Manuscript Number: NIMG-11-1446R2

Title: Imitation and observational learning of hand actions: Prefrontal involvement and connectivity

Article Type: Regular Article

Section/Category: Systems Neuroscience

Corresponding Author: Dr Stefan Reinhold Vogt, Dr.

Corresponding Author's Institution: Lancaster University

First Author: Satomi Higuchi, PhD

Order of Authors: Satomi Higuchi, PhD; Henning Holle, PhD; Neil Roberts, Prof.; Simon B Eickhoff, Prof.; Stefan Reinhold Vogt, Dr.

Abstract: The first aim of this event-related fMRI study was to identify the neural circuits involved in imitation learning. We used a rapid imitation task where participants directly imitated pictures of guitar chords. The results provide clear evidence for the involvement of dorsolateral prefrontal cortex, as well as the fronto-parietal mirror circuit (FPMC) during action imitation when the requirements for working memory are low. Connectivity analyses further indicated a robust connectivity between left prefrontal cortex and the components of the FPMC bilaterally. We conclude that a mechanism of automatic perception-action matching alone is insufficient to account for imitation learning. Rather, the motor representation of an observed, complex action, as provided by the FPMC, only serves as the 'raw material' for higher-order supervisory and monitoring operations associated with the prefrontal cortex. The second aim of this study was to assess whether these neural circuits are also recruited during observational practice (OP, without motor execution), or only during physical practice (PP). Whereas prefrontal cortex was not consistently activated in action observation across all participants, prefrontal activation intensities did predict the behavioural practice effects, thus indicating a crucial role of prefrontal cortex also in OP. In addition, whilst OP and PP produced similar activation intensities in the FPMC when assessed during action observation, during imitative execution, the practice-related activation decreases were significantly more pronounced for PP than for OP. This dissociation indicates a lack of execution-related resources in observationally practised actions. More specifically, we found neural efficiency effects in the right motor cingulate-basal ganglia circuit and the FPMC that were only observed after PP but not after OP. Finally, we confirmed that practice generally induced activation decreases in the FPMC during both action observation and imitation sessions and outline a framework explaining the discrepant findings in the literature.

1. Cover Letter

LANCASTER
UNIVERSITY
Department of Psychology

Scott Grafton
Section Editor Systems Neuroscience for NeuroImage

Lancaster, 9th September 2011

Dear Prof. Grafton,

Warm thanks again for the quick turnaround and your invitation for a minor revision of our ms. We were delighted that the reviewers found the revision thorough, exhaustive, and satisfactory.

Pleased find attached the electronic submission of our re-revised manuscript.

We have made the following changes in the ms, as suggested by Reviewer 1:

1. p. 27: We have replaced the term ‘existence hypothesis’ (which was literally translated from German) as follows: “The relatively modest aim of the present analyses was to prove the existence of a robust functional coupling between…”

2. ‘blobs’ is now replaced by ‘areas’ throughout the ms, as suggested by the reviewer. To explain: ‘Blobs’ was only used to denote the red or yellow areas in Figs. 4B and 4C on p. 19, 20, Footnote 6, and in the legend of Figure 4C. It was always used in the context of more specific terminology establishing what the statistical maps are indicating.

In addition, we have removed the bold passages that were used in the first revision to indicate the changes, we fixed a few typos and a missing title in the ref.s (Kilner, 2011), we slightly rephrased the legend of supplementary Fig. S1 (no changes to the content or the renderings), and we slightly extended the Acknowledgements.

The manuscript has not been submitted or published previously. All co-authors have approved the final revised version of the manuscript. All experiments have been carried out in accordance with local and national guidelines.

Thank you very much again for your time and consideration,

Stefan Vogt

on behalf of Satomi Higuchi, Henning Holle, Neil Roberts, and Simon Eickhoff

Dr Linden Ball
Head of Department

Lancaster University
Lancaster LA1 4YF
United Kingdom

Tel : +44(0) 1524 65201
Fax : +44(0) 1524 593744

Research Highlights

Imitation and observational learning of hand actions: Prefrontal involvement and connectivity

- Prefrontal cortex was involved in a rapid imitation task with low memory load
- Connectivity confirmed between prefrontal cortex and mirror neuron system
- Prefrontal cortex activations were correlated with observational practice effects
- Observational practice lacked neural efficiency effects in putamen and cingulate
- We confirmed practice-induced activation decreases in imitation and observation

Higuchi et al.: Imitation and observational learning of hand actions

Responses to Reviewers 9.9.2011

We were delighted that the reviewers found the revision thorough, exhaustive, and satisfactory.

We have made the following changes in the ms, as suggested by Reviewer 1:

1. p. 27: We have replaced the term 'existence hypothesis' (which was literally translated from German) as follows: "The relatively modest aim of the present analyses was to prove the existence of a robust functional coupling between…"

2. 'blobs' is now replaced by 'areas' throughout the ms, as suggested by the reviewer. To explain: 'Blobs' was only used to denote the red or yellow areas in Figs. 4B and 4C on p. 19, 20, Footnote 6, and in the legend of Figure 4C. It was always used in the context of more specific terminology establishing what the statistical maps are indicating.

In addition, we have removed the bold passages that were used in the first revision to indicate the changes, we fixed a few typos and a missing title in the ref.s (Kilner, 2011), we slightly rephrased the legend of supplementary Fig. S1 (no changes to the content or the renderings), and we slightly extended the Acknowledgements.

Minor REVISION 9th September 2011

Imitation and observational learning of hand actions: Prefrontal involvement and connectivity

S. Higuchi [a,b,c], H. Holle [d], N. Roberts [e], S. B. Eickhoff [f,g], S. Vogt [a,b,*]

[a] Department of Psychology, Lancaster University
[b] Magnetic Resonance and Image Analysis Research Centre, University of Liverpool, UK
[c] Center for Experimental Research in Social Sciences, Hokkaido University, Japan
[d] School of Psychology, University of Sussex, UK
[e] Queens Medical Research Institute, University of Edinburgh, UK
[f] Department of Psychiatry, RWTH Aachen University, Germany
[g] Institute for Medicine, Research Center Jülich, Germany

---

* Corresponding author. E-mail: s.vogt@lancaster.ac.uk

Address:
Dr. S. Vogt, Department of Psychology, Lancaster University, Lancaster LA1 4YF, UK.
Tel. 01524-594625, Fax. 01524-593744, s.vogt@lancaster.ac.uk

Keywords: Dorsolateral prefrontal cortex; Mirror neuron system; Imitation learning; Action observation; Neural efficiency; Connectivity analysis

Running title: Imitation and Observational Learning

Abstract

The first aim of this event-related fMRI study was to identify the neural circuits involved in imitation learning. We used a rapid imitation task where participants directly imitated pictures of guitar chords. The results provide clear evidence for the involvement of dorsolateral prefrontal cortex, as well as the fronto-parietal mirror circuit (FPMC) during action imitation when the requirements for working memory are low. Connectivity analyses further indicated a robust connectivity between left prefrontal cortex and the components of the FPMC bilaterally. We conclude that a mechanism of automatic perception-action matching alone is insufficient to account for imitation learning. Rather, the motor representation of an observed, complex action, as provided by the FPMC, only serves as the ‘raw material’ for higher-order supervisory and monitoring operations associated with the prefrontal cortex. The second aim of this study was to assess whether these neural circuits are also recruited during observational practice (OP, without motor execution), or only during physical practice (PP). Whereas prefrontal cortex was not consistently activated in action observation across all participants, prefrontal activation intensities did predict the behavioural practice effects, thus indicating a crucial role of prefrontal cortex also in OP. In addition, whilst OP and PP produced similar activation intensities in the FPMC when assessed during action observation, during imitative execution, the practice-related activation decreases were significantly more pronounced for PP than for OP. This dissociation indicates a lack of execution-related resources in observationally practised actions. More specifically, we found neural efficiency effects in the right motor cingulate–basal ganglia circuit and the FPMC that were only observed after PP but not after OP. Finally, we confirmed that practice generally induced activation decreases in the FPMC during both action observation and imitation sessions and outline a framework explaining the discrepant findings in the literature.

Introduction

Imitation learning refers to the learning of motor actions guided by observing a skilled model. Typically, imitation learning consists of alternating phases of observation and of motor execution, whereas the term observational practice (Vogt, 1995) refers to learning by observing in the absence of motor execution (e.g., Mattar and Gribble, 2005). Over the last 15 years, a large number of neuroimaging studies have assessed the brain networks underlying the imitation of relatively simple, familiar actions, whereas to date, only a handful of studies have explored the more complex imitation learning.

With respect to familiar actions, the meta-analysis by Caspers et al. (2010) confirmed that both action observation and imitative execution involve a bilateral network within ventral premotor and inferior parietal cortex. This fronto-parietal ‘mirror’ circuit (FPMC, Rizzolatti and Sinigaglia, 2010) has become the subject of intense debate, particularly regarding its role in action recognition and conceptual processing (Mahon and Caramazza, 2008; Hickok and Hauser, 2010; Kalenine et al., 2010; Gallese et al., 2011; Kilner, 2011). In contrast, the view that the engagement of the FPMC during action observation is functionally related to the engagement of the same regions during subsequent imitative execution (e.g., Vogt, 2002; Vogt et al., 2007) has not been challenged to date. Indeed, experiments using transcranial magnetic stimulation (TMS) over regions of the FPMC indicate their crucial role in imitation performance (e.g., Heiser et al., 2003).

With respect to actions that are not in the observer’s behavioural repertoire, recent neuroimaging studies from our group revealed three key findings: First, the FPMC was activated more strongly during observation of non-practised actions compared to practised actions (Vogt et al., 2007; see Discussion for other, potentially conflicting findings). Second, the activations in the FPMC were stronger during action observation in order to imitate than during passive action observation (Buccino et al., 2004; see also Frey and Gerry, 2006). Third, in addition to the FPMC, the dorsolateral prefrontal cortex (DLPFC) was also activated during action observation and motor preparation (Buccino et al., 2004; Vogt et al., 2007). As in the FPMC, activations in DLPFC were also more pronounced for novel than for practised actions. The involvement of DLPFC has inspired a hierarchical model of imitation learning (ibid., see also Iacoboni, 2009; Ferrari et al., 2009), according to which left DLPFC engages in supervisory operations of selection and combination of the elementary action representations in the FPMC, and right DLPFC engages in monitoring operations during imitative execution.

The first aim of the present study was to further elucidate the role of the DLPFC in imitation learning. In their dual-route model of imitation, Ferrari et al. (2009) proposed that the 'indirect mirror pathway' (involving FPMC and DLPFC) is crucial (1) in tasks with delayed behavioural responses that require the maintenance of motor information beyond the available visual input, as well as (2) for behavioural parsing and recombination of motor elements, and (3) inhibitory control. These suggestions were partly based on our previous studies, in which observation and execution were separated by a relatively long preparatory pause (4 to 10 s). It is thus possible that the activations in DLPFC reflected predominantly the requirement to maintain motor representations in the absence of visual input, that is, explanation (1) above. Also Johnson-Frey et al. (2005) interpreted their activation in left DLPFC during the (non-imitative) planning of tool-use actions in this way. In addition, specific evidence for the role of DLPFC for supervisory and monitoring functions, rather than working memory per se, is only available from non-imitative tasks (e.g., Rowe and Passingham, 2001; Lau et al., 2004; Cunnington et al., 2006; Rowe et al., 2010). Therefore, we aimed to assess if prefrontal activations are present in the initial stage of imitation learning specifically when the task demands for maintenance of motor information are minimised. To this end, we used a rapid imitation paradigm in the present study: in each trial, participants were shown a picture of the to-be-imitated hand posture (guitar chord), which they executed immediately. In addition to this IMI condition, we included separate OBS sessions with the same trial structure, except that participants did not execute the chord during observation. Furthermore, the scanning parameters of the present study were optimised to allow for functional connectivity analyses between the DLPFC and the two key regions of the FPMC. This connectivity is a crucial, but yet untested assumption of the hierarchical model of imitation learning (Buccino et al., 2004).

The second aim of the present study was to contrast the neural correlates of two forms of practice: imitation learning, where action observation is immediately followed by imitative execution (‘Physical Practice’, PP), and learning by observing without motor execution (‘Observational Practice’, OP; for reviews of behavioural studies, see Vogt and Thomaschke, 2007; Maslovat et al., 2010). Regarding the possible neural network underlying OP of complex, novel actions, two accounts are feasible that differ regarding the involvement of the DLPFC. The first account is a straightforward extension of Buccino et al.’s (2004) hierarchical model of imitation learning to observational practice. This assumes the involvement of the indirect pathway (FPMC under the control of DLPFC) also for periods of OP. However, a number of findings tentatively contradict this account. In our previous studies, DLPFC was only found to be activated when action observation was followed by imitative execution within the same trial (Buccino et al., 2004: IMI condition; Vogt et al., 2007). In contrast, no DLPFC activations were found during trials (Buccino et al., 2004: OBS condition) or sessions (Frey and Gerry, 2006) where action observation was not followed by execution, even when participants watched novel, complex actions with the intention to imitate these after scanning (Cross et al., 2009; Cunnington et al., 2006; Frey and Gerry, 2006). The only available evidence in support of the first account comes from the study by Torriero et al. (2007), who demonstrated that repetitive TMS over the right DLPFC prior to observational practice of a spatial sequencing task selectively disrupted subsequent reproduction of the practised sequence.

The second account assumes that Ferrari et al.’s (2009) direct pathway, largely consisting of the FPMC, is sufficient to explain the effects of OP of simple, as well as of more complex, novel actions. For simple actions, Stefan et al. (2005, 2008; see also Celnik et al., 2006) demonstrated longer-term effects of observational practice on TMS-evoked thumb movements, which are most likely underpinned by downstream activations from the FPMC to primary motor cortex (M1) during action observation (Kilner and Frith, 2009; Tkach et al., 2007). A similar conclusion was reached by Brown et al. (2009), who demonstrated that repetitive TMS over M1 applied after observational practice reduced the practice effects in learning a novel force environment (see also Malfait et al., 2010). In the present study, the OBS scanning sessions were used to assess the functional activations during OP. We further ran correlation analyses between the functional data and the behavioural learning outcomes for a full assessment of the involvement of the DLPFC in action observation.

Our second motivation for studying physical and observational practice conditions (Aim 2.2) was to identify specific patterns of neural activation, in OBS and IMI sessions, that might result from each form of practice. To our knowledge, only two fMRI studies have pursued this approach to date: Nyberg et al. (2006) contrasted the effects of PP and motor imagery of finger-tapping sequences. Relative to non-practised sequences, participants who had engaged in PP exhibited stronger activations in the supplementary motor area (SMA) and the cerebellum, whereas participants who had engaged in motor imagery exhibited stronger activations in visual association cortex (BA 18). The authors interpreted their findings to indicate training-specific neuroplastic changes. In the second study (Cross et al., 2009), participants passively observed one set of dance sequences and engaged in PP with another set. Overall, the results indicated a strong overlap between the danced and watched conditions in the regions of the FPMC, and the small differences obtained can be attributed to the absence of an instruction to learn the observed sequences. In contrast, participants in the present study knew that they would be tested for both the physically and the observationally practised actions. They were further encouraged to engage in motor imagery simultaneously and/or following action observation in order to maximise the possible beneficial effects of learning by observing. In addition, our study is the first to examine functional activations not only during observation of the differently practised actions (OBS sessions), but also during imitative execution (IMI sessions).

The third aim of the present study was to investigate practice effects in the guitar chord paradigm over a slightly longer period than previously studied. Whereas a number of earlier studies on expertise effects on action observation found stronger activations for motor experts or for practised actions (see Discussion), Vogt et al. (2007) found reduced activations for observation of practised relative to novel actions. To assess the reliability and stability of this finding, participants in the present study were scanned after one day of practice (on Day 2, as in Vogt et al., 2007) and they were scanned again (on Day 4) after a further day of practice. The scanning data from Day 4 also served as the main database for the comparisons between the OP- and PP-actions (Aim 2.2).

To summarise, in the present study participants practised one set of guitar chords via observational practice (OP) and another set via imitative execution (PP) in a within-subjects design over two practice sessions (Days 1 and 3). The scanning sessions on Days 2 and 4 comprised IMI blocks where participants imitated the PP-, OP-, as well as non-practised chords, and OBS blocks where participants observed these chord types. The study was designed with the following aims in mind:

(1) to assess the involvement of prefrontal cortex in the initial stage of imitation learning, as well as its connectivity to the FPMC, using a rapid imitation paradigm that minimised requirements for maintenance of motor information;

(2.1) to explore the neural correlates of observational practice and specifically the involvement of the DLPFC during action observation;

(2.2) to identify patterns of activation, during observation and imitation sessions, that might distinguish actions that had been practised by OP vs. by PP; and

(3) to assess the reliability of activation differences between practised and non-practised actions as reported in Vogt et al. (2007), as well as to assess their stability after further practice.

Methods

Participants

Eighteen healthy, right-handed volunteers (aged 24.2 ± 3.8 years) participated in the study. All participants had normal or corrected-to-normal visual acuity, and no participant had experience with string musical instruments. One participant was excluded from the data analysis due to lack of practice effects in the behavioural data. Participants gave their written informed consent to the experimental procedure, which was approved by the local Ethics committee.

Design and experimental conditions

All participants attended two practice sessions outside the MRI scanner (Days 1 and 3), interleaved with two scanning sessions (Days 2 and 4).

<u>Practice sessions</u>. In the practice sessions, each participant learned one set of four guitar chords by physical practice (PP) and another set of four chords by observational

practice (OP). The PP-periods involved chord observation followed by imitative execution, and OP involved chord observation and motor imagery without overt hand movements. A third set of four chords was only used in the scanning sessions in order to assess the processing of non-practised (NP) chords. The assignment of the three sets of chords to PP-, OP-, and NP-conditions was counterbalanced across participants.

Scanning sessions. Each scanning session consisted of two blocks of 32 imitation trials (IMI blocks), followed by one block of 48 observation trials (OBS block; for constituent trials, see below). Whereas the IMI blocks allowed us to simultaneously assess functional activations and speed of execution of the different chord types, the OBS blocks served to assess chord observation independent of execution-related activations. Given this control function of the OBS blocks, they were run second to the IMI blocks on both days.

Regardless of the condition in which a given chord had been practised (PP, OP, or NP), in the IMI blocks participants observed and executed all chords on a scanner-compatible guitar neck, and in the OBS blocks they observed all chords without execution while their fingers remained in a rest position on the guitar neck (see Fig. 1, left image). The OBS block consisted of 16 trials of PP-chords (4 repetitions of each PP-chord), 16 trials of OP-chords, and 16 NP-chords, all presented in quasi-random order. The NP-chords included the four chords of the participant's non-practised set, plus 12 additional novel chords that were of equal complexity to the three main sets of chords. The latter chords were used in order to minimise practice effects for the NP-chords. In each IMI block, participants executed eight PP-, eight OP-, and eight NP-chords, plus eight Simple (S) chord trials, again presented in quasi-random order. In the S-trials, participants simply moved their fingers from the rest position leftwards over the distance of one string. This condition served to assess activations for finger movements of low complexity and was used as baseline in the connectivity analyses (see below).

Scanning trials. Figure 1 shows a timeline of the scanning trials. First, a picture of the model's hand in rest position was shown for one second, on which a cue was superimposed (green square in IMI blocks, red square in OBS blocks) to indicate the onset of the trial. Second, in the main event a chord picture was shown for three seconds. In the IMI blocks, participants imitated the chord as quickly and precisely as possible during this event using their left hand. In the OBS blocks, participants were asked to carefully observe the chord picture and to imagine motor execution of the observed chord without moving their fingers away from the rest position. Third, the model's hand was shown again in the rest position (duration jittered over 3 to 9 seconds), as a reminder for participants to return their fingers (physically or imagined) to the rest position and to disengage from the task while keeping their hand still.

Insert Figure 1 about here

Apparatus and stimuli

We used essentially the same apparatus as described in Vogt et al. (2007), including a short wooden guitar neck without strings (height 20 cm) and Presentation software (Neurobehavioral Systems, Inc., Version 10.1) for experimental control. Each of the three main chord sets consisted of two 2-finger chords and two 3-finger chords, using only the index, middle, and ring finger.

<u>Practice sessions</u>. The practice sessions were held in a separate room, where participants were laying on a bed and stimuli were presented on a 15 inch flat panel display that was mounted approx. 75 cm above their head. To provide visual feedback in the familiarisation period on Day 1, the model stimuli could be swapped against a live image of the participant's hand on the practice guitar neck.

<u>Scanning sessions</u>. During scanning, the visual stimuli were displayed by a LCD data projector (Panasonic PT-L785U) onto a rear-projection screen at the head end of the scanner, which participants could watch via a mirror above their head. They did not see their hand during scanning. The participants' hand movements were videotaped on miniDV cassettes together with an image of the displayed stimuli. This served the subsequent analysis of response times and the removal, from the functional analysis, of individual events where participants did not follow instructions (i.e., any overt movement during the OBS blocks or during the cue and rest events of the IMI blocks, or no execution during the execution event of the IMI blocks). Since the rest event was used as baseline, particular attention was paid to any finger movement during this event. As a result, in less than 3% of trials of the IMI sessions, events were added to an error

regressor in any condition (PP2, OP2, NP2, S2, PP4, OP4, NP4, and S4), and no events were removed from the OBS sessions. Most of the exclusions were due to hand movement during the rest events.

Instruction and procedure

At the beginning of the first practice session, participants were familiarised with the imitation task using two chords that were not part of the three main chord sets. They were then introduced to the four chords to be learned via physical practice (PP-chords) and to the four OP-chords. Only the PP-chords were overtly imitated, and for the first eight trials only, participants were given visual feedback of their hand during execution.

Following this familiarisation period, both practice sessions comprised two types of trials, off-line and on-line re-enactment. In off-line trials, participants were shown a video clip of the model's right hand moving the fingers from the rest position to the chord posture and back to the rest position. At the end of the movie, participants either overtly imitated the chord (PP-chords) using their left hand or they imagined chord execution (OP-chords). The required mapping of the participant's finger positions to the displayed chord was facilitated by the mirror-symmetric arrangement of the video clips (Koski et al., 2003), which was maintained throughout the experiment. In on-line trials, a picture of the model hand in rest was followed by a chord picture, and participants were asked to imitate the displayed hand posture as quickly as possible (PP-chords), or to imagine execution (OP-chords). Whereas the off-line trials helped participants to segment each chord more carefully without time pressure, the on-line trials prepared them for the procedure during scanning (except for the jittering of Event 3 during scanning, the trial structure of the IMI and OBS scanning blocks resembled the trial structure in the on-line practice trials for PP- and OP-chords, respectively). The first practice session was approx. 90 min. long and included three blocks of 24 off-line trials followed by 48 on-line trials. The second practice session (Day 3, approx. 60 min. long) comprised two such blocks, followed by an additional block of on-line trials. Off-line and on-line blocks were further subdivided into PP- and OP-blocks of 12 trials each. The scanning sessions on Days 2 and 4 of the experiment were approx. 90 min. long and began with a short preparatory block of on-line trials, followed by the main IMI and OBS blocks in the scanner.

Functional magnetic resonance imaging

Functional MR data were acquired with a 3T Siemens Trio whole-body scanner with an eight-channel head coil. Whole-brain echo-planar images (EPIs) were obtained from a gradient-echo sequence with the following parameters: 32 axial slices, TE = 30 ms, TR = 2000 ms, flip angle = 90°, FoV = 192 x 192 mm^2, slice thickness = 3 mm, inter-slice gap = 1.2 mm, in-plane resolution = 3 x 3 x 4.2 mm^3, bandwidth = 2604 Hz/Px, echo spacing = 0.45 ms. FoV was tilted in order to encompass the whole brain and to minimise susceptibility artefacts in the frontal cortex. For each IMI block, 143 volumes were acquired, and for each OBS block 214 volumes. T1-weighted images were obtained at the end of Day 2 with the following parameters: TE = 5.57 ms, TR = 2040 ms, flip angle= 8°, FoV= 224 x 256 mm^2, slice thickness= 1 mm, in-plane resolution = 1 x 1 x 1 mm^3, SENSE factor = 2. The total time spent in the scanner was approx. 60 min. per day.

Image processing and statistical analysis

The entire data analysis was performed with SPM5 (http://www.fil.ion.ucl.ac.uk) running on MATLAB 2006a (The Mathworks, Inc., Natick, MA). The first five images of each run were discarded to allow for T1 equilibration effects. For each participant, all volumes were spatially realigned to the first volume of the first session to correct for between-scan motion. The realigned T1-weighted image was segmented into gray, white and cerebrospinal fluid and was spatially normalized (Ashburner and Friston, 2005) to the Montreal Neurological Institute (MNI) anatomical brain template available in SPM5. The spatial transformation derived from this segmentation was then applied to the realigned EPIs for normalization and re-sampled in 2 x 2 x 2 mm^3 voxels using trilinear interpolation in space. All functional volumes were then spatially smoothed with an 8-mm full-width at half-maximum (FWHM) isotropic Gaussian kernel for the group analysis. Data were analyzed using a random-effects model (Friston et al., 1999), implemented in a two-level procedure. At the first level, single-subject fMRI responses were modelled in a General Linear Model (GLM) by a single design-matrix comprising, for each of the six functional runs (4 IMI and 2 OBS), onsets and duration of the main chord-picture event separately for each experimental condition. For the OBS blocks, three main regressors were used to model the main event of the PP-, OP-, and NP-trials, and one further regressor was included to model incorrect events which had to be excluded from the main task regressors (see Apparatus and stimuli). For the IMI blocks, four main regressors were used to model the main event of the PP-, OP-, NP-, and S-trials, plus one error regressor. All regressors were convolved with the canonical hemodynamic response function, and parameter estimates for all regressors were obtained by maximum-likelihood estimation. At the second level, the contrast images for each participant were entered into three separate ANOVAs to compute statistical maps for each experimental condition. The first ANOVA comprised the six conditions of the two OBS blocks, the second ANOVA comprised the eight conditions of the four IMI blocks, and a third ANOVA combined all OBS and IMI blocks. All focussed comparisons and conjunction analyses were based on these ANOVAs. Where appropriate, direct contrasts and conjunctions were inclusively masked by the relevant minuend contrast in order to avoid false positives. The results reported are significant at $p_u<0.001$ (uncorrected for multiple comparisons) at voxel level and at $p_u<0.05$ at cluster level. For anatomical localisation, the functional data were referenced to probabilistic cytoarchitectonic maps using version 1.7 of the SPM Anatomy Toolbox (Eickhoff et al., 2005, 2006, 2007).

Connectivity analyses

One crucial, yet untested assumption of Buccino et al.’s (2004) hierarchical model of imitation learning is that there should be a robust functional coupling between the DLPFC and the frontal and parietal and components of the FPMC, particularly in the early stage of imitative skill acquisition. To test this hypothesis, we investigated the effective connectivity of the DLPFC during chord imitation by means of whole-brain Psycho-Physiological Interactions (PPIs, Friston et al., 1997) for both scanning days. A PPI reflects the degree to which the influence of a seed area upon other brain areas is modulated by the experimental context. In contrast to other forms of connectivity analyses (e.g., Dynamic Causal Modelling, Friston et al., 2003), a PPI does not require a specified anatomical model. A further difference is that, unlike other methods (Dynamic Causal Modelling, or Granger Causality, Roebroeck et al., 2005), a PPI provides no information about the direction of causal influences between source and target regions (cf.

Nummenmaa et al., 2010). Thus, a PPI is particularly suited for an initial investigation of whether a functional link exists (Aim 1 of the present study), which can then be followed up by future studies that ask more specific questions about the causal relationship within a specified anatomical model.

The present analysis was restricted to the left middle frontal gyrus (MFG) according to its dominant role in supervisory control (Shallice, 2004; Vogt et al., 2007). Note that we use the anatomical term ‘MFG’ and the common functional term ‘DLPFC’ (or ‘prefrontal cortex’ for short) interchangeably in the present paper. The identification of the seed regions was based on significant activations in the conjunction of (PP ∩ OP ∩ NP) during chord imitation on Day 2 (Fig. 4A), at which time point prefrontal activations are typically more pronounced than at later stages of practice (Kelly and Garavan, 2005). As in our two previous studies, we observed two distinct group activation peaks within the left MFG, a more rostral (MNI coordinates: -28, 52, 18) and a more caudal peak (-32, 38, 32), and seed regions were defined as 6 mm spheres around these two peaks. After ensuring that each participant had significant activation in each seed region (at $p_u<0.05$), time series for both seed regions were extracted and deconvolved with a hemodynamic response function, as suggested by Gitelman et al. (2003). The subsequent PPI analyses looked at how the effective connectivity of the seed regions in left MFG with other brain areas was modulated by chord complexity, as defined by the contrast ‘physically and observationally practiced > simple chords’ [Footnote 1]. A total of four whole-brain PPI analyses were conducted, one for each seed region (caudal MFG, rostral MFG) and scanning session (Day 2, Day 4), using the same statistical threshold as for the functional analyses. As our focus was on the connectivity between the MFG and the FPMC, we only report those target areas of significant modulation that were located within the frontal (BA 44 and PMv) and parietal sectors of the FPMC as defined by the SPM Anatomy Toolbox (the whole-brain renderings can be found in supplemental Figure S1).

Results

Behavioural data

Figure 2 shows the participants' response times, measured from chord display onset to stable finger positioning on the fretboard and averaged across the two IMI blocks on each scanning day. Prior to analysis, trials with late or no hand movements were excluded. These amounted to only 2.6% each for the NP- and OP-trials, and only 1 trial was excluded for the PP- and S-trials. We confined the analysis to the chronometric data due to the ultimately subjective nature of error scoring in this task. A two-way ANOVA for the response times indicated significant main effects of chord type, $F(3, 16)=108.62$, $p<0.001$, and of day, $F(1, 16)=32.26$, $p<0.001$. The interaction between day and chord type was not significant, but it reached significance for the linear trend across chord types (PP, OP, NP, S), $F(1, 16)=5.81$, $p=0.028$. Contrast-contrast interactions (Rosenthal and Rosnow, 1985) narrowed this effect down to a significant interaction between day and PP- vs. S-chords, $F(1, 16)=5.36$, $p=0.034$, indicating that improvements across days were more pronounced for the PP-chords than for the S-chords. Additional pairwise comparisons within each day confirmed that the RTs for each chord type differed significantly from each adjacent chord type (all *p*s<0.01), thus confirming the expected pattern NP>OP>PP>S. Overall, these results confirm that the practice effects were item specific (see also Vogt et al., 2007), and that observational practice took the typical, intermediate position between no practice and physical practice (Vogt and Thomaschke, 2007). The significant interaction between day and linear trend across chord types suggests that these differential practice effects were already established on Day 2 (after one day of practice) and that they diverged slightly further on Day 4.

Insert Figure 2 about here

Functional imaging data

Plan of analysis. One possible experimental design to address our aims would have been to run the first scanning session without prior practice, and then to hold a series of practice sessions before the second scanning session takes place. The statistical analysis would then test for interactions of day and practice type, and of day x practice type x block. Our experimental design was slightly different. As in Vogt et al. (2007), participants had one practice session before the first scanning session. We then ran only one further practice session before the second scanning session, because we were keen not to miss any nonlinear effects that might be associated with longer practice (Cross et al., in press). As such, our design is not particularly suited for a statistical analysis that capitalises on changes between days, since such comparisons would only contrast an early with a slightly more intermediate stage of practice. We have therefore chosen the following, focussed plan of analysis (Rosenthal and Rosnow, 1985) to address our aims. We first describe the results of the action observation (OBS) blocks, since activations in these blocks were more confined than those in the IMI blocks which contained widespread execution-related activations. Within both sections, we first describe the common activations across chord types for Day 2 (Figs. 3A and 4A). These data were used as the primary resource to assess the involvement of DLPFC (Aims 1 and 2.1), because prefrontal activations are typically most pronounced at an early stage of practice (Kelly and Garavan, 2005) and because we wanted to maintain comparability to a previous study (Vogt et al., 2007). For the subsequent assessment of practice-specific effects (Aims 2.2 and 3), we focus on the comparisons between chord types within Day 4 (Figs. 3B, 3C, 4B, and 4C). At this point, the differences between observational and physical practice had been firmly established, as confirmed by the behavioural data. The activation changes between days are then reported as supplementary evidence.

Action observation. Figure 3A (left panel) and Table 1 show the common pattern of activations during observation of the PP-, OP-, and NP-chords after one day of practice (OBS block on Day 2). All chord types induced strong activations in the bilateral ventral premotor cortex (PMv), dorsal premotor cortex (PMd), inferior parietal lobule (IPL, area PFt) and adjacent postcentral gyrus (BA 2), the superior parietal lobule (SPL), and the left cerebellum. The activations in PMv extended to the dorsal-most part of pars opercularis of the inferior frontal gyrus (IFG). In addition, large parts of occipital cortex were activated, including bilateral foci in the extrastriate body area (EBA, Peelen and Downing, 2007; all present foci were less than 10 mm from the coordinates reported in

Peelen and Downing, 2005). For economy of exposition, however, occipital activations are not discussed in the present paper. Importantly, prefrontal activations were absent in the conjunction across chord types as well as in the individual basic contrasts for PP-, OP-, and NP-chords. The contrast estimates shown in Fig. 3A (right panel) indicate that the non-practised chords tended to induce stronger activations in PMv and IPL than the practised (PP- and OP-) chords. In the related contrast map NP2>(PP2+OP2), this was confirmed for bilateral PMv, right IPL, PMd and SPL bilaterally, for right BA 2, but not for the prefrontal cortex. No cortical region was found more strongly activated for the practised chords on Day 2.

Insert Figure 3 and Table 1 about here

The differences between chord types became more pronounced at the end of practice (Day 4). As shown in Fig. 3B (supplemental Table S1), activations during observation of the practised chords were now strongly reduced relative to the NP-chords in bilateral PMv, PMd, IPL, BA 2, SPL, hippocampus, and the left cerebellum [Footnote 2]. Overall, the results shown in Figs. 3A and 3B indicate that the main regions of the FPMC (PMv and IPL), as well as PMd, SPL, and BA 2, were strongly involved in action observation at an early stage of practice. Later in practice, these activations, as well as activations in the cerebellum, were markedly reduced relative to the non-practised chords.

These results are complemented by the activation decreases and increases between Days 2 and 4. Activation decreases that were consistent across the three chord types were not found at the chosen cluster level threshold, and only a marginally significant decrease in right IPL (50% area PFt: 42, -30, 38 $^{Z=3.55}$, k=39 voxels) was found for the practised chords. Thus, the trend for reduced activations across days in areas of the FPMC, as apparent in the contrast estimates (Fig. 3A), was only marginally significant for right IPL. Activation increases between days were only found in regions outside the FPMC and included the superior temporal sulcus (STS), angular gyrus, and SMA [Footnote 3].

In the direct contrasts between observation of OP- and PP-chords (Fig. 3C), activation differences were again only found in regions other than the FPMC. On both scanning days, a number of regions were more strongly activated for the OP-chords than for the PP-chords, whereas significantly larger activations for the PP-chords were not found [Footnote 4]. On Day 4, the OP-chords induced stronger activations than the PP-chords in the anterior midcingulate cortex (aMCC, area 24c': 18, 24, 24 $^{Z=5.04}$; Vogt, 2009) extending into the anterior cingulate cortex (pACC: 12, 32, 14 $^{Z=4.45}$; ibid.), and in a number of subcortical regions, namely the caudate nucleus (-22, 2, 18 $^{Z=5.01}$), pallidum (-16, 4, -6 $^{Z=4.49}$), and different sectors of the cerebellum (lobule VI: -4, -74, -26 $^{Z=4.25}$; -10, -70, -20 $^{Z=4.04}$; -30, -62, -30 $^{Z=3.63}$; vermis: -4, -66, -6 $^{Z=4.12}$). Most of these regions showed higher activations for the OP-chords than for both PP- and NP-chords (see Footnote 2), and in the related conjunction analysis, this pattern approached significance for the aMCC (18, 22, 24 $^{Z=4.40}$, k=52 voxels). Only the cerebellar activations followed the standard NP>OP>PP pattern. In a further analysis, we were seeking to identify brain regions with differential activations between OP- and PP-chords that were consistent across action observation and imitation. In the related conjunction analysis between OBS and IMI blocks for the contrast OP4>PP4, a single region in the anterior midcingulate cortex was marginally significant (aMCC: 4, 20, 34 $^{Z=3.58}$, k=53 voxels).

Finally, we were interested in activations during the observation of novel actions, particularly in the prefrontal cortex and the FPMC that would predict the behavioural benefits gained from observational or physical practice. To this end, we ran two correlation analyses between the activations during observation of the non-practised chords (averaged across days) and the behavioural response time data shown in Fig. 2. In the first analysis, the functional data were correlated with the average performance gains of NP- vs. OP-chords for each participant, where the index 'NP-OP' (Fig. 3D) stands for: (NP2-OP2)+(NP4-OP4). In the second analysis, the same functional data were correlated with the performance gains of NP- vs. PP-chords using the index 'NP-PP': (NP2-PP2)+(NP4-PP4). Importantly, both analyses indicated that activations in bilateral MFG were correlated with the behavioural effects of observational and physical practice (Fig. 3D and supplemental Table S2). Also bilateral SPL, thalamus, and right putamen and insula were found correlated with both NP-OP and NP-PP indices. In addition, activations in the superior occipital gyrus and in different sectors of the cerebellum were present for the correlation with index NP-OP, and extended activations in right IPL and SMA were found for the index related to performance gains by physical practice (NP-PP).

The results of the action observation blocks can be summarised as follows: On Day 2 the regions of the FPMC were activated for all chord types, with the strongest activations present for the NP-chords. This pattern became more pronounced on Day 4, where the activations for the practised (PP- and OP-) chords were markedly reduced relative to the NP-chords. This was also reflected in significantly reduced activations in right IPL from Day 2 to Day 4 for the practised chords. These data confirm both the reliability and the stability of our earlier findings (Aim 3). Regarding Aim 2.1, we found no consistent involvement of the MFG during action observation across all participants. As an exception to this basic finding, bilateral MFG was found differentially activated in the contrast OP4>NP4, along with sectors of the cingulate cortex and the putamen (see Footnote 2). In addition, we found that activation in bilateral MFG during observation of the NP-chords predicts the behavioural practice gains by OP and PP, which indicates a crucial role of the prefrontal cortex in both forms of practice. Regarding Aim 2.2, observing observationally vs. physically practised chords did not induce activation differences in the FPMC or MFG, and the differences found were confined to aMCC and a small number of subcortical sites.

<u>Action imitation.</u> The activations in the imitation (IMI) blocks were a superset of those in the OBS blocks and showed additional activation foci in the pars opercularis of IFG, SMA, middle cingulate cortex, insula, primary sensory-motor cortex, insula, parietal operculum, basal ganglia, and different sectors of the cerebellum (Fig. 4A and Tab. 2). Importantly, also the MFG was activated bilaterally during the imitation of the PP-, OP-, and NP-chords, which informs Aim 1 of the present study. As illustrated by the related parameter estimates (Fig. 4A, bottom panels), activations in MFG were of a similar magnitude across PP-, OP-, and NP-conditions within Day 2 as well as within Day 4, with a slight decrease between days. That is, in contrast to previous results (Vogt et al., 2007), the non-practised chords did not induce significantly stronger activations in these MFG sites than the practised chords, which was confirmed by the direct contrasts NP2>PP2 and NP2>OP2. This most likely reflects the high difficulty of the rapid

imitation task even for the practised chords. In addition, as one might expect, during the simple chord trials the activations in MFG were significantly reduced (-30, 50, 20 $^{Z=5.40}$; 36, 44, 20 $^{Z=6.19}$), which was confirmed by the contrast (PP2+OP2+NP2)>S2. Further, the direct contrast of the common activations in IMI and OBS blocks (IMI_PP2+OP2+NP2 > OBS_PP2+OP2+NP2) confirmed that the activations in MFG were more pronounced in the IMI block (MFGros: -30, 46, 22 $^{Z=5.33}$; 36, 42, 20 $^{Z=7.09}$; MFGcau: -32, 40, 30 $^{Z=6.17}$; 38, 34, 30 $^{Z=7.68}$).

Regarding the FPMC, the contrast estimates for IPL and PMv on Day 2 (Fig. 4A, top and middle panels) indicate basically the same trend as those for the MFG, namely similar activation intensities across the three main chord types, where the PP-chords showed numerically the smallest activations. Whereas the related direct contrast maps indicated significant differences between the NP- and PP-chords for PMv bilaterally, no differences were found for IPL. Only for the S-chords, activations were substantially reduced in IPL and PMv relative to the other three chord types.

Insert Figure 4 and Table 2 about here

As in the OBS condition, also in the IMI condition the differences between chord types became more pronounced on Day 4. As shown in Fig. 4B (yellow areas, supplemental Table S3), the non-practised chords induced stronger activations than the practised chords in the frontal sectors of the FPMC (PMv and IFG), as well as in IPS and large parts of posterior cortex [Footnote 5]. However, whereas in the OBS condition the pattern of activations in the FPMC was essentially NP4>OP4=PP4, in the IMI condition this pattern was essentially NP4=OP4>PP4 (cf. contrast estimates for Day 4 in Figs. 3A and 4A). That is, the activations during imitative execution of the OP-chords were similarly high to those for the NP-chords, and they did not show the same practice-related decreases as the PP-chords. This observation informs Aim 2.2 and was confirmed in the following ways: First, in the more focussed comparison NP4>PP4 (Fig. 4B, red areas), the activation differences were more extensive than in the contrast NP4>(PP4+OP4) and further included IPL bilaterally (area PF: -60, -30, 32 $^{Z= 3.86}$; 54, -32, 50 $^{Z=3.98}$) plus the caudal sector of left MFG (-40, 28, 32 $^{Z=4.36}$). Second, the contrast NP4>OP4 indicated significant differences in substantially smaller sectors of left BA 44 and right PMv and BA 45 than the two contrasts above. Third, as shown in Fig. 4C (red areas, supplemental Table S4), we found substantial activation differences between the OP- and PP-chords on Day 4. In contrast to the OBS block where differences were confined to the cingulate cortex and subcortical regions (Fig. 3C), imitation of the OP-chords induced stronger activations than for the PP-chords across the whole network of areas involved in action observation (bilateral PMv, PMd, BA 44, SMA, intraparietal sulcus, IPL, SPL, and right postcentral gyrus), plus activations in bilateral caudal MFG, insula, and inferior temporal gyrus, and lateralised sectors of the middle and anterior cingulate cortex, thalamus and vermis. That is, during action execution the activations for the PP-chords indicated substantially stronger practice effects than those for the OP-chords. Fourth, the hypothesis that the differences between OP- and PP-chords were more pronounced in the IMI than in the OBS blocks was tested in a focussed interaction analysis, (IMI_OP > IMI_PP) > (OBS_OP > OBS_PP), inclusively masked by (IMI_OP > IMI_PP). As shown in Fig. 4C (yellow areas, supplemental Table S4A), a large subset of the differential activations between chord types in the IMI block (red areas) was also found significant in the interaction analysis. This provides direct statistical support for the notion that while observational practice produces similar effects to physical practice during action observation, it induces widespread activation increases relative to physical practice effects when assessed during imitative execution.

However, it is conceivable that these activation increases for the OP-chords reflect, at least in part, a global compensatory response to a more localised lack of observational practice effects. In order to identify these more localised regions, we analysed the practice-related changes between days which only occurred for the PP-chords and not for the OP-chords. Accordingly, the contrast IMI_PP2 > IMI_PP4, exclusively masked by IMI_OP2 > IMI_OP4 (Fig. 4D), identified a cluster including the right rostral putamen (30, 14, 6 $^{Z=4.62}$), the insula (40, 4, 4 $^{Z=3.85}$), and the IFG (60% BA 44: 50,12, 8 $^{Z=3.72}$), as well as clusters in the right posterior MCC (pMCC, Vogt, 2009, 10, -4, 38 $^{Z=4.41}$), in the tail of the caudate nucleus (12, 6, -10 $^{Z=4.41}$), in the right IPL (60% area PFt: 52, -30, 48 $^{Z=3.76}$, 44% of cluster in PFt), and in posterior middle temporal gyrus (MTG, 44, -72, 2 $^{Z=4.10}$). A further cluster in the right primary sensory-motor cortex was found marginally significant (70% BA 3b: 32, -36, 58 $^{Z=3.80}$, k=52 voxels). These regions exhibited significantly reduced activations between days that were specific to the PP-chords and were not found for the OP-chords (for trends, see the contrast estimates in Fig. 4D). The corresponding comparison in the OBS condition did not reveal any significant effects. Furthermore, in the IMI condition two of the above foci, in right putamen and pMCC, were also significant in a more stringent interaction analysis between day and form of practice, (IMI_PP2 > IMI_PP4) > (IMI_OP2 > IMI_OP4), inclusively masked by (IMI_PP2 > IMI_PP4) [Footnote 6].

Finally, these practice-specific effects are complemented by the activation decreases from Day 2 to Day 4 that were consistent across the PP-, OP-, and NP-chords. These were present in a posterior sector of the SMA (-2, -16, 60 $^{Z=4.84}$; 6, -18, 56 $^{Z=4.40}$), right SII (20% OP4: 48, -2, 14 $^{Z=4.58}$), left precentral gyrus (50% BA 4p: -32, -22, 48 $^{Z=4.25}$), putamen (-18, 14, 6 $^{Z=4.28}$; 28, -8, 6 $^{Z=4.52}$), and pallidum (-24, -6, -2 $^{Z=4.13}$). Consistent with the analyses above, the activation decreases between days were most pronounced for the PP-chords, and these further included a considerable subset of the regions shown in Fig. 4B, notably PMv and IFG, MCC, primary sensory-motor cortex, right inferior parietal cortex, cerebellum, and right rostral MFG (38, 44, 18 $^{Z=3.72}$). No significant activation increases from Day 2 to Day 4 were found.

Functional connectivity during action imitation. Generally, an increase in chord complexity (from S-chord to PP- and OP-chords) was found to be associated with an increased effective connectivity of the left MFG to both frontal and parietal nodes of the FPMC. This was observed for both rostral and caudal seed regions within the MFG, and across both scanning days (Fig. 5 and supplemental Table S5; for the whole-brain renderings, see supplemental Fig. S1). Three points are worth noting: First, the functional coupling was bi-hemispheric, with the left MFG showing a significant connectivity effect not only to the left, but also to the contralateral right FPMC regions. Second, not only rostral sectors of inferior parietal cortex (BA 40, Caspers et al., 2006) showed a functional coupling to MFG, but also intraparietal cortex and angular gyrus (BA 39). Third, according to the pattern of peak coordinates, right parietal areas only showed increased effective connectivity on Day 2 but not on Day 4. This trend might reflect a reduced demand for supervisory control of the prefrontal cortex over the FPMC on Day 4. However, direct contrasts between the connectivity increases on both days did not indicate significant differences within the target regions in the FPMC (and only sparse differences in two other, unassigned regions). This result is consistent with the chosen psychological variable of chord complexity, which should indeed be largely unaffected by the additional practice for the PP- and OP-chords between Days 2 and 4. In addition, no significant differences between the connectivity increases for rostral versus caudal MFG were found for the FPMC on either day. In summary, chord complexity was found to be linked with an increased functional coupling between the left MFG and the two regions of the FPMC bilaterally, and this coupling was similarly pronounced on both scanning days and for the seed regions in rostral and caudal MFG.

Insert Figure 5 about here

Discussion

The results of this study inform three areas of research, one concerned with the role of prefrontal cortex in imitation learning, the second concerned with the neural correlates of learning by observing, and the third with neural efficiency and practice more generally. In short, we have presented clear evidence for the involvement of the DLPFC in a complex imitation task with low demands on working memory (Aim 1, see Introduction), and we have demonstrated a robust functional connectivity between DLPFC and the FPMC. In contrast to action imitation, DLPFC was not consistently involved in action observation across all participants. Importantly, however, DLPFC activity was found to be correlated with the behavioural outcome of learning by observing (Aim 2.1). Regarding Aim 2.2, we found that observationally and physically practised actions evoked similar cortical activation intensities in the FPMC during action observation. In contrast, during imitative execution the PP-actions exhibited markedly reduced activations, relative to the OP-actions, across all regions of the FPMC, as well as in the DLPFC. This dissociation suggests a lack of execution-related encoding during observational practice. Finally, we found that extended practice was associated with activation decreases within the FPMC, during both action observation and imitation (Aim 3). We begin the discussion with the latter finding, which forms the background for interpreting the other results.

Activation changes with practice

Imitating guitar chords, novel or practised, under time pressure and after only a single practice session, is a highly demanding task. Generally, the initial stage of skill acquisition is known to be associated with activations in cortical regions involved in attention and supervisory control, which in turn upregulate information processing in task-related sensory-motor regions (Kelly and Garavan, 2005; Halsband and Lange, 2006), in the present case the FPMC. Decreases in the extent and intensity of activations with practice are reported in the majority of related studies, and are proposed to reflect increased neural efficiency (ibid.; see also Babiloni et al., 2009, 2010). In particular, supervisory control can be economised with the increasing build-up of internal representations of task characteristics, such as their spatial or temporal structure, and of appropriate sensory-motor procedures. For highly practised performance, the latter can be reflected in activation increases in sensory-motor areas (e.g., Karni et al., 1995), or in higher-order areas related to stored representations (Kelly and Garavan, 2005).

In the present study, the primary source for assessing practice effects were the differences between chord types within each scanning session. We found pronounced <u>activation decreases</u> with practice, and these consistently included the FPMC (IPL and PMv). These activation differences were already present for PMv in the comparisons between non-practised and practised chords on Day 2, and they became more pronounced on Day 4 in both OBS and IMI blocks, when they included the two core regions of the FPMC bilaterally, as well as BA 2 (Keysers et al., 2010), SPL, and right PMd (see Filimon et al., 2007, for the involvement of the latter two regions in observation and execution of reaching movements). These results confirm the reliability and particularly the stability of our previous findings for the FPMC (Vogt et al., 2007).

A secondary source for assessing practice effects were the activation changes between days. Consistent with the above results, the activations in the FPMC for the practised chords tended to reduce between days (right IPL in OBS and IMI blocks, plus premotor and primary sensory-motor regions in the IMI blocks). Overall, the between-days effects were relatively small, which likely reflects the fact that the PP- and OP-chords had already been practised on Day 1, that is, before the first scanning session. We also found a small number of activation increases between days during action observation. The increase in bilateral posterior STS (see Footnote 3) can indeed be interpreted as the build-up of complex visual representations, as predicted in Vogt et al. (2007; for the different roles of the STS and the FPMC in imitation, see Iacoboni, 2009). In addition, the activation increases in angular gyrus and SMA might be related to an enhanced intermodal integration and an improved coordination between the fingers, respectively. However, since we also found reduced activations with practice for these regions in the comparisons between chord types, we refrain from further interpretation.

Taken together, these results indicate a functional redistribution (Kelly and Garavan, 2005) among representational systems in action observation, namely from the FPMC during early practice to other representational regions including posterior temporal cortex (STS) during later stages of practice. In addition, also the nature of action encoding within the FPMC is likely to change with practice: if we envisage the FPMC as a workspace specialised for encoding the identity and posture of an observed action, then the period of most frequent ‘access’ to this workspace will be early in practice, in the form of frequent, DLPFC-controlled shifts of attention between different action elements (here: fingers and their postures). When these become grouped into a single unit (here: a chord), the efficiency of coding increases. We thus suggest two main drivers for the pronounced activation decreases in the FPMC from non-practised to practised actions in the present paradigm: First, a trend for functional redistribution from the FPMC to posterior temporal regions, and, second, processes of grouping or unitisation within the FPMC [Footnote 7].

These considerations help to clarify the apparently contradictory activation trends for the FPMC in our studies and those by Babilioni et al. (2009, 2010) on the one hand, and a number of studies on expertise (Calvo-Merino et al., 2005, 2006) and practice effects (Cross et al., 2006, 2009; Orgs et al., 2008) in dance observation on the other hand: According to the above framework, we can distinguish three cases:

(1) The FPMC should be strongly engaged for novel (non-unitised) actions in case

these need segmentation or parsing (Byrne, 2003, 2006; Byrne and Bates, 2010), for purposes of either subsequent imitation or complex judgements.

(2) An intermediate level of FPMC activation can be expected for actions that are already in the observer's motor repertoire, since these are accessed primarily as complete units rather than discrete elements. Again, the purpose of observation can be imitation or complex judgements.

(3) Lower FPMC activations will be induced by action observation without purpose or for aesthetic appreciation, due to the lack of top-down modulation via DLPFC. In this case, one might well find that familiar actions induce stronger activations than unfamiliar actions since only the former activate an existing representation, and no parsing is required in either case.

In the present paradigm, participants observed each chord with the intention to imitate. In our interpretation, this involves stronger top-down, prefrontal modulation of the FPMC for unfamiliar actions than for familiar, already unitised actions (cases 1 and 2, resp.). In addition, the recent EEG studies by Babilioni et al. (2009, 2010) indicate that neural efficiency in expert observers can also be found in complex judgement tasks: Expert observers of sports actions (case 2) showed lower activations, as indexed by less pronounced event-related desynchronisations in alpha rhythms, than non-experts (case 1) during fine-grained, technical judgements of the athletic level of each performance. In contrast, in the above studies on dance observation, participants were asked to judge, e.g., 'how tiring' each movement was, or to 'simply observe' without a later imitation requirement. Such instructions will induce primarily bottom-up, stimulus-driven activity in the FPMC (case 3), which can indeed be stronger for unitised actions than for unfamiliar actions (for a related framework based around stimulus familiarity and predictive coding, see Cross et al., in press). In support of this interpretation, no prefrontal activations were reported in these studies.

Prefrontal involvement in imitation learning and connectivity

The first specific aim of the present study was to demonstrate the involvement of the prefrontal cortex in imitation learning when the working memory load is reduced relative to previous studies (Buccino et al., 2004; Vogt et al., 2007). Therefore, we used a paradigm where participants were asked to rapidly imitate pictures of guitar chords while these were visible on the screen. This reduced average response times to approx. 1.5 s from stimulus onset, in comparison to an average delay of approx. 15 s in our previous studies (movie observation plus preparation interval). The present results clearly indicate that DLPFC is involved in action imitation under these conditions. Before we turn to the significance of this finding, two differences to the results of our previous studies are worth noting. First, in Vogt et al. (2007), we observed a shift of activations from left MFG during action observation (most likely supervisory control) to right MFG during execution (most likely monitoring operations; Shallice, 2004). Whilst in the present study, activations in left rostral and caudal MFG, as well as right caudal MFG, were coextensive with those found in the earlier studies, the rapid imitation paradigm did not allow us to separate these different phases of imitation. Most likely, supervisory control and monitoring functions were operating in parallel in the present task. Second, whereas observation and execution of the practised chords induced only weak prefrontal activations in our previous study, the present paradigm induced substantial prefrontal activations not only for the non-practised but also for the practised chords. A viable interpretation of this discrepancy is that the present, rapid imitation paradigm was more demanding than the previous task, and that it required prefrontal control also for the practised chords. Unexpectedly, imitation of the non-practised chords did not induce more pronounced prefrontal activations than the practised chords on Day 2, although on Day 4, differential activations emerged in caudal MFG in the contrasts between NP- and PP-actions (Fig. 4B) and between OP-and PP-actions (Fig. 4C). Thus, the lack of differential prefrontal activations on Day 2 is probably related to the already strong activations for the practised chords (a ceiling effect). In addition, it is noteworthy that in our previous study (Vogt et al., 2007) activation differences in prefrontal cortex between non-practised and practised actions were only found for the observation and preparation events, and not during subsequent execution. Given the strong execution component in the present imitation condition (cf. Figs. 3A and 4A), the paucity of practice-related activation differences in prefrontal cortex is actually not in conflict with our previous findings. Taken together, we conclude that the time window for a possible differential involvement of the DLPFC in rapid imitation tasks such as ours is apparently very short. This calls for future research employing highly time-resolved imaging methods.

Whereas the role of prefrontal cortex in the early stages of non-imitative skill acquisition is undisputed (Kelly and Garavan, 2005; see also Imamizu et al., 2007; Leff et al., 2008), the previously available evidence for its role in imitation learning was ambiguous (see Introduction). Therefore, the present study provides unique support for the restructuring hypothesis of imitation learning (Buccino et al., 2004), in that we were able to render an explanation of prefrontal involvement in terms of working memory alone highly unlikely. These results demonstrate that a basic mechanism of perception-action matching, which likely underlies phenomena of automatic imitation (Heyes, 2011), is insufficient to explain the imitation learning of complex actions (see also Iacoboni, 2009). Rather, we maintain that the motor representation of an observed, complex action, as provided by the FPMC, only serves as the ‘raw material’ for higher-order supervisory and monitoring operations associated with the DLPFC (Vogt et al., 2007).

This conclusion is further supported by the present connectivity analyses. Whereas the connectivity between the two main nodes of the FPMC (PMv and IPL) has been studied previously (Emmorey et al., 2010; Schippers and Keysers, 2011; for observational learning: van der Helden et al., 2010), the focus of our analysis was on the functional connectivity between the DLPFC and the FPMC, which is a critical assumption of our hierarchical model of imitation learning (for a related analysis in learning sound-action associations, see McNamara et al., 2008; and for a conectivity analysis of the network involved in imitative response inhibition, see Bien et al., 2009). We found that an increase in chord complexity was associated with increased connectivity of left rostral and caudal MFG to both nodes of the FPMC. Thus, our study is the first to provide evidence for the previously untested assumption of a functional link between the MFG / DLPFC and the FPMC. Note that we do not dispute that sites other than the DLPFC might also show a modulation of connectivity to the FPMC by task complexity, or that the connectivity of the DLPFC might involve other areas than the FPMC. The relatively modest aim of the present analyses was to prove the existence of a robust functional coupling between the DLPFC and the two components of the FPMC, as assumed in the hierarchical model by Buccino et al. (2004).

Given that the PPI method does not inform us about the direction of functional connections, the present analyses do not indicate whether this functional connection is of a top-down (DLPFC modulates FPMC), bottom-up (FPMC modulates DLPFC), or bi-directional nature. Thus, our finding of a functional link paves the way for future studies that can test more specific models about the interplay between prefrontal regions and the FPMC using methods that include the directionality of information flow, such as Dynamic Causal Modeling (Friston et al., 2003) or Granger Causality (Roebroeck et al., 2005). For example, the fact that left prefrontal cortex exhibited functional connectivity to the FPMC bilaterally (especially to the frontal component of the FPMC) might be related to the interhemispheric connectivity between left and right DLPFC, and/or to a direct connectivity between left DLPFC and the right FPMC. Additional questions for future research include the nature of the connectivity of the DLPFC to intraparietal cortex and angular gyrus, and a possible functional specificity of rostral versus caudal prefrontal regions in imitation tasks, which was not found in the present analysis.

A place for the prefrontal cortex in observational practice

Aim 2.1 of this study was to assess two accounts of the neural networks underlying observational practice. Both accounts assume the involvement of the FPMC, but they differ regarding the involvement of the DLPFC (see Introduction). The results of the present study are in line with the existing literature, in that a) the FPMC was indeed found activated during early observational practice and throughout action imitation, and in that b) we did not find DLPFC activated in the basic contrast map of the action observation sessions, in which no execution was required (Fig. 3A; Buccino et al., 2004; Frey and Gerry, 2006). The latter result is supplemented by the finding that prefrontal activations were significantly more pronounced during imitation than during observation. Importantly, however, we found that bilateral DLPFC activity was correlated with the behavioural outcome of learning by observing. In addition, on Day 4 bilateral DLPFC was found to be more strongly activated during observation of the OP-actions than of the NP-actions (see Footnote 2). These two findings allow us to reject a general account of observational learning without involvement of the DLPFC. Rather, our data provide the first support for the validity of extending Buccino et al.’s (2004) restucturing model to observational practice. Incidentally, Hard et al. (2006) have proposed a similar theoretical account of observational learning to ours, based on hierarchical encoding mechanisms, but unfortunately their results turned out to be unreliable (Hard et al., 2008). We regard our results, as well as those by Torriero et al. (2007), to be most encouraging for further research into the specific roles of DLPFC in observational learning. The fact that we found left and right DLPFC correlated with the behavioural data suggests that both supervisory and monitoring functions of the DLPFC can be active during OP. In conclusion, we suggest that the two accounts of observational practice as outlined in the Introduction apply to different task categories: DLPFC is likely exerting a supervisory and monitoring role while learning complex, hierarchically organised actions that require the parsing of visual input. In contrast, other, dominantly associative, aspects of motor behaviour such as preferred movement directions (Stefan et al., 2005) or novel force environments (Brown et al., 2009; Malfait et al., 2010) are apparently learnt with little DLPFC involvement.

An additional finding of the correlation analysis was the significant correlation of right IPL (area PF) with the behavioural gains in response times. This finding strengthens the present evidence for the role of the FPMC in learning by observing. Frey and Gerry (2006) found that the activation of the right intraparietal sulcus during the observation of complex sequences predicted the accuracy of sequence reproduction. Thus, whereas in the present study the formation of representations of individual hand postures seems to rely primarily on the right IPL, representations of sequential procedures engage primarily the intraparietal sulcus.

Observationally practiced actions lack execution-related representations

Aim 2.2 of this study was to identify specific patterns of neural activation that might distinguish observationally from physically practised actions. Since action observation was a common component of OP and PP in the present experiment, it is perhaps not surprising that we did not find activation differences in the FPMC during the OBS blocks (see also Cross et al., 2009). On the cortical level, we observed only two regions in cingulate cortex, aMCC and pACC, that were more strongly activated for the OP-chords, of which aMCC was also differentially activated during action imitation. In the four-region model of Vogt (2009; Palomero-Gallagher et al., 2009), midcingulate cortex is a premotor region: “MCC provides a cognitive interface with skeletomotor systems via projections to the spinal cord, striatum, supplementary / pre-supplementary motor cortices, and other motor systems … and may play a pivotal role in reorganizing activity in many motor structures to produce new behavioural outputs” (Vogt, 2009, p. 15). More specifically, the activated subregion of aMCC (area 24c’) is part of the cingulate motor area (B. Vogt, pers. comm.). During action observation, activations in aMCC for the OP-actions were not only stronger than those for the PP-actions but also stronger than those for the NP-chords. This might reflect a specific motivational readiness to execute the OP-chords, which one would neither expect for motorically practised nor for non-practised actions. Further research would be required to contrast this with alternative interpretations such as conflict monitoring and related behavioural adjustments (Botvinick et al., 2004; Morecraft and Tanji, 2009; see also below).

In stark contrast to the results for action observation, during action imitation all regions of the FPMC, as well as sectors of the DLPFC, were more strongly activated for the OP-actions than for the PP-actions (Fig. 4C). Given the clear trend for reduced activations in the FPMC with increasing practice in the present paradigm, this finding indicates fairly limited effects of observational practice when assessed during execution. The functional data are thus fully in line with the behavioural data (Fig. 2). How can we explain that the same action representation network (FPMC) exhibits practically identical activation intensities for the OP- and PP-actions during action observation, but substantially different intensities when the observed chords are imitated? Given that the OBS blocks were run subsequent to the IMI blocks in the present study, one possible explanation is an order effect: Participants might have benefited from executing all chords during the IMI blocks, which might have reduced the activation differences between chord types in the OBS block. A further study using a counterbalanced order of these blocks across participants would be required to validate this interpretation. However, our results are consistent with those of Cross et al. (2009) who only scanned during action observation, and order effects can of course not explain the strong differences obtained during action imitation in the present study. We are therefore inclined to accept the dissociation between observation and imitation as a genuine dissociation. An interpretation of this result in terms of reduced practice effects throughout the FPMC can be challenged, however, a) given the absence of differences between the PP- and OP-actions in this circuit during action observation, and b) if we consider the possibility that a more localised lack of execution-related resources should invoke a similar, global response of the observation / imitation network, that is, as a compensatory strategy (for a related parallel networks model, see Hikosaka et al., 1999, 2002). That is, whereas the FPMC might well allow the observer to learn to identify an observationally practised action as a complete unit (see Footnote 7) and to form a related high-level motor representation, these processes per se might not be sufficient for skilled motor execution. Rather, in case that lower-level, associative motor representations have not been established in parallel with these higher-level representations, one would indeed expect increased visuo-motor processing in the FPMC and DLPFC relative to the physically practised actions – which is exactly what we found for the OP-chords.

Whereas a thorough empirical test of this proposal is beyond the scope of the present study, the analysis of activation changes across days which selectively occurred for the PP-chords gives valuable clues. In this analysis (Fig. 4D), we found the following regions in the right (contralateral) hemisphere which exhibited execution-related neural efficiency effects after PP but not after OP: a cluster comprising the rostral putamen, insula, and BA 44, as well as activations in pMCC, caudate nucleus, IPL (area PFt), and posterior MTG. Interestingly, the activation in area PFt overlapped with the focus in right IPL that correlated with the behavioural benefit of physical practice (Fig. 3D). This provides convergent evidence indicating that the contralateral (right) FPMC (specifically areas PFt and BA 44), as well as posterior MTG, indeed contribute to the execution-related advantages of physical practice. However, the most pronounced activation differences in the above analysis were found for the right rostral putamen and pMCC. According to Middleton (2009), these regions are part of the motor cingulate–basal ganglia closed-loop circuit. Imaging studies have further shown that (1) the putamen is part of the (right-lateralised) cortico-striatal pathway involved in implicit sequence learning (Halsband and Lange, 2006), that (2) in a comparison of expert and novice golfers, putamen and caudate were active only in novices (Milton et al., 2007), and that (3) the rostral putamen and caudate are involved in non-routine movement planning

(Jankowski et al., 2009). Based on these results and on further evidence for goal-directed control in the basal ganglia (Redgrave et al., 2010), a tentative interpretation of our finding is that the selective functions of the motor cingulate–basal ganglia circuit which enable associative motor learning are primarily operational during physical practice (as indicated by neural efficiency effects) and substantially less so during observational practice [Footnote 8].

In a wider context, this interpretation implies that a two-level representation model (e.g., Hikosaka et al., 1999, 2002) is well suited to account for the present dissociation (Fig. 4C), according to which action parsing and execution rely on the FPMC at an early stage of practice (under the supervisory control of the DLPFC), whereas quasi-autonomous visual and motor structures assist in these functions later in practice. For visual-pictorial action encoding, we have already discussed a tentative functional redistribution from the FPMC to posterior temporal regions in the present task. In order to pinpoint the motor structures specifically associated with PP (with the FPMC, the primary sensory-motor areas, and the cerebellum as likely candidates), further research would be required, possibly employing longer periods of practice than used in the present study. Nevertheless, the present analyses highlight the differential involvement of the motor cingulate–basal ganglia circuit in shaping these motor representations via physical and, substantially less so, via observational practice.

Independent support for a two-level representation model comes from recent behavioural work on motor sequence learning (e.g., Kovacs et al., 2010; Panzer et al., 2009; reviewed in Shea et al., 2011). In these studies, inter-limb transfer of a learned sequential pattern was assessed separately for practice-congruent visuo-spatial representations and for practice-congruent low-level muscular and biomechanical patterns. Also these results accord with the parallel networks model by Hikosaka et al. (1999, 2002). Most recently, Grützmacher et al. (2011) demonstrated that observational and physical practice produced similar results in the visuo-spatial transfer task, whereas PP produced superior performance to OP in the low-level motor transfer test. These results nicely complement the imaging results of the present study.

Conclusions

Heyes (2009) noted “a growing body of theory and evidence suggesting that mimicry and imitation learning are continuous”, and that “imitation learning enlists additional, general purpose mechanisms of learning and cognitive control” (p. 2295). The present results support both proposals, in that we indeed found the FPMC involved in imitation learning, and that prefrontal cortex is most likely exerting a supervisory and monitoring role over the elementary representations provided by the FPMC, particularly at the early stages of learning (see also Vogt et al., 2007). In addition, we show that this hierarchical model of imitation learning also applies to learning by observing, with the qualification that prefrontal activations during observational practice are found less consistently than during imitative execution. Further, we found a strong overlap between observationally and physically practised actions when assessed during action observation (see also Cross et al., 2009). However, the limitations of OP became apparent both in the behavioural data and in the functional activations during imitative execution. In line with recent behavioural work on sequence learning, our results point to a lack of execution-related processing during observational practice, which was primarily associated with a lack of neural efficiency effects in the motor cingulate–basal ganglia circuit.

Taken together, these results suggest a three-level model of imitation learning, where, in the early stages of practice, the DLPFC exerts transient supervisory control over the FPMC, which in turn is increasingly assisted by lower-level visual and motor associative structures after longer practice. Observational practice overlaps widely with physical practice regarding the neural efficiency effects in the FPMC, and its behavioural effects are correlated with activations in DLPFC during action observation, but it does not foster the formation of lower-level motor associative processes to the same extent as physical practice.

Acknowledgements

We would like to thank Valerie Adams, Anna Anderson, and Bill Bimson (Liverpool), as well as Dave Gaskell and Gordon Johnson (Lancaster) for their kind technical and administrative support during setup and running of this study. Virginia Kellond (Liverpool) helped with participant-management and with scoring the video-recordings, and Daniel Eaves (Teesside and Lancaster) and Peter Walker (Lancaster) helped improve the English. Special thanks go to Brent Vogt (New York) for his invaluable advice on the cingulate cortex, to Peter Redgrave (Sheffield) for discussions on the basal ganglia, and to all participants for their sustained engagement in the study. This work was supported by a research project grant from the Leverhulme Trust (F/00 185/K) to S. Vogt and N. Roberts.

Supplementary Data

Supplementary data associated with this article can be found in the on-line version at doi…

Table of Footnotes

Footnote 1 (p. 13): Since all three complex chords conditions NP, OP, and PP activated the left MFG to a similar degree (see Fig. 4A and Discussion section on prefrontal involvement), we did not chose the comparison amongst these conditions (i.e., non-practiced vs. practiced chords) as the experimental context in the PPI analysis: In the absence of a functional effect within MFG, it is unlikely that such a factor would reliably modulate the effective connectivity of the seed regions.

Footnote 2 (p. 16, Results): As on Day 2, also on Day 4 the inverse contrast PP4>NP4 did not show any significant activations. However, the contrast OP4>NP4 indicated significant differences in midcingulate cortex (pMCC: 0, 16, 34 $^{Z=4.44}$; 0, 4, 24 $^{Z=3.92}$; aMCC: 18, 22, 24 $^{Z=4.40}$; Vogt, 2009), anterior cingulate cortex (pACC: 16, 38, 14 $^{Z=4.06}$; ibid.), the middle frontal gyrus (MFGros: -26, 56, 14 $^{Z=4.09}$; 30, 50, 26 $^{Z= 4.65}$; MFGcau: -30, 38, 26 $^{Z=3.64}$), and in the putamen (-24, 14, -8 $^{Z=4.49}$; 22, 12, -4 $^{Z=4.72}$).

Footnote 3 (p. 16): Activation increases between days that were consistent across all chord types were found in right STS (56, -28, 2 $^{Z=4.33}$), superior medial gyrus (4, 30, 46 $^{Z=4.64}$), left angular gyrus (30% area PGa: -56, -50, 30 $^{Z=3.62}$), and caudalmost MFG (-32, 12, 42 $^{Z=4.11}$; 42, 10, 50 $^{Z=4.27}$), as assessed via a conjunction analysis. In the more focussed conjunction of activation increases for the practised chords, additional activation peaks were found in left STS (-58, -48, -4 $^{Z=3.86}$; -50, -32, -6 $^{Z=3.71}$), SMA (30% BA 6: -2, 12, 64 $^{Z=3.99}$), right angular gyrus (40% area PGa: 48, -62, 48 $^{Z=3.74}$), and in pars orbitalis of right IFG (-40, 22, -14 $^{Z=4.16}$).

Footnote 4 (p. 17): On Day 2, stronger activations for the OP-chords than the PP-chords were confined to the SMA (-12, -2, 46 $^{Z=4.63}$; 10, -2, 60 $^{Z=4.30}$), right middle orbital gyrus (36, 58, -2 $^{Z=4.82}$), and left caudal middle frontal gyrus (-20, 36, 22 $^{Z= 4.48}$). Since none of these overlapped with the activation differences on Day 4, and since for the SMA no significant difference was found between OP- and NP-chords, we refrain from further interpretation.

Footnote 5 (p. 19): The inverse contrast (PP4+OP4)>NP4 indicated a single activation increase in the superior temporal gyrus (60, -10, -6 $^{Z=4.81}$). This was the only practice-related activation increase found in all comparisons between chord types in the IMI and OBS blocks.

Footnote 6 (p. 21): Note that this interaction analysis, as well as the contrast shown in Fig. 4D, do not show effects for the MFG and are thus potentially relevant regarding Aim 2.1. However, we found that bilateral MFG was more strongly activated during imitation of OP-chords than PP-chords on Day 4 (Fig. 4C, red areas, and supplemental Table S4B), which indicates a lack of practice for the OP-chords. Whereas the latter comparison appropriately reflects the cumulative effects of both practice sessions, the interaction analysis only reflects the practice-specific effects of one practice session (Day 3) and is thus less sensitive (see also Section ‘Plan of analysis’).

Footnote 7 (p. 24, Discussion): Evidence for the initial segmentation of observed actions into discrete elements (see also Byrne, 2003, 2006; Bates and Byrne, 2010, for the concept of behavioural parsing) and the subsequent organisation into larger, hierarchically organised units is available for both sequential (Keele et al. 2003; Hard et al., 2011) and configural actions (Hazeltine et al., 2007). The concept of unitisation was originally developed in the context of reading (Healy, 1994). Whereas most other models of reading assume that words cannot be identified without the prior identification of the components, the unitisation hypothesis postulates that fluent readers process high-frequency words at the syllable, word or phrase level, whereas only low-frequency words are processed at the level of individual letters. Here we use the concept of unitisation to chracterise an important aspect of visuo-motor pattern learning.

Footnote 8 (p. 31): Our emphasis on the motor cingulate–basal ganglia circuit is tentatively strengthened by the fact that components of this circuit were also differentially activated during the OBS block on Day 4 (for contrast OP4 > PP4: aMCC, caudate nucleus, and pallidum, see Fig. 3C and Results section; for contrast OP4 > NP4: aMCC, pMCC, and putamen, see Footnote 2). However, since the overlap in MCC across the different contrasts in the OBS and IMI sessions was far from complete, we cannot assume identical functions (see Morecraft and Tanji, 2009, for the different premotor functions of anterior and posterior MCC). In addition, the specific pattern across chord types found in the OBS condition did not match that in the IMI condition, where the NP-chords showed similar activation intensities as the OP-chords, even at the peak coordinates in the OBS condition. Therefore, further research will be required to clarify if the findings for OBS and IMI conditions reflect similar processes or not.

References

Ashburner, J., Friston, K.J., 2005. Unified segmentation. NeuroImage 26, 839-851.

Babiloni, C., Del Percio, C., Rossini, P.M., Marzano, N., Iacoboni, M., Infarinato, F., Lizio, R., Piazza, M., Pirritano, M., Berlutti, G., Cibelli, G., Eusebi, F., 2009. Judgment of actions in experts: A high-resolution EEG study in elite athletes. Neuroimage 45, 512–521.

Babiloni, C., Marzano, N., Infarinato, F., Iacoboni, M., Rizza, G., Aschieri, P., Cibelli, G., Soricelli, A., Eusebi, F., Del Percio, C., 2010. “Neural efficiency” of experts’ brain during judgment of actions: A high-resolution EEG study in elite and amateur karate athletes. Behavioural Brain Research 207, 466-475.

Bates, L.A., Byrne, R.W., 2010. Imitation: what animal imitation tells us about animal cognition. Wiley Interdisciplinary Reviews: Cognitive Science 1, 685-695. DOI: 10.1002/wcs.77

Bien, N., Roebroeck, A., Goebel, R., Sack, A.T. (2009). The brain’s intention to imitate: The neurobiology of intentional versus automatic imitation. Cerebral Cortex 19, 2338–2351.

Botvinick, M.M., Cohen, J.D., Carter, C.C., 2004. Conflict monitoring and anterior congulate cortex: an update. Trends in Cognitive Sciences 18, 539-546.

Brown, L.E., Wilson, E.T., Gribble, P.L., 2009. Repetitive transcranial magnetic stimulation to the primary motor cortex interferes with motor learning by observing. Journal of Cognitive Neuroscience 21, 1013-22.

Buccino, G., Vogt, S., Ritzl, A., Fink, G.R., Zilles, K., Freund, H.-J., Rizzolatti, G., 2004. Neural circuits underlying imitation learning of hand actions: an event-related fMRI study. Neuron 42, 323-334.

Byrne, R.W., 2003. Imitation as behaviour parsing. Philosophical Transactions of the Royal Society of London Series B: Biological Sciences 358, 529-536.

Byrne, R.W., 2006. Parsing behaviour: A mundane origin for an extraordinary ability? In: Enfield, N., Levinson, S.C. (Eds.), Roots of Human Sociality: Culture, Cognition, and Human Interaction. Oxford: Berg, pp. 478-505.

Calvo-Merino, B., Glaser, D.E., Grèzes, J., Passingham, R.E., Haggard, P., 2005. Action observation and acquired motor skills: An fMRI study with expert dancers. Cerebral Cortex 15, 1243-1249.

Calvo-Merino, B., Grèzes, J., Glaser, D.E., Passingham, R.E., Haggard, P., 2006. Seeing or Doing? Influence of visual and motor familiarity in action observation. Current Biology 16, 1905-1910.

Caspers, S., Geyer S., Schleicher A., Mohlberg, H., Amunts, K., Zilles, K., 2006. The human inferior parietal cortex: Cytoarchitectonic parcellation and interindividual variability, NeuroImage 33, 430-448.

Caspers, S., Zilles, K., Laird, A.R., Eickhoff, S.B., 2010. ALE meta-analysis of action observation and imitation in the human brain. NeuroImage 50, 1148-1167.

Celnik, P., Stefan, K., Hummel, F., Duque, J., Classen, J., Cohen, L.G., 2006. Encoding a motor memory in the older adult by action observation. Neuroimage 29, 677–684.

Cross, E.S., Hamilton, A.F., Grafton, S.T., 2006. Building a motor simulation de novo: Observation of dance by dancers. NeuroImage 31, 1257-1267.

Cross, E.S., Kraemer, D.J.M., Hamilton, A.F., Kelley, W.M., Grafton, S.T., 2009. Sensitivity of the action observation network to physical and observational learning. Cerebral Cortex 19, 315-326.

Cross, E.S., Liepelt, R., Hamilton, A.F., Parkinson, J., Ramsey, R., Stadler, W., Prinz, W. (in press). Robotic movement preferentially engages the action observation network. Human Brain Mapping.

Cunnington, R., Windischberger, C., Robinson, S., Moser, E., 2006. The selection of intended actions and the observation of others' actions: A time-resolved fMRI study. NeuroImage 29, 1294–1302.

Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., Zilles, K., 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. NeuroImage 25, 1325-1335.

Eickhoff, S.B., Heim, S., Zilles, K., Amunts, K., 2006. Testing anatomically specified hypotheses in functional imaging using cytoarchitectonic maps. NeuroImage 32, 570-582.

Eickhoff, S.B., Paus, T., Caspers, S., Grosbras, M.H., Evans, A., Zilles, K., Amunts, K., 2007. Assignment of functional activations to probabilistic cytoarchitectonic areas revisited. NeuroImage 36, 511-521.

Emmorey, K., Xu, J., Gannon, P., Goldin-Meadow, S., Braun, A., 2010. CNS activation and regional connectivity during pantomime observation: No engagement of the mirror neuron system for deaf signers. NeuroImage 49, 994-1005.

Ferrari, P.F., Bonini, L., Fogassi, L., 2009. From monkey mirror neurons to primate behaviours: Possible 'direct' and 'indirect' pathways. Philosophical Transactions of the Royal Society B: Biological Sciences, 364, 2311–2323.

Filimon, F., Nelson, J.D., Hagler, D.J., Sereno, M.I., 2007. Human cortical representations for reaching: mirror neurons for execution, observation, and imagery. NeuroImage 37, 1315–1328.

Frey, S.H., Gerry, V.E., 2006. Modulation of neural activity during observational learning of actions and their sequential orders. Journal of Neuroscience 26, 13194-13201.

Friston, K. J., Buechel, C., Fink, G. R., Morris, J., Rolls, E., Dolan, R. J., 1997. Psychophysiological and modulatory interactions in neuroimaging. Neuroimage 6, 218-229.

Friston, K.J., Harrison, L., Penny, W., 2003. Dynamic causal modelling. NeuroImage 19, 1273-1302.

Friston, K.J., Holmes, A.P., Worsley, K.J., 1999. How many subjects constitute a study? NeuroImage 10, 1-5.

Gallese, V., Gernsbacher, M.A., Heyes, C., Hickok, G., Iacoboni, M., 2011. Mirror neuron forum. Perspectives on Psychological Science 6, 369-407.

Gitelman, D.R., Penny, W.D., Ashburner, J., Friston, K.J., 2003. Modeling regional and psychophysiologic interactions in fMRI: The importance of hemodynamic deconvolution. Neuroimage 19, 200-207.

Gruetzmacher, N., Panzer, S., Blandin, Y., Shea, C.H., 2011. Observation and physical practice: Coding of simple motor sequences. Quarterly Journal of Experimental Psychology 64, 1111-1123.

Hard, B. M., Lozano, S. C., and Tversky, B., 2006. Hierarchical encoding of behavior: Translating perception into action. Journal of Experimental Psychology: General 135, 588-608.

Hard, B.M., Lozano, S.C., Tversky, B., 2008. Retraction of Hard, Lozano, and Tversky (2006). Journal of Experimental Psychology: General 137, 672.

Hard, B.M., Recchia, G., Tversky, B., 2011. The shape of action. Manuscript submitted for publication.

Halsband, U., Lange, R.K., 2006. Motor learning in man: A review of functional and clinical studies. Journal of Physiology – Paris 99, 414-424.

Hazeltine, E., Aparicio, P., Weinstein, A., Ivry, R., 2007. Configural response learning: The acquisition of a nonpredictive motor skill. Journal of Experimental Psychology: Human Perception and Performance 33, 1451-1467.

Heiser, M., Iacoboni, M., Maeda, F., Marcus, J. and Mazziotta, J.C., 2003. The essential role of Broca's area in imitation. European Journal of Neuroscience 17, 1123-1128.

Healy, A.F., 1994. Letter detection: A window to unitization and other cognitive processes. Psychonomic Bulletin and Review 1, 333–344.

Heyes, C., 2009. Evolution, development and intentional control of imitation. Philosophical Transactions of the Royal Society B: Biological Sciences 364, 2293-2298.

Heyes, C., 2011. Automatic imitation. Psychological Bulletin 137, 463-483.

Hickok, G., Hauser, M., 2010. (Mis)understanding mirror neurons. Current Biology 20, R593–R594.

Hikosaka, O., Nakahara, H., Rand, M.K., Sakai, K., Lu, X., Nakamura, K., Miyachi, S., Doya, K., 1999. Parallel neural networks for learning sequential procedures. Trends in Neurosciences 22, 464–471.

Hikosaka, O., Nakamura, K., Sakai, K., Nakahara, H., 2002. Central mechanisms of motor skill learning. Current Opinion in Neurobiology 12, 217-222.

Iacoboni, M., 2009. Neurobiology of imitation. Current Opinion in Neurobiology 19, 661-665.

Imamizu, H., Higuchi, S., Toda, A., Kawato, M., 2007. Reorganization of brain activity for multiple internal models after short but intensive training. Cortex 43, 338-349.

Jankowski, J., Scheef, L., Hüppe, C., Boecker, H., 2009. Distinct striatal regions for planning and executing novel and automated movement sequences. NeuroImage 44, 1369-1379.

Johnson-Frey, S.H., Newman-Norlund, R., Grafton S.T., 2005. A distributed left hemisphere network active during planning of everyday tool use skills. Cereb. Cortex 15, 681-695.

Kalenine, S., Buxbaum, L.J., Coslett, H.B., 2010. Critical brain regions for action recognition: lesion symptom mapping in left hemisphere stroke. Brain 133, 3269-3280.

Karni, A., Meyer, G., Jezzard, P., Adams, M.M., Turner, R., Ungerleider, L.G., 1995. Functional MRI evidence for adult motor cortex plasticity during motor skill learning. Nature 377, 155–158.

Keele, S.W., Ivry, R., Mayr, U., Hazeltine, E., Heuer, H., 2003. The cognitive and neural architecture of sequence representation. Psychological Review 110, 316-339.

Kelly, A.M.C., Garavan, H., 2005. Human functional neuroimaging of brain changes associated with practice. Cerebral Cortex 15, 1089-1102.

Keysers, C., Kaas, J.H., Gazzola, V., 2010. Somatosensation in social perception. Nature Reviews Neuroscience 11, 417-428.

Kilner, J.M., 2011. More than one pathway to action understanding. Trends in Cognitive Sciences 15, 352-357.

Kilner, J.M., Marchant, J.L., Frith, C.D., 2009. Relationship between activity in human primary motor cortex during action observation and the mirror neuron system. PLoS ONE 4(3): e4925. DOI: 10.1371/journal.pone.0004925

Koski, L., Iacoboni, M., Dubeau, M.-C., Woods, R.P., Mazziotta, J.C., 2003. Modulation of cortical activity during different imitative behaviors. Journal of Neurophysiology 89, 460-471.

Kovacs, A.J., Boyle, J., Grutmatcher, N., Shea, C.H., 2010. Coding of on-line and pre-planned movement sequences. Acta Psychologica 133, 119–126.

Lau, H.C., Rogers, R.D., Ramnani, N., Passingham, R.E., 2004. Willed action and attention to the selection of action. Neuroimage 21, 1407–1415.

Leff, D.R., Elwell, C.E., Orihuela-Espina, F., Atallah, L., Delpy, D.T., Darzi, A.W., Yan, G.Z., 2008. Changes in prefrontal cortical behaviour depend upon familiarity on a bimanual co-ordination task: An fNIRS study. NeuroImage 39, 805-813.

Mahon, B.Z., Caramazza, A., 2008. A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. Journal of Physiology – Paris 102, 59-70.

Malfait, N., Valyear, K.F., Culham, J.C., Anton, J.L., Brown, L.E., Gribble, P.L., 2010, fMRI activation during observation of others' reach errors. Journal of Cognitive Neuroscience 22, 1493-1503.

Maslovat, D., Hayes, S.J., Horn, R.R., Hodges, N.J., 2010. Motor learning through observation. In: Elliott, D., Khan, M. (Eds.), Vision and Goal-Directed Movement: Neurobehavioral Perspectives. Human Kinetics, Champaign, pp. 315–339.

Mattar, A.G., Gribble, P.L., 2005. Motor learning by observation. Neuron 46, 153-160.

McNamara, A., Buccino, G., Menz, M.M., Gläscher, J., Wolbers, T., Baumgärtner, A., Binkofski, F., 2008. Neural dynamics of learning sound-action associations. PLoS ONE 3(12): e3845. DOI: 10.1371/journal.pone.0003845

Middleton, F.A., 2009. The contribution of anterior cingulate-basal ganglia circuitry to complex behavior and psychiatric disorders. In: Vogt, B.A. (Ed.), Cingulate Neurobiology and Disease. Oxford: Oxford University Press, pp. 619-632.

Milton, J., Solodkin, A., Hlustik, P., Small, S., 2007. The mind of expert motor performance is cool and focused. NeuroImage 35, 804-813.

Morecraft, R.J., Tanji, J., 2009. Cingulofrontal interactions and the cingulate motor areas. In: Vogt, B.A. (Ed.), Cingulate Neurobiology and Disease. Oxford: Oxford University Press, pp. 113-144.

Nummenmaa, L., Passamonti, L., Rowe, J., Engell, A.D., Calder, A.J., 2010. Connectivity analysis reveals a cortical network for eye gaze perception. Cerebral Cortex 20, 1780-1787.

Nyberg, L., Eriksson, J., Larsson, A., Marklund, P., 2006. Learning by doing versus learning by thinking: An fMRI study of motor and mental training. Neuropsychologia 44, 711-717.

Orgs, G., Dombrowski, J.H., Heil, M., Jansen-Osmann, P., 2008. Expertise in dance modulates alpha/beta event-related desynchronization during action observation. European Journal of Neuroscience 27, 3380–3384.

Palomero-Gallagher, N., Vogt, B.A., Schleicher, A., Mayberg, H.S., Zilles, K., 2009. Receptor architecture of human cingulate cortex: Evaluation of the four-region neurobiological model. Human Brain Mapping 30, 2336-2355.

Panzer, S., Krueger, M., Muehlbauer, T., Kovacs, A.J., Shea, C.H., 2009. Inter-manual transfer and practice: Coding of simple motor sequences. Acta Psychologica 131, 99–109.

Peelen, M.V., Downing, P.E., 2005. Within-subject reproducibility of category-specific visual activation with functional MRI. Human Brain Mapping 25, 402-408.

Peelen, M.V., Downing, P.E., 2007. The neural basis of visual body perception. Nature Reviews Neuroscience 8, 636-648.

Redgrave, P., Rodriguez, M., Smith, Y., Rodriguez-Oroz, M.C., Lehericy, S., Bergman, H., Agid, Y., DeLong, M.R., Obeso, J.A., 2010. Goal-directed and habitual control in the basal ganglia: implications for Parkinson’s disease. Nature Reviews Neuroscience 11, 760–772.

Rizzolatti, G., Sinigaglia, C., 2010. The functional role of the parieto-frontal mirror circuit: Interpretations and misinterpretations. Nature Reviews Neuroscience 11, 264-274.

Roebroek, A., Formisano, E., Goebel, R., 2005. Mapping directed influence over the brain using Granger causality and fMRI. NeuroImage 25, 230-242.

Rosenthal, R., Rosnow, R.L., 1985. Contrast analysis: Focused comparisons in the analysis of variance. Cambridge: Cambridge University Press.

Rowe, J.B., Passingham, R.E., 2001. Working memory for location and time: Activity in Prefrontal area 46 relates to selection rather than maintenance in memory. Neuroimage 14, 77-86.

Rowe, J.B., Hughes, L., Nimmo-Smith, I., 2010. Action selection: A race model for selected and non-selected actions distinguishes the contribution of premotor and prefrontal areas. NeuroImage 51, 88-896.

Schippers, M.B., Keysers, C., 2011. Mapping the flow of information within the putative mirror neuron system during gesture observation. NeuroImage 57, 37-44.

Shallice, T., 2004. The fractionation of supervisory control. In: Gazzaniga, M.S. (Ed.), The Cognitive Neurosciences, Third edition. MIT Press, Cambridge, MA, pp. 943-956.

Shea, C.H., Kovacs, A.J., Panzer, S., 2011. The coding and inter-manual transfer of movement sequences. Frontiers in Psychology, 2, 52. DOI: 10.3389/fpsyg.2011.00052

Stefan, K., Cohen, L. G., Duque, J., Mazzocchio, R., Celnik, P., Sawaki, L., Ungerleider, L. and Classen, J., 2005. Formation of a motor memory by action observation. Journal of Neuroscience 25, 9339-9346.

Stefan, K., Classen, J., Celnik, P., Cohen, L.G., 2008. Concurrent action observation modulates practice-induced motor memory formation. European Journal of Neuroscience 27, 730-738.

Tkach, D. Reimer, J., Hatsopoulos, N.G., 2007. Congruent activity during action and action observation in motor cortex. Journal of Neuroscience 28, 13241-13250.

Torriero, S., Oliveri, M., Koch, G., Caltagirone, C., Petrosini, L., 2007. The what and how of observational learning. Journal of Cognitive Neuroscience 19, 1656-1663.

van der Helden, J., van Schie H.T., Rombouts, C., 2010. Observational learning of new movement sequences is reflected in fronto-parietal coherence. PLoS ONE 5(12): e14482. DOI: 10.1371/journal.pone.0014482

Vogt, B.A., 2009. Regions and subregions of the cingulate cortex. In: Vogt, B.A. (Ed.), Cingulate Neurobiology and Disease. Oxford: Oxford University Press, pp. 3-30.

Vogt, S., 1995. On relations between perceiving, imagining and performing in the learning of cyclical movement sequences. British Journal of Psychology 86, 191-216.

Vogt, S., 2002. Visuomotor couplings in object-oriented and imitative actions. In A. N. Meltzoff and W. Prinz (Eds.), The Imitative Mind: Development, Evolution, and Brain Bases. Cambridge: Cambridge University Press, pp. 206-220.

Vogt, S., Buccino, G., Wohlschläger, A.M., Canessa, N., Shah, N., Zilles, K., Eickhoff, S.B., Freund, H.-J., Rizzolatti, G., Fink, G.R., 2007. Prefrontal involvement in imitation learning of hand actions: Effects of practice and expertise. NeuroImage 37, 1371-1383.

Vogt, S., Thomaschke, R., 2007. From visuo-motor interactions to imitation learning: Behavioural and brain imaging studies. Journal of Sports Sciences 25, 497-517.

Figure captions

Figure 1: Sequence of stimuli in the imitation and observation scanning sessions. Except for the condition cue, the stimulus presentation was identical in both conditions: First, a picture of the model’s hand in rest position was shown for 1 second (IMI: green cue; OBS: red cue). Second, a chord picture was shown for 3 seconds (main event). Third, the model’s hand was shown again in the rest position (jittered durations), followed immediately by the next trial. In the imitation block, participants were asked to imitate the chord picture as quickly and precisely as possible using their left hand, and to move their fingers back to the rest position in time with the appearance of the rest stimulus. In the observation block, participants were asked to carefully observe the chord picture and to imagine motor execution without any overt movement.

Figure 2: Mean response times for all chord types during scanning, averaged across the two imitation blocks on each scanning day. The error bars show the standard error of the mean. Response times were assessed via video recordings and were measured from chord display onset to stable finger positioning on the fretboard.

Figure 3*: Activations during chord observation (OBS blocks). Panel A: Conjunction between observation of PP-, OP-, and NP-chords on Day 2, indicating common activations in the OBS block (for peak coordinates see Table 1). The contrast estimates (right panels) illustrate the activation trends between chord types and across days for inferior parietal lobule (IPL) and ventral premotor cortex (PMv).

Panel B: Direct contrasts between observation of non-practised and practised chords on Day 4. Yellow areas: NP>(PP+OP), inclusively masked with NP; for peak coordinates see supplemental Table S1. Red areas: NP>PP only (inclusively masked with NP); blue areas: NP>OP only (inclusively masked with NP).

Panel C: Direct contrast between observation of OP- vs. PP-chords on Day 4 (OP>PP, inclusively masked with OP); for peak coordinates see text. The contrast estimates (right panels) illustrate the activation trends between chord types and across days for the cerebellum and anterior midcingulate cortex (aMCC).

Panel D: Activations during observation of non-practised chords, averaged across days and correlated separately with performance gains by observational practice and with performance gains by physical practice. Index ‘NP-OP’ stands for (NP2-OP2)+(NP4-OP4), and index ‘NP-PP’ stands for (NP2-PP2)+(NP4-PP4). For peak coordinates see supplemental Table S2. Although the activations in IPL, SMA, and superior occipital gyrus were significantly correlated with only one of the two indices, we also found (weaker) positive correlations for these regions when using the other index. We thus regard the apparent differences between the indices largely as the result of thresholding.

Figure 4*: Activations during chord imitation (IMI blocks). Panel A: Conjunction between imitation of PP-, OP-, and NP-chords on Day 2, indicating common activations in the IMI blocks (for peak coordinates see Table 2). The contrast estimates (right panels) illustrate the activation trends between chord types and across days for IPL, PMv, and rostral MFG. For reasons of comparability, and since localisation was less contaminated by execution-related activations in the OBS blocks, the contrast estimates for IPL and PMv refer to the same coordinates as those in Fig. 3A.

Panel B: Direct contrast between imitation of non-practised and practised chords on Day 4. Yellow areas: NP>(PP+OP), inclusively masked with NP; for peak coordinates see supplemental Table S3. Red areas: NP>PP only (inclusively masked with NP); blue areas: NP>OP only (inclusively masked with NP).

Panel C: Differences between OP- and PP-chords in the IMI and OBS conditions on Day 4. Red areas: Direct contrast between imitation of OP- vs. PP-chords (OP>PP, inclusively masked with OP). Yellow areas: Interaction of practice type (OP, PP) by session type (IMI, OBS), masked by OP>PP in the IMI condition. The interaction indicates regions of stronger differences between the chord types in the IMI condition compared to the OBS condition (for peak coordinates see supplemental Table S4).

Panel D: Reduced activations between Days 2 and 4 that occurred for the PP-chords but not of the OP-chords (IMI_PP2 > IMI_PP4, exclusively masked by IMI_OP2 > IMI_OP4). The leftmost panel shows sections at X=10 and Z=6. Differential activations were only found in the right hemisphere. The contrast estimates (right panels) illustrate the activation trends between chord types and across days for the posterior midcingulate cortex (pMCC), putamen, inferior parietal lobule (IPL), and BA 44.

Figure 5*: Effective connectivity between seed regions in left MFG (red circle: rostral MFG at -28, 52, 18; blue circle: caudal MFG at -32, 38, 32) and the sectors of the FPMC in parietal areas PF (plus PG and intraparietal cortex), as well as BA 44 and adjacent (pre-)motor cortex during action imitation on Day 2 (dark dots) and Day 4 (bright dots; for peak coordinates see supplemental Table S5). Connectivity to other regions is not shown (for the whole-brain renderings, see supplemental Fig. S1). Chord complexity was used as the psychological variable, operationalised as (PP+OP)>S-chord.

* Figures 3 to 5 are intended for colour reproduction on the Web and in print.

8. Table

Table 1. Common activations during observation of PP-, OP-, and NP-chords on Day 2 (conjunction for OBS condition). Local maxima of activated areas as shown in Fig. 3A, given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=54 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas]

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Precentral gyrus (PMv)	-54	6	30	4.36	20% BA 6	54	6	32	4.62	10% BA 6
Superior frontal gyrus (PMd)	-26	-8	56	7.73	30% BA 6	32	-8	58	6.65	20% BA 6
Postcentral gyrus	-42	-38	52	7.04	60% BA 2 *	36	-38	50	6.84	100% BA 2 *
Inferior parietal lobule	-52	-26	40	5.43	70% BA 2 * 60% PFt	42	-30	38	6.26	50% PFt *
Superior parietal lobule	-22	-56	58	8.23	40% SPL 7A *	28	-50	64	8.06	20% SPL 7PC *
	-16	-72	54	7.32	50% SPL 7A *	16	-66	60	7.61	50% SPL 7P *
Superior occipital gyrus	-20	-68	38	5.62		28	-78	40	7.23	10% SPL 7P
Middle occipital gyrus	-32	-88	18	6.71		34	-84	24	6.93	
	-18	-100	8	7.10	50% BA18 *	34	-78	16	6.88	
	-42	-82	6	7.53	10% hOC5 (V5)					
Inferior occipital gyrus	-34	-90	-6	6.66	50% hOC4v (V4) *	38	-88	-2	8.20	20% hOC4v (V4)
Occipito-temporal cortex (EBA)	-42	-80	-6	7.38	10% hOC4v (V4)	48	-70	-2	8.50	40% hOC5 (V5) *
Calcarine fissure / Lingual gyrus	0	-88	-4	4.52	100% BA 17 *	6	-90	-6	4.75	80% BA 17 *
	-12	-94	-10	4.64	60% BA 18 *	18	-84	-10	4.93	80% BA 18 *

Fusiform gyrus	-34	-78	-14	6.55	40% hOC4v (V4) *	28	-78	-16	6.26	50% hOC4v (V4) *
	-36	-60	-20	5.96		38	-60	-18	6.79	
Cerebellum	-24	-54	-52	4.04	60% lobule VIIIb *					
	-16	-52	-50	4.36	54% lobule IX					

8. Table

Table 2. Common activations during imitation of PP-, OP-, and NP-chords on Day 2 (conjunction for IMI condition). Local maxima of activated areas as shown in Fig. 4A, given in MNI standard brain coordinates at voxel-level $p_u<0.0001$, cluster-level $p_u<0.05$, k=54 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas]

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Middle frontal gyrus (caudal)	-32	38	32	6.71		38	36	30	7.73	
Middle frontal gyrus (rostral)	-28	52	18	4.61		36	42	20	6.57	
Precentral gyrus (PMv)	-52	0	38	8.51	30% BA 6	56	6	34	8.64	40% BA 6 *
Inferior frontal gyrus (pars opercularis)	-56	4	26	8.72	30% BA 44 *	54	8	12	8.26	40% BA 44 *
Superior frontal gyrus (PMd)	-24	-12	62	9.21	50% BA 6 *	32	-16	66	9.48	80% BA 6 *
Supplementary motor area	-2	-6	58	9.26	80% BA 6 *	6	-2	52	9.29	80% BA 6 *
Midcingulate cortex (pMCC)	-8	10	42	8.85		2	10	30	7.23	
Precentral gyrus (M1)						36	-32	58	9.27	60% BA 3b * 40% BA 4p
Postcentral gyrus	-40	-30	46	9.16	60% BA 2 *	28	-48	64	8.66	60% BA 2 *
	-30	-46	58	9.15	50% BA 1 *	44	-28	60	9.22	90% BA 1 *
						36	-32	58	9.27	60% BA 3b *
Inferior parietal lobule						54	-22	24	8.37	40% PFop *
Parietal operculum (SII)	-60	-18	22	8.35	50% OP1 *	44	-28	18	6.31	80% OP1 *

Superior parietal lobule	-20	-56	62	8.81	70% SPL 7A *	18	-58	60	7.97	90% SPL 7A *
Precuneus						22	-56	24	6.42	
Middle occipital gyrus	-28	-72	28	7.15		30	-78	36	7.42	10% SPL 7A
	-26	-92	8	8.10	10% BA 18	34	-82	24	7.47	10% PGp
	-40	-88	0	8.47	10% hOC4v (V4)	30	-90	12	8.29	10% BA 18
						42	-74	20	7.39	30% PGp
Inferior occipital gyrus	-36	-88	-6	8.32	50% hOC4v (V4) *	42	-80	-2	8.83	
Occipito-temporal cortex (EBA)	-46	-78	-4	8.62		48	-72	0	8.96	30% hOC5 (V5)
Inferior temporal gyrus						44	-58	-10	8.31	10% hOC5 (V5)
Calcarine fissure	-6	-72	14	5.35	40% BA 17 *	22	-62	4	7.48	80% BA 17 *
	-20	-64	4	7.06	60% BA 17 *	0	-88	-6	7.38	90% BA 17 *
Fusiform gyrus	-36	-74	-16	8.05	50% hOC4v (V4) *	34	-68	-10	7.95	30% hOC4v (V4)
						40	-50	-16	8.56	
Pallidum	-22	0	2	8.97		26	-4	2	8.72	
Putamen	-22	10	2	8.90		26	6	-8	8.74	
Thalamus	-12	-16	2	8.53		14	-16	2	8.81	
Cerebellum	-16	-48	-26	9.15	9% lobule V					
	-30	-46	-30	8.96	86% lobule VI *	24	-52	-24	9.07	95% lobule VI *
	-14	-56	-52	8.03	52% lobule IX	26	-56	-54	7.84	67% lobule VIIIa *

8. Table

Table Supplement 1. Observation of non-practised vs. practised chords on Day 4 (NP>(PP+OP), OBS condition, inclusively masked by observation of NP-chords. Local maxima of activation differences as shown in Fig. 3B (yellow blobs), given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=54 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas]

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Precentral gyrus (PMv)	-52	-2	48	4.17	100% BA 6 *	48	8	30	5.90	30% BA 44
	-42	-2	34	4.09	10% BA 6					
Superior frontal gyrus (PMd)	-26	-6	58	4.12	30% BA 6	34	-6	64	4.54	30% BA 6
Postcentral gyrus	-42	-36	52	4.73	50% BA 2	44	-38	52	5.90	50% BA 2 *
Inferior parietal lobule	-48	-18	30	4.32	50% PFt *	50	-28	48	5.50	60% PFt 60% BA 2 *
Intraparietal sulcus						36	-42	44	5.42	40% hIP1 *
Angular gyrus						34	-72	40	6.65	30% PGp
Superior parietal lobule	-20	-58	54	4.26	60% SPL 7A *	14	-70	54	5.85	60% SPL 7P *
						30	-56	62	4.34	40% SPL 7A *
Middle occipital gyrus	-28	-84	28	4.04		32	-78	20	4.38	
	-24	-88	10	3.92						
Inferior occipital gyrus	-32	-82	-8	4.49	40% hOC4v (V4) *					
Occipito-temporal cortex (EBA)	-44	-66	-12	4.47		48	-66	-4	4.98	20% hOC5 (V5)

Middle temporal gyrus						54	-54	-2	5.26	
						48	-62	12	4.63	10% hOC5 (V5)
Inferior temporal gyrus						46	-54	-16	5.23	
						46	-32	-20	4.39	
Calcarine fissure						28	-60	0	4.43	60% BA 17 *
						24	-56	6	3.93	60% BA 18 *
Fusiform gyrus	-40	-60	-14	4.87		30	-64	-4	4.51	10% BA 18
						36	-50	-16	5.05	
Hippocampus	-20	-32	-4	3.72	20% Hipp (SUB)	20	-36	-4	5.17	70% Hipp (SUB) *
						20	-8	-28	4.42	70% Hipp (EC) *
Thalamus						14	-22	6	3.69	
Cerebellum	-24	-68	-48	5.66	74% lobule VIIb *	22	-34	-24	4.23	67% lobule V *
	-12	-76	-22	5.42	89% lobule VI *					
	-26	-50	-54	3.81	50% lobule VIIIa *					

Table Supplement 2. Correlations between functional data (observation of non-practised chords, averaged across Days 2 and 4) and behavioural benefits of observational and physical practice (Panels A and B, respectively); for behavioural scores, see text. Local maxima of activated areas as shown in Fig. 3D, given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=37 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas]

A) Correlation between functional data and behavioural benefits of observational practice (index ‘NP-OP’)

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Middle frontal gyrus	-26	56	30	3.98		36	54	22	4.10	
						50	48	6	4.20	
Insula						52	12	-6	3.98	
Superior parietal lobule	-4	-58	64	3.96	50% SPL 7A	4	-56	64	4.09	40% SPL 5M *
Superior occipital gyrus	-24	-86	40	4.13						
Inferior temporal gyrus	-50	-44	-12	4.06						
Putamen						24	16	2	3.69	
Thalamus	-14	-10	12	3.66		20	-28	12	3.43	
Cerebellum	-36	-70	-28	3.78	100% lobule VIIa *					
	-16	-76	-36	3.78	79% lobule VIIa *	10	-78	-38	3.61	45% lobule VIIa *
	-28	-68	-46	3.56	45% lobule VIIb *					
	-18	-44	-54	4.22	78% lobule VIIIb *					

B) Correlation between functional data and behavioural benefits of physical practice (index ‘NP-PP’)

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Middle frontal gyrus	-28	60	18	4.07		36	56	22	4.14	
						40	36	44	3.65	
Supplementary motor area						14	-6	56	4.17	40% BA 6
Insula						52	14	-4	3.68	20% BA 44
Inferior parietal lobule						60	-32	30	4.61	80% PF *
Superior parietal lobule	-4	-58	62	3.51	40% SPL 7A	6	-50	56	3.93	40% SPL 5M *
Putamen						24	16	2	3.88	
Thalamus	-14	-10	12	3.31		16	-10	12	3.25	
Cerebellum	-20	-46	-54	3.91	87% lobule VIIIb *					

8. Table

Table Supplement 3. Imitation of non-practised vs. practised chords on Day 4 (NP>(PP+OP), IMI condition, inclusively masked by imitation of NP-chords). Local maxima of activation differences as shown in Fig. 4B (yellow blobs), given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=64 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas]

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Precentral gyrus (PMv)	-36	0	30	4.98		40	4	30	5.74	10% BA 6
	-56	14	38	3.76	30% BA 44					
Inferior frontal gyrus	-38	14	26	5.17	30% BA 44	44	30	18	5.87	20% BA 45
	-46	16	8	4.28	40% BA 44 *	42	24	4	4.07	50% BA 45 *
Precentral gyrus (PMd)	-34	-6	50	4.22	20% BA 6	34	-8	50	3.70	50% BA 6 *
Supplementary motor area	-6	10	46	4.73	20% BA 6	8	16	54	5.97	30% BA 6
Midcingulate cortex (aMCC)						10	20	36	4.48	
Insula	-32	18	-10	4.94						
Postcentral gyrus	-46	-38	50	3.92	60% BA 2 *					
Intraparietal sulcus	-44	-40	46	3.83	20% hIP3	34	-44	44	4.27	30% hIP3 *
Angular gyrus	-34	-82	26	6.47	30% PGp	42	-76	20	6.64	50% PGp *
Superior parietal lobule	-20	-70	46	4.53	30% SPL 7A *	26	-68	48	5.63	10% SPL 7A
	-36	-46	48	4.50	20% SPL 7PC *	18	-74	54	4.49	70% SPL 7P *

Superior occipital gyrus	-22	-72	34	5.07	10% SPL 7A	24	-88	28	5.25	
Middle occipital gyrus	-32	-86	20	5.78		34	-82	24	7.18	10% PGp
	-38	-88	4	6.36	20% hOC3v (V3v)					
Inferior occipital gyrus						34	-82	-6	5.42	30% hOC4v (V4)
Occipito-temporal cortex (EBA)	-44	-68	-6	6.66	10% hOC5 (V5)	48	-68	-4	6.19	40% hOC4v (V4) *
Middle temporal gyrus						58	-60	6	6.16	10% PGp
Inferior temporal gyrus						42	-58	-10	7.02	
Calcarine fissure	-6	-98	-2	5.18	80% BA 17 *	14	-94	-4	5.81	80% BA 17 *
Cuneus						12	-100	12	5.41	60% BA 18 *
Fusiform gyrus	-40	-50	-18	5.92		40	-48	-14	8.04	
Amygdala	-26	-2	-26	3.99	90% LB *	36	-4	-18	3.89	30% LB
Pallidum	-16	-2	6	3.89						
Thalamus	-4	-12	0	4.11		10	-12	-2	4.86	

8. Table

Table Supplement 4. Differences between OP- and PP-chords in the IMI and OBS conditions on Day 4. Panel A: Interaction of practice type (OP, PP) by session type (IMI, OBS), inclusively masked by OP4>PP4 in the IMI condition, indicating regions of stronger differences between the chord types in the IMI condition compared to the OBS condition. Local maxima of activated areas as shown in Fig. 4C (yellow blobs), given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=54 voxels. Panel B: Additional activations in the contrast OP4>PP4 for the IMI condition, inclusively masked by OP4. Local maxima of activated areas as shown in Fig. 4C (red blobs), given in MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=64 voxels [ATB: most probable anatomical region in the Anatomy Toolbox 1.7, Eickhoff et al., 2005; asterisks (*) denote assigned areas].

A) Interaction: practice (OP, PP) x session (IMI, OBS)

	Left					Right				
Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Precentral gyrus (PMv)	-40	-2	38	4.42	10% BA 6					
Inferior frontal gyrus (pars opercularis)	-44	6	24	3.88	50% BA 44 *	48	10	16	3.69	50% BA 44 *
						50	18	4	4.15	40% BA 45 *
Superior frontal gyrus (PMd)	-28	-10	46	3.95	10% BA 6	26	0	52	4.28	10% BA 6
	-22	-12	70	3.72	70% BA 6	18	2	62	3.76	30% BA 6
Supplementary motor area	-10	12	46	5.46	20% BA 2					
Midcingulate cortex (aMCC)	-8	24	28	3.90		10	20	44	3.34	
						8	16	40	4.73	10% BA 6
Insula	-30	24	0	5.94		32	20	4	4.55	
Postcentral gyrus	-44	-32	50	4.87	70% BA 2 *	50	-26	44	4.03	70% BA 2 *
						56	-18	44	3.83	70% BA 1 *
						46	-18	40	3.73	60% BA 3b *

Intraparietal sulcus	-38	-42	48	4.37	40% hIP3 *	42	-34	40	3.80	30% hIP2 *
Inferior parietal lobule	-46	-26	36	3.52	40% PFt *	54	-34	52	3.35	50% PF *
Angular gyrus	-30	-80	36	4.07	20% PGp	36	-74	38	4.51	60% PGp *
Superior parietal lobule	-20	-52	56	5.38	40% SPL 7A *	12	-62	58	4.42	70% SPL 7A *
	-34	-46	58	5.50	60% SPL PC *	22	-66	54	3.99	40% SPL 7P *
Thalamus	-8	-18	6	3.86						
	-8	-10	12	3.59						

B) Activations, additional to those shown in Panel A, for imitation OP4>PP4

Anatomical region	x	y	z	Z-score	ATB	x	y	z	Z-score	ATB
Middle frontal gyrus (caudal)	-40	30	30	3.98	20% BA 45	42	34	32	3.83	
Middle frontal gyrus (rostral)	-34	50	32	4.22	(k=55 voxel, p_u=0.065)					
Precentral gyrus (PMv)	(-40	-2	38	4.69	10% BA 6)	48	4	34	3.69	10% BA 6
Inferior parietal lobule	-62	-28	32	3.98	60% PF *	52	-28	42	4.54	80% PFt *
Occipito-temporal cortex (EBA)	-44	-78	-4	3.45		48	-64	-4	3.46	10% hOC5 (V5)
Middle temporal gyrus						48	-58	8	3.85	PGp 10%
Inferior temporal gyrus	-48	-68	-10	3.89		50	-56	-12	4.13	
Cerebellum						4	-64	-14	4.23	49% lobule V *
						6	-64	-18	4.07	59% lobule VI *

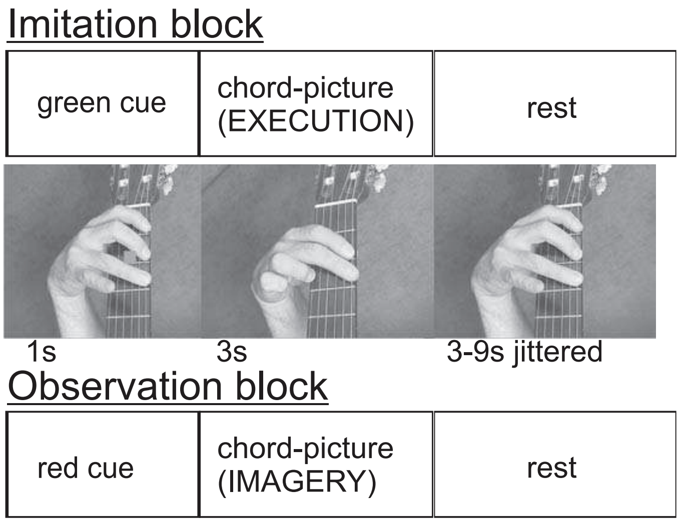
8. Table

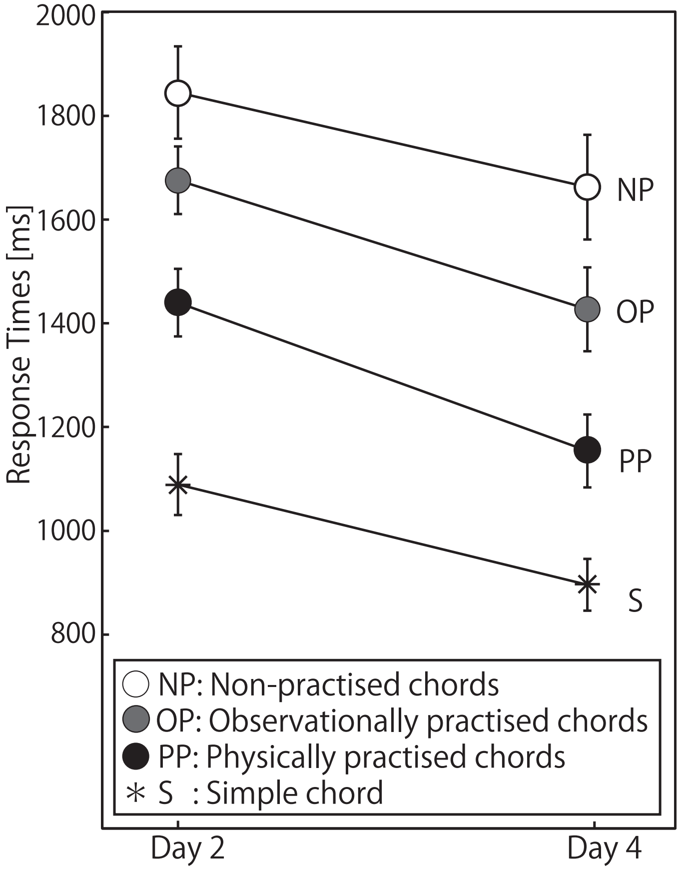
Table Supplement 5. Peak coordinates of effective connectivity between seed regions in left MFG (rostral MFG at -28, 52, 18; caudal MFG at -32, 38, 32) and target regions in inferior parietal cortex (IPL/PF, PG, plus hIP), as well as BA 44 and adjacent (pre-)motor cortex during action imitation on Days 2 and 4, as illustrated in Fig. 5. Only peak coordinates in the above anatomical sites are shown, as defined by the Anatomy Toolbox 1.7 (Eickhoff et al., 2005). For PMv, 15mm spheres were used as target regions with center coordinates of -54, 6, 30 and 54, 6, 32 (see Table 1). Chord complexity was used as the psychological variable, operationalised as (PP+OP)>S-chords. The table shows MNI standard brain coordinates at voxel-level $p_u<0.001$, cluster-level $p_u<0.05$, k=52 voxels. Z-scores are given in brackets, followed by the most probable anatomical region(s) in the Anatomy Toolbox. Asterisks (*) denote assigned areas.

	left IPL	right IPL	left BA 44 and PMv	right BA 44 (PMv n.a.) *cont'd*
Left rostral MFG				
Day 2	-60 -44 24 (4.06) 60% PF *	56 -34 26 (4.44) 60% PFcm * 30% PF	-	-
Day 4	-58 -52 28 (3.82) 40% PF *	-	-42 16 34 (3.77) 20% BA 44	52 16 10 (3.67) 50% BA 44 *
Left caudal MFG				
Day 2	-58 -48 22 (3.70) 50% PF *	62 -32 24 (3.77) 60% PF *	-44 14 28 (3.74) 70% BA 44 *	44 10 16 (3.40) 30% BA 44
		64 -22 36 (3.90) 70% PFt *		
	-40 -60 38 (4.54) 20% PFm *	46 -52 54 (4.27) 60% PFm *	-44 2 20 (3.55) Precent. gyrus (PMv) 10% BA 44	
		54 -38 48 (4.01) 70% PF *		
Day 4	-58 -52 30 (3.85) 60% PFm * 40% PF	-	-54 12 22 (3.29) 50% BA 44 *	52 10 6 (3.74) 40% BA 44 *
			-46 16 36 (3.75) 40* BA 44 *	

Table Supplement 5 *(continued)*

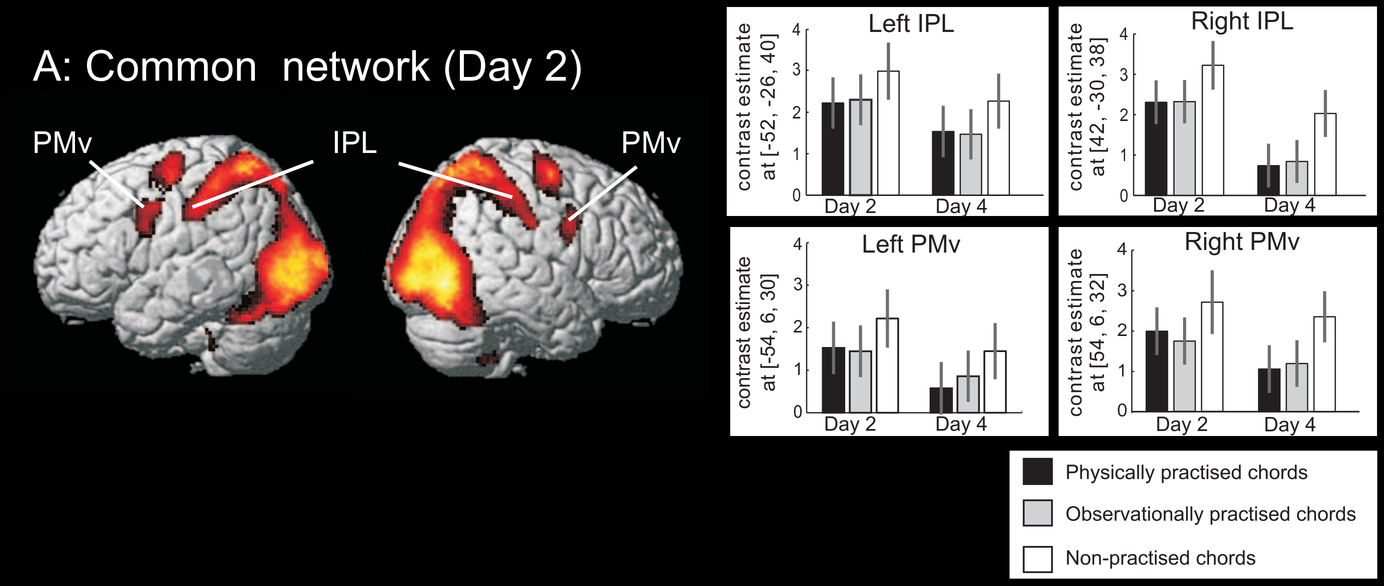
	left PG and hIP	right PG and hIP
Left rostral MFG		
Day 2	-	62 -54 24 (4.81) 90% PGa *
Day 4	-	-
Left caudal MFG		
Day 2	-36 -64 44 (3.76) 40% PGa *	44 -60 50 (4.16) 40% PGa *
	-36 -50 36 (4.05) 50% hIP1 *	50 -36 40 (3.66) 30% hIP2 *
		62 -54 22 (3.78) 90% PGa *
Day 4	-40 -52 50 (3.50) 40% hIP1 *	-


Imitation block
green cue
chord-picture (EXECUTION)
rest
1s
3s
3-9s jittered
Observation block
red cue
chord-picture (IMAGERY)
rest


2000
1800
1600
1400
1200
1000
800
Response Times [ms]
NP
OP
PP
S
Day 2
Day 4
○ NP: Non-practised chords
● OP: Observationally practised chords
● PP: Physically practised chords
∗ S : Simple chord

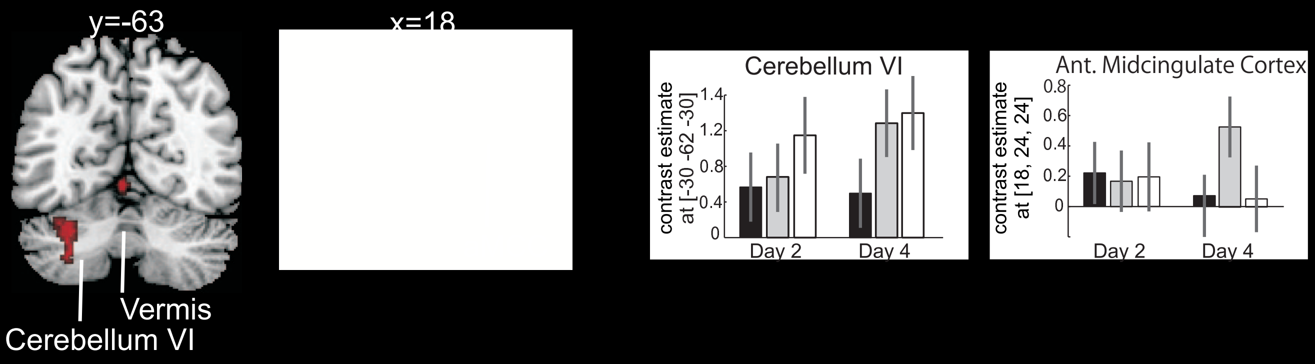
ACTIVATIONS DURING CHORD OBSERVATION

A: Common network (Day 2)

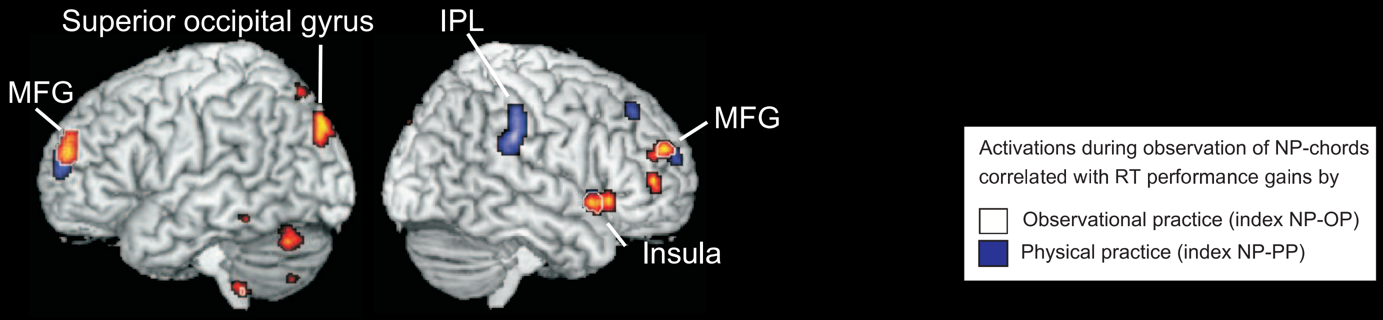


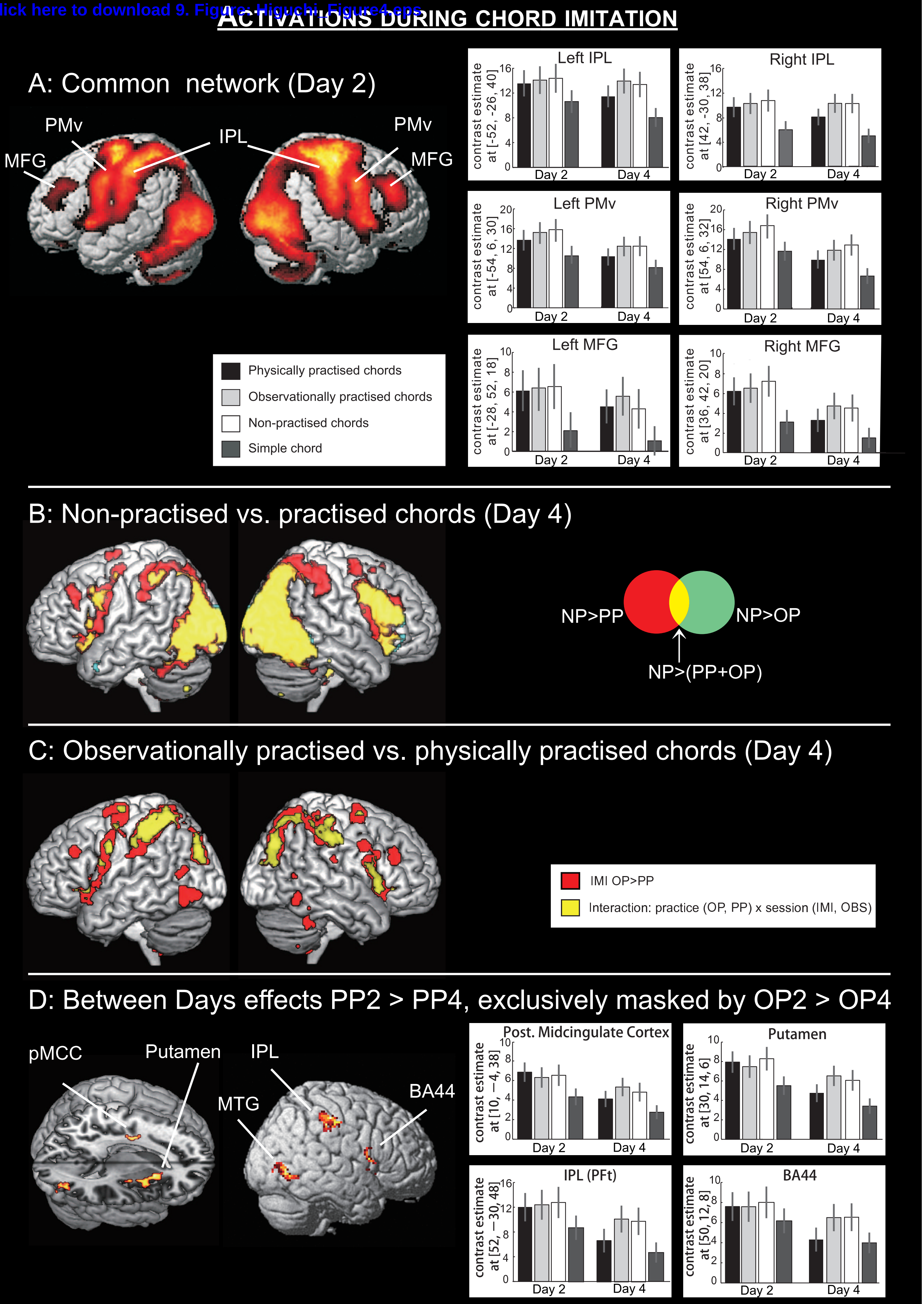
B: Non-practised vs. practised chords (Day 4)

C: Observationally practised vs. physically practised chords (Day 4)



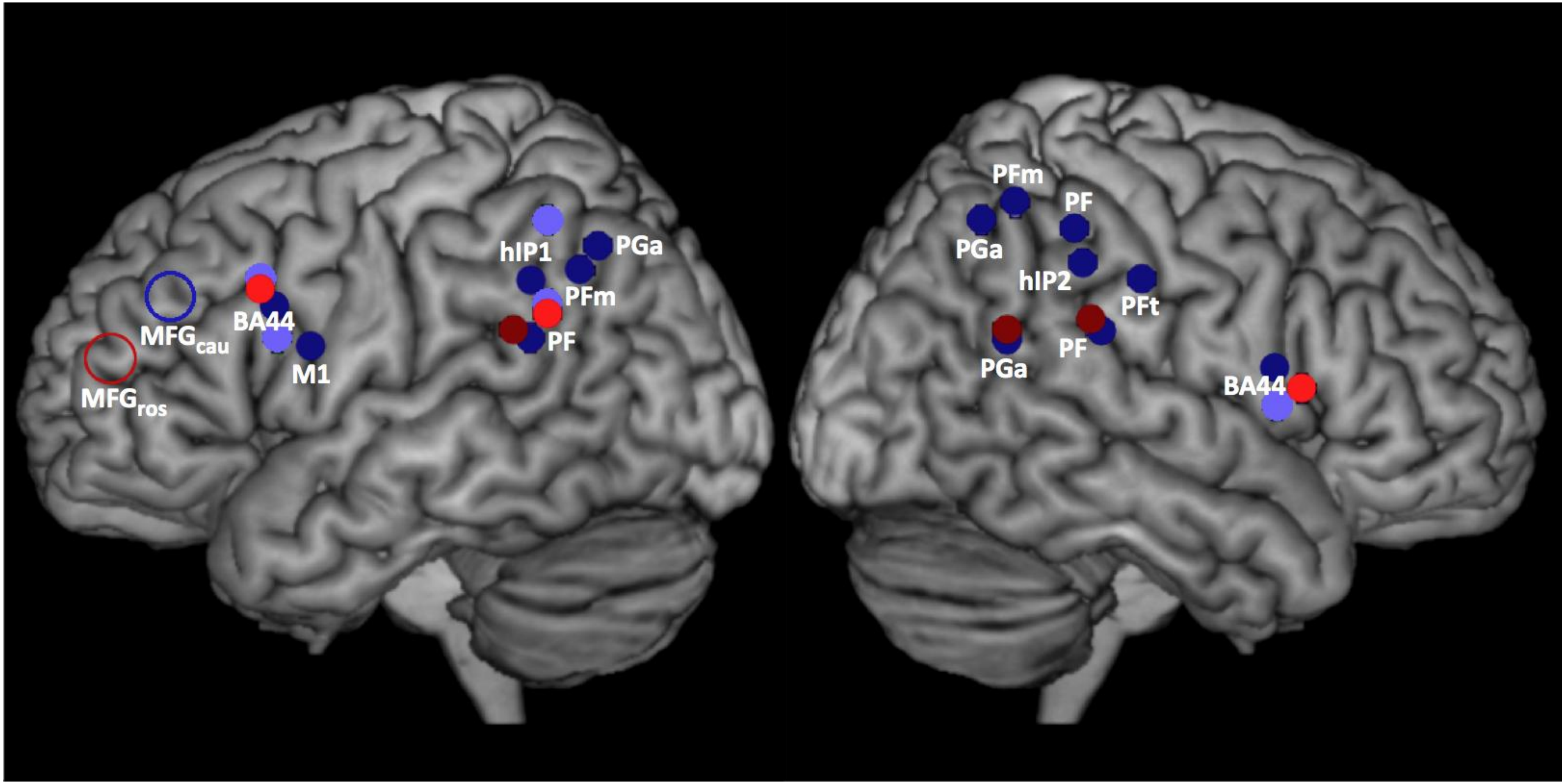
D: Correlation between functional and behavioural data




ACTIVATIONS DURING CHORD IMITATION
A: Common network (Day 2)
PMv
IPL
PMv
MFG
MFG
Left IPL
contrast estimate at [-52, -26, 40]
Right IPL
contrast estimate at [42, -30, 38]
Left PMv
contrast estimate at [-54, 6, 30]
Right PMv
contrast estimate at [54, 6, 32]
Left MFG
contrast estimate at [-28, 52, 18]
Right MFG
contrast estimate at [36, 42, 20]
Day 2
Day 4
Physically practised chords
Observationally practised chords
Non-practised chords
Simple chord
B: Non-practised vs. practised chords (Day 4)
NP>PP
NP>OP
NP>(PP+OP)
C: Observationally practised vs. physically practised chords (Day 4)
IMI OP>PP
Interaction: practice (OP, PP) x session (IMI, OBS)
D: Between Days effects PP2 > PP4, exclusively masked by OP2 > OP4
pMCC
Putamen
IPL
MTG
BA44
Post. Midcingulate Cortex
contrast estimate at [10, −4, 38]
Putamen
contrast estimate at [30, 14, 6]
IPL (PFt)
contrast estimate at [52, −30, 48]
BA44
contrast estimate at [50, 12, 8]
Day 2
Day 4

9. Figure

Click here to download 9. Figure: Higuchi_Figure5.pptx



10. Supplementary Material

10. Supplementary Material