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# Gray matter volume is associated with rate of subsequent skill learning after a long term training intervention

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ABSTRACT

The ability to predict learning performance from brain imaging data has implications for selecting individuals for training or rehabilitation interventions. Here, we used structural MRI to test whether baseline variations in gray matter (GM) volume correlated with subsequent performance after a long-term training of a complex whole-body task. 44 naïve participants were scanned before undertaking daily juggling practice for 6 weeks, following either a high intensity or a low intensity training regime. To assess performance across the training period participants' practice sessions were filmed. Greater GM volume in medial occipito-parietal areas at baseline correlated with steeper learning slopes. We also tested whether practice time or performance outcomes modulated the degree of structural brain change detected between the baseline scan and additional scans performed immediately after training and following a further 4 weeks without training. Participants with better performance had higher increases in GM volume during the period following training (i.e., between scans 2 and 3) in dorsal parietal cortex and M1. When contrasting brain changes between the practice intensity groups, we did not find any straightforward effects of practice time though practice modulated the relationship between performance and GM volume change in dorsolateral prefrontal cortex. These results suggest that practice time and performance modulate the degree of structural brain change evoked by long-term training regimes.



## Introduction

As adults, we are often faced with the challenge of learning novel visuo-motor skills, such as using the touchscreen on a new smartphone. Intuitively, we might expect that how well we acquire these skills depend on multiple factors including how much practice we put in, and our individual aptitude for such learning. Studies in both animals and humans show that motor skill learning is associated with structural brain plasticity in the adult and during development (Draganski et al., 2004, 2006; Hyde et al., 2009; Kleim et al., 1996; Scholz et al., 2009; Taubert et al., 2010). However, it remains unclear whether brain structural properties at baseline are associated with subsequent complex skill acquisition, and also whether the degree of brain structural change with long-term training depends on factors such as the amount of practice time and the performance outcome.

The ability to make predictions about an individual's future long term motor skill learning based on baseline brain structural characteristics could be applied in the context of talent identification (e.g. in elite athletes) and also has relevance in clinical scenarios, such as predicting response to the rehabilitation of movement abilities after brain damage. Inter-individual variability in human brain structure has been shown to correlate with variation in task performance in both expert and non-expert populations in cross-sectional studies (Gaser and Schlaug, 2003a,b; Johansen-Berg et al., 2007; Kuhn et al., 2012). However, studies that have tested whether baseline brain structural measures relate to subsequent behavioral response, have been limited to simple hand motor tasks and shorter time periods (between one and five training sessions) (Gryga et al., 2012; Tomassini et al., 2011). Here we test if baseline brain structure is associated with subsequent performance outcome with long-term training (several weeks) of a complex whole-body motor skill.

Evidence for a relationship between brain structural change and amount of practice or performance outcome is also limited. Amount of practice refers to the duration and or number of training sessions. Some studies have also examined practice density or intensity by defining a fixed number of training hours but not training sessions.

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Performance outcomes can be assessed by measuring performance after long-term training, average performance throughout training, or the rate of change in performance throughout the training period. While some previous studies have used fixed training schedules, others have allowed subjects to train at their own pace, or until they reach a particular performance criterion. In the context of juggling training, a popular experimental paradigm in this area, most studies have reported that brain structural changes are not correlated with how quickly subjects learn to juggle or how well they perform after training (Boyke et al., 2008; Draganski et al., 2004; Driemeyer et al., 2008; Scholz et al., 2009). One possibility is that structural changes reflect the amount of time spent training rather than training outcome; previous studies have predominantly used fixed amounts of training or fixed outcome criteria, making it difficult to tease apart effects of training time and performance outcomes. In the context of golf training, there is a recent evidence that higher training intensity, reflected in the number of days necessary to complete 40 h of training, results in greater gray matter increases, although no correlations with performance outcomes were reported (Bezzola et al., 2011).

The absence of a correlation between training outcome and structural changes in human neuroimaging studies is puzzling as functional plasticity and map reorganization as measured in animal studies seem to be associated with learning outcome rather than with amount of practice (Kleim et al., 1998; Plautz et al., 2000). It is not clear whether this apparent lack of a relationship between training outcome and structural brain change is real or reflects methodological factors. For example, the lack of an effect might be due to the assessment of the training outcome, i.e., the behavioral measures used might not be sensitive or might not represent the important aspects of learning that drive the structural changes.

In this study, we tested whether individuals' ability to learn a complex whole-body visuo-motor skill (juggling) could be explained by brain structural measures obtained before learning. We also tested if baseline brain structure was associated with brain structure change after long-term skill training. Furthermore, we varied the amount of training time in order to directly test whether an amount of practice or performance outcome modulates structural brain changes. To assess performance across the training period participants' practice sessions were filmed.

## Methods

### *Participants*

All subjects gave their informed consent to participate in the study in accordance with local ethics committee approval (REC B 07/Q1605/65).

44 participants with no prior experience of juggling were recruited and randomly assigned to one of the 2 groups: a high intensity training group that learned to juggle for 30 min per day, 5 days a week, for 6 weeks; and a lower intensity group that practiced for 15 min per day, 5 days a week, for 6 weeks. From the initial 44 recruited participants, 40 completed the study (22 in the higher intensity group and 18 on the lower intensity group) (mean age 23.8, standard deviation 3.5; 22 female). Participants were scanned at baseline, after 6 weeks of training and 4 weeks after the end of training. During the final 4-week interval participants were asked not to juggle.

All participants were right handed and matched for age and gender (low intensity group: mean age 23.8, standard deviation 3.3, 10 females) (high intensity group: mean age 23.9, standard deviation 3.6, 12 females).

### *Behavioral assessment*

Participants in the training groups had a group juggling lesson on the first training day, where the fundamentals of the 3-ball cascade were taught. Subsequently, participants were instructed to practice continuously for 15 (low intensity group) or 30 (high intensity group) minutes per day for 29 days. There was no fixed structure or number of juggling attempts per training session. Volunteers who mastered the '3-ball cascade' before the end of the training period were encouraged to practice more advanced juggling patterns. After the training period, participants were not told to juggle for 4 weeks. Participants filmed every home training session using a webcam and were required to upload their training videos to a secure website daily. After the final scan (following the four-week period without juggling) participants were asked to film themselves again for 5 min while juggling. Videoing of training sessions ensured compliance and provided us with objective information for later assessment. For the daily performance scores the experimenter rated each of the 29 training videos per participant on a scale of 0–10 (Scholz et al., 2009) (0: 2 balls; 1: 1 cycle of '3-ball cascade'; 2: 2 cycles; 3: 3 cycles; 4: 5–10 s of sustained 3-ball cascade; 5: 10–20 s; 6: 20–30 s; 7:>30 s; 8:>60 s; 9:>60 s and at least one other pattern for <60 s; 10:>60 s and at least one other pattern for >60 s). A learning curve was plotted for each participant based on the score for each day. A logarithm curve was then fitted to each participant's learning curve and the slope of the curve (learning rate) was calculated (see Inline Supplementary Figure S1b).

Inline Supplementary Fig. S1 can be found online at http://dx.doi.org/10.1016/j.neuroimage.2014.03.056.

For each subject we calculated the following measures: daily performance score, best performance score over all training days, performance on the last day of practice, average performance over 29 days, and learning rate. Furthermore long-term retention was calculated as the difference between the final behavioral test (4 weeks after participants stopped juggling) and the average performance of the last 3 days of juggling training. These scores were used to explore behavioral differences between groups.

We tested for performance differences over time and between groups with a Repeated Measures ANOVA (RM — ANOVA) of the daily scores including the factors of day (29 days of training) and group (high vs low intensity). When Mauchly's test of sphericity was statistically significant, Greenhouse–Geisser F-test was used and the respective degrees of freedom are reported.

Additionally, T-tests were used to investigate between-group differences in: performance on the last day of practice, best performance, learning rate, the last performance measure acquired after the last scan (4 weeks after participants were asked to stop juggling), and long-term retention. Of the several performance parameters calculated, average performance over 29 days per participant (from now on referred to as average performance or just performance) (mean = 4.83, SD = 1.78) was used to test for the effects of performance outcome on structural brain changes as this measure captured performance over the whole training period and showed a wide variation across subjects (See Inline Supplementary Figure S1c).

### *MRI acquisition*

Data was acquired on a 3 T Trio scanner (Siemens, Erlangen, Germany) with a 12-channel head coil. We acquired one axial T1-weighted anatomical image using a MPRAGE sequence (TR = 20.4 ms; TE = 4.7 ms; flip angle = 8°; voxel size = $1 \times 1 \times 1$ mm$^3$).

Two sets of whole brain diffusion weighted volumes (60 directions; b-value = 1000 s/mm$^2$; 65 slices; voxel size $2 \times 2 \times 2$ mm$^3$; repetition time (TR) = 9.3 s; echo time (TE) = 94 ms) plus six volumes without diffusion weighting (b-value = 0 s/mm$^2$) were also acquired. Due to technical problems DTI was only acquired in 35 participants (19 from the high intensity group and 16 from the low intensity group).

### *MRI analysis*

We carried out analyses with the FSL package, version 4.1 (http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/). We analyzed T1-weighted anatomical images using FSL–VBM (Douaud et al., 2007, http://fsl.fmrib.ox.ac.uk/fsl/