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Rapid changes in brain structure predict improvements induced by perceptual learning

Thomas Ditye [a,*], Ryota Kanai [a], Bahador Bahrami [a], Neil G. Muggleton [a], Geraint Rees [a,b], Vincent Walsh [a]

[a] Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London WC1N 3AR, United Kingdom
[b] Wellcome Trust Center for Neuroimaging, University College London, 12 Queen Square, London WC1N 3BG, United Kingdom

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ABSTRACT

Practice-dependent changes in brain structure can occur in task relevant brain regions as a result of extensive training in complex motor tasks and long-term cognitive training but little is known about the impact of visual perceptual learning on brain structure. Here we studied the effect of five days of visual perceptual learning in a motion–color conjunction search task using anatomical MRI. We found rapid changes in gray matter volume in the right posterior superior temporal sulcus, an area sensitive to coherently moving stimuli, that predicted the degree to which an individual's performance improved with training. Furthermore, behavioral improvements were also predicted by volumetric changes in an extended white matter region underlying the visual cortex. These findings point towards quick and efficient plastic neural mechanisms that enable the visual brain to deal effectively with changing environmental demands.

Introduction

The capacity to adapt to environmental changes is an intrinsic property of the human brain (Pascual-Leone et al., 2005). In visual perceptual learning (VPL), extensive training results in specific and long-lasting performance improvements in trained visual tasks (Karni and Sagi, 1993; Sasaki et al., 2010; Watanabe et al., 2001). Previous studies in humans and monkeys identified functional correlates of neural plasticity in VPL whereby improvements in VPL were associated with changes in brain activation both in early visual cortex and higher regions associated with attention and decision-making (e.g. Chowdhury and DeAngelis, 2008; Furmanski et al., 2004; Law and Gold, 2008; Mukai et al., 2007; Schoups et al., 2001; Schwartz et al., 2002; Yotsumoto et al., 2009).

These findings suggest that VPL involves long-lasting changes in neural and synaptic organizations, which may induce macroscopic structural changes of the brain. We therefore hypothesized that VPL would be reflected in such structural changes.

Macroscopic changes in brain structure have been demonstrated in training paradigms other than VPL, including motor tasks such as juggling, and following complex cognitive training (Bueti et al., 2012; Draganski et al., 2004, 2006; Driemeyer et al., 2008; Gryga et al., 2012; Sagi et al., 2012; Scholz et al., 2009; Takeuchi et al., 2010; Woollett and Maguire, 2011). These findings suggest that dynamic neural mechanisms generate new physical resources in a task-specific manner during the acquisition of a new skill.

In this study, we tested the hypothesis that performance improvement in VPL is reflected in gray matter (GM) and white matter (WM) volumetric changes in brain regions relevant to VPL. We measured brain structure with MRI in twenty-one healthy adults before and after they underwent a five day training program on a motion–color conjunction task (Fig. 1). We compared regional volumetric changes of GM and WM using longitudinal voxel-based morphometry (VBM; May and Gaser, 2006; Ashburner and Friston, 2000). The training was carried out for five consecutive days for 1 h per day and performance and brain data were measured on the pre- and post-training days (test session 1, T1, and test session 2, T2). Similar search tasks have previously been used to induce behavioral improvements following training in humans and monkeys (Buracas and Albright, 1999, 2009). Task difficulty was adjusted by adaptively varying motion coherence during training (Ball and Sekuler, 1982; Watanabe et al., 2002). We predicted that practice-dependent changes in GM and WM volumes would be observed in areas sensitive to motion direction and motion coherence. To examine task specificity of structural changes, we included a control task on which participants were not trained and that required participants to search for a conjunction of contrast and orientation. Furthermore, a control experiment ($N = 20$) was conducted to control for effects other than those of the training, e.g. artifacts related to sequential MRI scanning. The design of the control experiment was identical to the main study, except there was no training on any task between T1 and T2.

* Corresponding author at: Institute of Cognitive Neuroscience, University College London, 17 Queen Square, London WC1N 3AR, United Kingdom.
E-mail address: thomas.ditye@gmail.com (T. Ditye).

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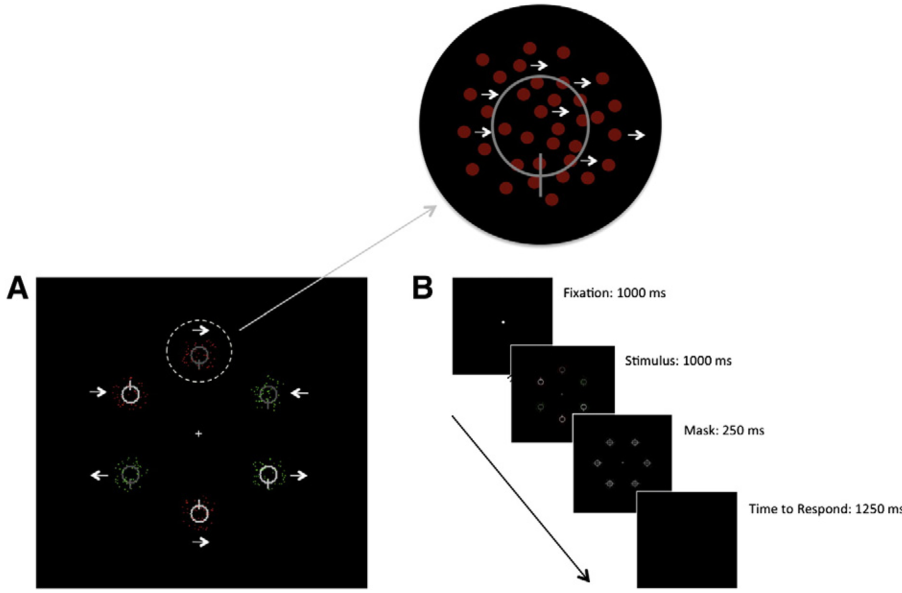

Fig. 1. Stimulus and trial sequence. (A) Search array. Arrows indicating the direction of dot movements have been included for illustration purposes and were not present in the actual task. In this particular trial the bottom right item is the target for both tasks (training task: green dots moving to the right; untrained task: high contrast symbols facing downwards). (B) The trial sequence consisted of a fixation screen, followed by the stimulus and a mask and time to respond. Total trial duration was 3500 ms and there was an inter-trial interval of 500 ms (see text for details).

Materials & methods

Participants

Twenty-one healthy university students (13 female; mean age: 23.8 years, ranging from 20 to 30 years) took part in the main experiment. A separately recruited control group consisted of 20 students (10 female; mean age: 21.6 years; range: 19 to 29 years). All participants were right-handed, had normal or corrected to normal vision, and gave written informed consent for the entire study. The study was approved by the UCL ethics committee.

Stimuli

The search array consisted of six circular items arranged in a circle around a fixation cross on a black background (100% contrast; Fig. 1). The fixation cross (18 × 18 arc min) was presented in white in the center of the screen. The items (1.5° diameter) were placed at a distance of 3.3° to the center of the array in the following positions: 30°, 90°, 150°, 210°, 270°, and 330°. Each item consisted of 60 random dots (2.4 × 2.4 arc min) that were superimposed on a symbol: a circle (46 arc min diameter) with a line (23 arc min) attached to it (4.6 arc min line width). All dots of an item were colored either red (50%) or green (50%) and were isoluminant (17 cd/m^2). The dots in red items were moving to the right at a speed of 1.3° per second. Dots in green items were moving to the left at the same speed. Independent of color the symbols for 50% of the items were high in contrast (white, 85 cd/m^2) and the other 50% were low in contrast (dark-gray, 11.3 cd/m^2). High contrast symbols were facing upwards with the attached line in the 90° positions whereas low contrast symbols were facing downwards with the line at 270°.

On target present trials the direction of movement of one of the green items was reversed (training task) and the orientation of one of the high contrast items was reversed (untrained task). In other words, the target item in the training task was a green item moving to the right, and the target item in the untrained task was a high contrast item facing down.

The stimuli were followed by a mask: stationary dots were used for masking movement and the symbol lines were replaced by a cross of the size of the entire item for masking symbol orientation. Both dots and symbols were presented at medium contrast in order to mask color and contrast, respectively (18.4 cd/m^2).

Tasks

Participants were tested on two different tasks using physically identical search arrays. On each trial of either task participants were instructed to fixate on the fixation cross, covertly search the array without making any eye movements, and report the absence or presence of a predefined target item. On the training task the target was defined by a specific conjunction of the color and the direction of movement of the dots of each item (i.e. an item with green dots moving to the right; Fig. 1). On the untrained task a conceptually similar conjunction had to be made between the contrast and the orientation of the symbols of each item with the target being defined as an item consisting of a high contrast symbol that was facing downwards. The target was present in 50% of the trials, randomized across trials. Target position was counterbalanced across the 6 possible locations.

Each trial started with the presentation of a fixation cross for 1000 ms followed by the stimulus presentation for 1000 ms and the presentation of the mask for 250 ms. The time window for making responses was set to the period between stimulus onset and 1250 ms after mask offset. Participants were instructed to base their responses on accuracy rather than speed. Trial duration was 3500 ms and there was an inter-trial interval (ITI) of 500 ms. See Fig. 1 for an illustration. Stimuli were presented at a resolution of 1024 × 768 pixels and a screen refresh rate of 60 Hz. The experiment was controlled by the graphics toolbox Cogent 2000 (http://www.vislab.ucl.ac.uk/cogent.php) running in MATLAB R2008b on a PC with a 2.13 GHz processor running Windows XP.

Study design

The study consisted of eight experimental sessions taking place on separate days: Practice (outside scanner), test session 1 (T1; scanning),