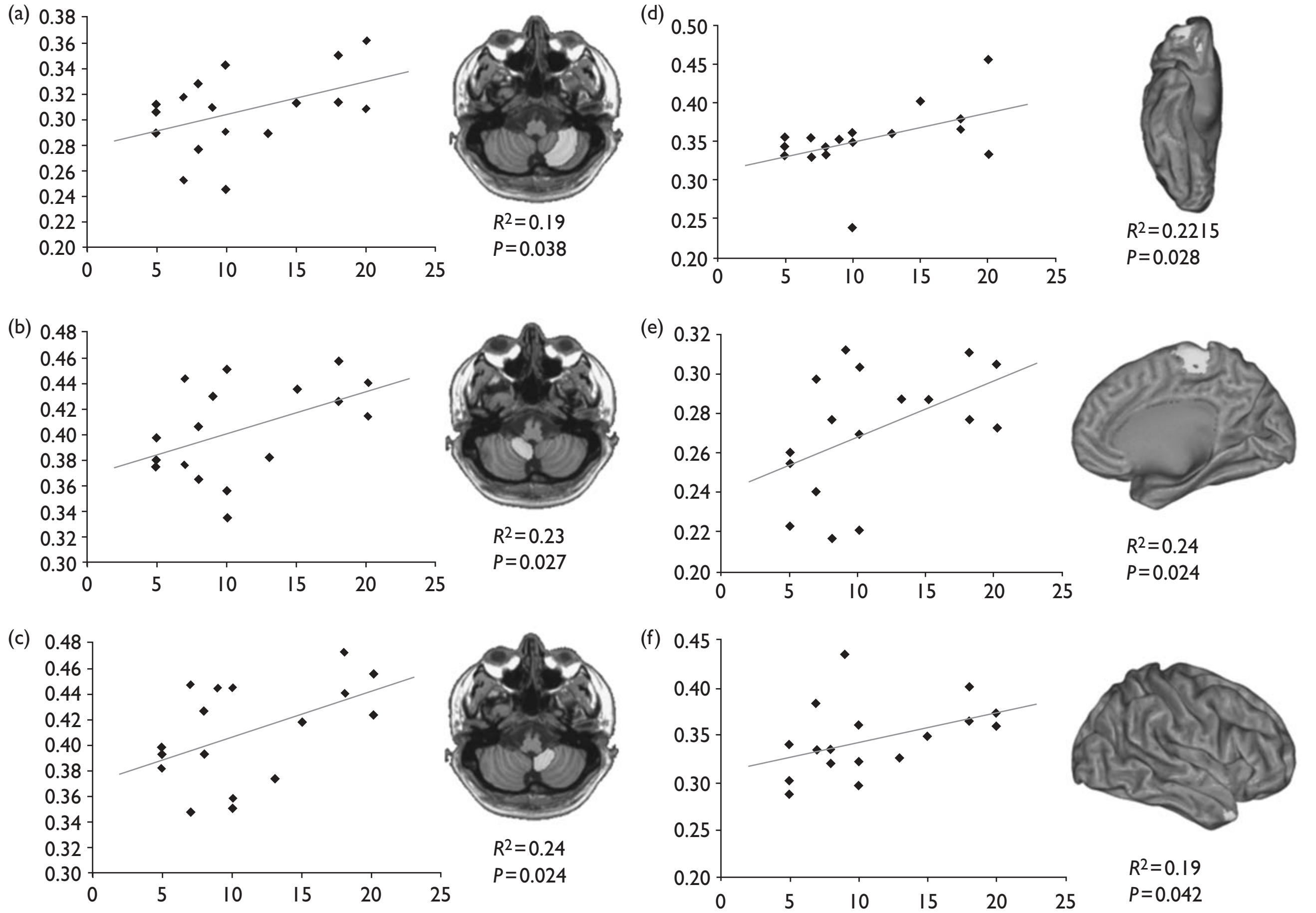

Fig. 1 Display ROIs, which showed a significant linear correlation between grey matter volume and time of typewriting training [infratentorial ROIs in (a), (b) and (c) and supratentorial ROIs in (d), (e) and (f)]. The graphs plot the distribution of grey matter volume for time of training. Each ROI is shown overlaid in a normal T1 template [(a), (b) and (c)] or in inflated normal cortical map (Caret: *www.brainmap.wustl.edu/*) [(d) inferior view, (e) medial view, (f) lateral view]. Each graph displays the significant linear correlation trendline. The corresponding squared *R* and *P* values are displayed underneath the ROI overlay. ROI, region of interest.

dictated by the dominant left hemisphere. As these individuals type for several hours a day, modulation function of the right hemisphere is in greater demand than the dominant hemisphere inducing structural brain plasticity in the areas of right hemisphere.

As a second hypothesis, brain imaging studies support the view that movements with the subdominant hand are more demanding [22,23]. In right-handed individuals, initially there is a limited capacity of the right hemisphere to control demanding left-hand movements, but with training, its ability becomes more efficient. For typing, both hands need to be skillful. This fact explains why the structural changes owing to long-term bimanual training are much more distinct in the right hemisphere contralateral to the subdominant hand.

We also observed that a positive correlation between typing duration and increased cerebellar cortex volume occurred bilaterally (Fig. 1a–c). The cerebellum has an ipsilateral limb influence. Lobule VIII, increased bilaterally in our study, is part of the second homunculus in the cerebellum and functional MRI studies have demonstrated its activation in nonmirror bilateral movements of the fingers [24].

Draganski *et al.* [10] studied a group of healthy adults practicing juggling and found an increase in the volume of the grey matter in regions of the brain directly related to trained skill, spatial perception and anticipation of the trajectory of moving objects. Moreover, the study of music training by Schlaug *et al.* [9] is possibly strong evidence of structural plasticity induced by training. The participants studied were under 9 years of age, when the neural plasticity is different from adults [25]. Our study adds to the above-mentioned studies [9,10] by showing that brain structural alterations are a result of training, occur in adults, and the changes were not random, but in areas related to motor learning and coordination for typing. In addition, the amount of cortical change is a consequence of duration of training.

Conclusion

Prolonged training of a complex motor action is associated with increased grey matter volume in brain areas associated with the execution of the task. Practicing a skilled movement possibly strengthens the circuitry involved in the execution of the action, thereby increasing the volume of the structures involved. Functional and structural changes in the motor networks are possibly the neural substrate for increased motor performance that comes with practice. Moreover, a longer time of training is associated with greater structural changes, serving as a neural foundation for the common sense knowledge that longer practice makes perfection.

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References

1. Doyon J, Benali H. Reorganization and plasticity in the adult brain during learning of motor skills. *Curr Opin Neurobiol* 2005; **15**:161–167.
2. Anderson BJ, Li X, Alcantara AA, Isaacs KR, Black JE, Greenough WT. Glial hypertrophy is associated with synaptogenesis following motor-skill learning, but not with angiogenesis following exercise. *Glia* 1994; **11**:73–80.
3. Kleim JA, Swain RA, Armstrong KA, Napper RM, Jones TA, Greenough WT. Selective synaptic plasticity within the cerebellar cortex following complex motor skill learning. *Neurobiol Learn Mem* 1998; **69**:274–289.
4. Gaser C, Schlaug G. Brain structures differ between musicians and non-musicians. *J Neurosci* 2003; **23**:9240–9245.
5. Hutchinson S, Lee LH, Gaab N, Schlaug G. Cerebellar volume of musicians. *Cereb Cortex* 2003; **13**:943–949.
6. Jancke L, Baumann S, Koeneke S, Meyer M, Laeng B, Peters M, *et al*. Neural control of playing a reversed piano: empirical evidence for an unusual cortical organization of musical functions. *NeuroReport* 2006; **17**:447–451.
7. Koeneke S, Lutz K, Wustenberg T, Jancke L. Long-term training affects cerebellar processing in skilled keyboard players. *NeuroReport* 2004; **15**:1279–1282.
8. Koeneke S, Lutz K, Herwig U, Ziemann U, Jancke L. Extensive training of elementary finger tapping movements changes the pattern of motor cortex excitability. *Exp Brain Res* 2006; **174**:199–209.
9. Schlaug G, Norton A, Overy K, Winner E. Effects of music training on the child's brain and cognitive development. *Ann N Y Acad Sci* 2005; **1060**:219–230.
10. Draganski B, Gaser C, Busch V, Schuierer G, Bogdahn U, May A. Neuroplasticity: changes in grey matter induced by training. *Nature* 2004; **427**:311–312.
11. Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 1971; **9**:97–113.
12. Rorden C, Brett M. Stereotaxic display of brain lesions. *Behav Neurol* 2000; **12**:191–200.
13. Friston KJHA, Worsley KJ, Poline J-B, Frith CD, Frackowiak RSJ. Statistical parametric maps in functional imaging: a general linear approach. *Hum Brain Map* 1994; **2**:189–210.
14. Good CD, Ashburner J, Frackowiak RS. Computational neuroanatomy: new perspectives for neuroradiology. *Rev Neurol (Paris)* 2001; **157**:797–806.
15. Brett MAJ, Valabregue R, Poline JB. Region of interest analysis using an SPM toolbox [abstract] Presented at the 8th International Conference on Functional Mapping of the Human Brain, June 2–6, 2002, Sendai, Japan. Available on CD-ROM in NeuroImage 2002; 16.
16. Pardo JV, Fox PT, Raichle ME. Localization of a human system for sustained attention by positron emission tomography. *Nature* 1991; **349**:61–64.
17. Mesulam MM. From sensation to cognition. *Brain* 1998; **121** (Pt 6): 1013–1052.
18. Brinkman C. Supplementary motor area of the monkey's cerebral cortex: short- and long-term deficits after unilateral ablation and the effects of subsequent callosal section. *J Neurosci* 1984; **4**:918–929.
19. Ogiso T, Kobayashi K, Sugishita M. The precuneus in motor imagery: a magnetoencephalographic study. *NeuroReport* 2000; **11**:1345–1349.
20. Sadato N, Yonekura Y, Waki A, Yamada H, Ishii Y. Role of the supplementary motor area and the right premotor cortex in the coordination of bimanual finger movements. *J Neurosci* 1997; **17**:9667–9674.
21. Chan JL, Ross ED. Left-handed mirror writing following right anterior cerebral artery infarction: evidence for nonmirror transformation of motor programs by right supplementary motor area. *Neurology* 1988; **38**:59–63.
22. Koeneke S, Lutz K, Esslen M, Jancke L. How finger tapping practice enhances efficiency of motor control. *NeuroReport* 2006; **17**:1565–1569.
23. Koeneke S, Lutz K, Wustenberg T, Jancke L. Bimanual versus unimanual coordination: what makes the difference? *Neuroimage* 2004; **22**:1336–1350.
24. Habas C, Axelrad H, Nguyen TH, Cabanis EA. Specific neocerebellar activation during out-of-phase bimanual movements. *NeuroReport* 2004; **15**:595–599.
25. Schlaug G. The brain of musicians. A model for functional and structural adaptation. *Ann N Y Acad Sci* 2001; **930**:281–299.