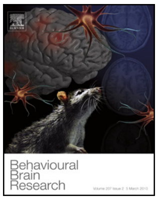
Behavioural Brain Research 319 (2017) 87–95

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr



Research report

Motor sequence learning-induced neural efficiency in functional brain connectivity

Helmet T. Karim[a], Theodore J. Huppert[b], Kirk I. Erickson[c], Mariegold E. Wollam[c], Patrick J. Sparto[d], Ervin Sejdić[e], Jessie M. VanSwearingen[f],*

[a] Department of Bioengineering, University of Pittsburgh, Pittsburgh PA, USA
[b] Department of Radiology and Bioengineering, University of Pittsburgh, Pittsburgh PA, USA
[c] Department of Psychology, University of Pittsburgh, Pittsburgh PA, USA
[d] Departments of Physical Therapy and Bioengineering, University of Pittsburgh, Pittsburgh PA, USA
[e] Department of Electrical and Computer Engineering, University of Pittsburgh, Pittsburgh PA, USA
[f] Department of Physical Therapy, University of Pittsburgh, Pittsburgh PA, USA

HIGHLIGHTS

- Brain activity was measured during motor sequence learning task.
- Posterior parietal and thalamus activated less during learning (vs. control).
- Putamen to frontal/mid. cingulate connectivity lower during learning (vs. control).
- Learning was associated with changes in brain activity/spatial extent/connectivity.

ARTICLE INFO

Article history:
Received 12 August 2016
Received in revised form 3 November 2016
Accepted 10 November 2016
Available online 11 November 2016

Keywords:
Motor learning
Motor skill
Functional connectivity
gPPI

ABSTRACT

Previous studies have shown the functional neural circuitry differences before and after an *explicitly* learned motor sequence task, but have not assessed these changes during the process of motor skill learning. Functional magnetic resonance imaging activity was measured while participants ($n = 13$) were asked to tap their fingers to visually presented sequences in blocks that were either the same sequence repeated (learning block) or random sequences (control block). Motor learning was associated with a decrease in brain activity during learning compared to control. Lower brain activation was noted in the posterior parietal association area and bilateral thalamus during the later periods of learning (not during the control). Compared to the control condition, we found the task-related motor learning was associated with decreased connectivity between the putamen and left inferior frontal gyrus and left middle cingulate brain regions. Motor learning was associated with changes in network activity, spatial extent, and connectivity.

1. Introduction

Motor learning is a process by which new movements are acquired. This motor learning, commonly termed motor skill learning, signifies increased spatial and temporal accuracy of the acquired movement patterns for a performance goal. The increased spatial and temporal accuracy can be achieved through practice alone, or by training (in cases where motor performance involves greater complexity of movement sequences across multiple joints, or inter-limb coordination). Motor skill learning also includes the establishment of new associations between environmental signals or targets and the motor actions. As such, the motor skill learning may involve development of the link between previously acquired movement patterns or environmental signals experienced in the context of the [new] performance goal [1,2]. Motor skill learning is associated with changes in the brain circuitry under-

---

* Corresponding author at: University of Pittsburgh, Department of Physical Therapy, Bridgeside Point 1, 100 Technology Drive, Suite 233, Pittsburgh, PA 15219, USA.

E-mail addresses: hek26@pitt.edu (H.T. Karim), huppertt@upmc.edu (T.J. Huppert), kiericks@pitt.edu (K.I. Erickson), mew83@pitt.edu (M.E. Wollam), psparto@pitt.edu (P.J. Sparto), esejdic@ieee.org (E. Sejdić), jessievs@pitt.edu (J.M. VanSwearingen).

http://dx.doi.org/10.1016/j.bbr.2016.11.021
0166-4328/

lying the motor performance [3–6]. During motor skill learning, functional connectivity among a broad array of regions including frontal, parietal, and limbic association areas involved in performance transition to a pattern of more efficient circuitry between premotor and dorsolateral prefrontal cortical regions and the dorsal striatum [7,8]. The performance of well-learned motor skills, such as walking is thought to be efficient and nearly automatic. Age-related brain changes can disrupt this neural circuitry. In response to this age-related disruption, the brain pattern of activation for performance of the once well-learned motor skill may regress to a pre-automatization phase [9]; a phase in which the brain activation associated with performance is inefficient (i.e. a broad spatial pattern of brain regions activated during performance) [10]. This pattern of activation in brain circuitry for performance may have a secondary impact on the efficiency of brain networks for performance in other motor and cognitive behaviors [5,11].

To better understand age-related changes in the neural circuitry of well-learned motor skill performance and potential intervention strategies to facilitate adaptive or restorative change in performance, it is important to have a greater understanding of motor skill learning-induced changes. Especially changes in neural circuitry during the process of acquiring or adapting the movement pattern [9]. Most investigations of changes in brain activation patterns with motor skill learning have involved performance of motor actions that can be done lying on the back, and require a small range of motion, usually of a single limb to avoid motion artifacts to the signal, such as a finger-tapping movement task [12–16].

Brain activation patterns for phases of motor skill learning in finger-tapping tasks have previously been described [4,17,18]. Much of the previous work has examined changes in the brain activation pattern but not network functional connectivity changes [4,18,19]. In addition, the functional neural circuitry changes have been defined before and after a period of practice of an *explicitly* learned finger-tapping motor sequence [3–5,17–19]. The explicitly learned task is more representative of conscious learning of the defined sequence of the movements of the performance. Explicitly learned movement task are, however, less reflective of the movement-related procedural learning characteristic of motor skill learning, or ‘learning while doing’ the finger-tapping task. Newer methods of functional connectivity (FC) analysis of fMRI signal processing [20], like psychophysiological interaction (PPI) [21–24], have made it possible to define the connectivity (task-related functional communications) among brain regions or circuits underlying motor performance.

In this study, we used FC methods, specifically generalized PPI (gPPI) [23], to define motor skill learning induced changes in the neural circuitry associated with repeated action of a finger-tapping sequenced task (e.g. practice) [20,24,25]. Generalized PPI investigates context-dependent differences in functional connectivity from a specified seed region of the brain. Based on our understanding of motor skill learning [1,2], and previous findings of brain activation patterns related to motor skill learning [3–7,26] we expected that spatial activation and functional connectivity would shift from an initial, inefficient pattern of high activity across a broad cortical network of prefrontal and premotor association areas, posterior parietal association areas, cingulate motor, and anterior cingulate areas to a more efficient pattern of neural activations. We expect, after repeated action of the simple finger-tapping task, the motor skill learning would induce the functional connectivity to be more restricted to a cortical-striatal network of premotor and dorsolateral prefrontal cortex with the putamen (motor component of the striatum). Changes in functional neural circuitry during motor skill learning may help explain changes in motor performance efficiency and in the identification of effective rehabilitation approaches to facilitate adaptive or restorative changes in motor skills.

2. Methods

2.1. Study design and subjects

Functional MR imaging was performed on 13 (self-reported) right-handed healthy adult volunteers (mean age 23.8 ± 3.1 years); 6 males and 7 females. Participants had no history of a neurological disorder, were not currently taking medications known to alter brain function, and were eligible to undergo MR imaging. The University of Pittsburgh Institutional Review Board approved the study, and all subjects provided written informed consent for participation.

2.2. MRI data collection

All scanning was conducted using a 3T Siemens Trio TIM scanner located at the Magnetic Resonance Research Center at the University of Pittsburgh using a 12-channel coil. A high-resolution T1-weighted 3D sequence was collected (TR = 19 ms/TE = 4.92/FA = 25) with a field of view 176 × 256 × 192 and voxel dimensions of $1.17 \times 1.17 \times 1.0\,\text{mm}^3$. T2*-weighted BOLD acquisition using gradient-echo echo-planar imaging (EPI) was collected during functional tasks (TR = 2000 ms/TE = 30 ms/FA = 90) with a field of view 64 × 64 × 34 and voxel dimensions of $3.12 \times 3.12 \times 3.00\,\text{mm}^3$. The head was immobilized using cushions to minimize motion artifacts.

2.3. Motor learning task

Subjects performed motor skill learning and a comparison control motor task. The sequencing of movements, which involves individual movements sequenced in a spatial pattern or in time, is a common component of motor skill learning for performance of a specific task. The motor skill learning studied involved performance of a finger-tapping motor sequence-learning task. Subjects used their dominant hand (right in all subjects). Specifics of the finger-tapping task are outlined in Fig. 1. The finger-tapping motor skill-learning task involved blocks of repeated learning sequences alternated with blocks of control sequences, with an equivalent number of learning and control sequences performed. Each functional scan (11 min) had six 32 s learning blocks and six 32 s control blocks with 20 s rest periods in between. In each task block, subjects were presented with five visual cues for the finger-tapping movement sequence. In learning blocks, the motor learning sequence was a pre-determined, 5-movement sequence (e.g. 4-2-3-1-2 with the index finger designated 1, and the little finger as 4). The sequence was repeated a total of five times within each 32 s block. The same pre-determined learning sequence was repeated across all six learning blocks within a functional scan. To control for improvement in the finger motor performance alone, in the control blocks participants were presented with random sequences of 5 finger movements; each tap was 1 s. During the interweaved 20 s rest blocks, subjects were instructed to stare at the white cross hair and stay awake.

Participants were positioned supine in the scanner and viewed the visual cues provided through a mirror fixed above the head coil. Worn on the right hand, an instrumented glove was used to record participant responses to the visual cues for the finger-tapping sequences viewed. A red box in one of four white boxes placed, side to side, visually-cued a finger tap of the sequence. Each white box corresponded to one finger of the right hand, starting with the second digit (index finger) to the fifth digit (little finger). When a red box appeared in the box corresponding to one of the