# RESEARCH ARTICLE | *Control of Movement*

# Ipsilateral finger representations in the sensorimotor cortex are driven by active movement processes, not passive sensory input

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**Berlot E, Prichard G, O'Reilly J, Ejaz N, Diedrichsen J.** Ipsilateral finger representations in the sensorimotor cortex are driven by active movement processes, not passive sensory input. *J Neurophysiol* 121: 418–426, 2019. First published December 5, 2018; doi:10.1152/jn.00439.2018.—Hand and finger movements are mostly controlled through crossed corticospinal projections from the contralateral hemisphere. During unimanual movements, activity in the contralateral hemisphere is increased while the ipsilateral hemisphere is suppressed below resting baseline. Despite this suppression, unimanual movements can be decoded from ipsilateral activity alone. This indicates that ipsilateral activity patterns represent parameters of ongoing movement, but the origin and functional relevance of these representations is unclear. In this study, we asked whether ipsilateral representations are caused by active movement or whether they are driven by sensory input. Participants alternated between performing single finger presses and having fingers passively stimulated while we recorded brain activity using high-field (7T) functional imaging. We contrasted active and passive finger representations in sensorimotor areas of ipsilateral and contralateral hemispheres. Finger representations in the contralateral hemisphere were equally strong under passive and active conditions, highlighting the importance of sensory information in feedback control. In contrast, ipsilateral finger representations in the sensorimotor cortex were stronger during active presses. Furthermore, the spatial distribution of finger representations differed between hemispheres: the contralateral hemisphere showed the strongest finger representations in Brodmann areas 3a and 3b, whereas the ipsilateral hemisphere exhibited stronger representations in premotor and parietal areas. Altogether, our results suggest that finger representations in the two hemispheres have different origins: contralateral representations are driven by both active movement and sensory stimulation, whereas ipsilateral representations are mainly engaged during active movement.

**NEW & NOTEWORTHY** Movements of the human body are mostly controlled by contralateral cortical regions. The function of ipsilateral activity during movements remains elusive. Using high-field neuroimaging, we investigated how human contralateral and ipsilateral hemispheres represent active and passive finger presses. We found that representations in contralateral sensorimotor cortex are equally strong during both conditions. Ipsilateral representations were mostly present during active movement, suggesting that sensorimotor areas do not receive direct sensory input from the ipsilateral hand.

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finger movements; fMRI; ipsilateral; motor; sensory

## INTRODUCTION

The primate hand is controlled mainly by descending projections from the motor areas in the contralateral cerebral hemisphere (Brinkman and Kuypers 1973). Although the hand also receives input from ipsilateral motor regions through uncrossed corticospinal projections, these projections lack the capacity to produce overt movement (Soteropoulos et al. 2011). If, and to what degree, the ipsilateral hemisphere directly or indirectly contributes to hand movements is currently debated (Chen et al. 1997; Verstynen et al. 2005). It is clear, however, that neural activity in ipsilateral motor regions is modulated during hand movements. Overall, there is a global suppression of activity as evidenced by a reduction in blood oxygen level-dependent (BOLD) signal measured using functional magnetic resonance imaging (fMRI) (Cramer et al. 1999; Verstynen et al. 2005). Below this suppressive effect, there are clear task-specific changes. For example, one can decode the identity of the moved effector (e.g., finger) from ipsilateral activity alone (electrocorticography: Fujiwara et al. 2017; Scherer et al. 2009; fMRI: Diedrichsen et al. 2013). These ipsilateral activity patterns appear to be weaker, but otherwise identical, versions of the pattern elicited by movement of the mirror-symmetric finger in the opposing hand (Diedrichsen et al. 2013, 2017). Altogether, these studies show that the ipsilateral hemisphere represents aspects of finger movements. The origin and functional relevance of these representations, however, remain unclear.

One puzzle regarding the function of these ipsilateral representations is whether they reflect processes involved in active motor planning and execution or whether they are a consequence of reafferent sensory input. In the contralateral hemisphere, passive somatosensory stimulation of individual fingers has been shown to evoke activity patterns that are very similar to those associated with active finger movements (Wiestler et al. 2011). This is even the case on the single-finger level; cortical patches that are especially activated by movement of the index finger are also activated by index finger stimulation.

The tight match between tuning for active and passive conditions is unsurprising given the importance of accurate sensory information for fine movement control (Augurelle et al. 2003; Pruszynski et al. 2016) and is consistent with the characterization of primary motor cortex as a feedback controller (Scott 2004).

In this study we ask whether ipsilateral sensorimotor cortex plays a role in the fine feedback control of finger movements. If so, we should see that ipsilateral representations can also be activated by passive sensory stimulation. Indeed, we would expect that passive finger stimulation recruits ipsilateral finger-specific circuits to approximately the same degree as active finger presses, as they do in the contralateral sensorimotor cortex. Alternatively, if the ipsilateral hemisphere is primarily recruited during movement planning, we would predict that ipsilateral representations are more pronounced during active presses and either weaker or absent during passive finger stimulation.

To test between these two possibilities, we used high-field fMRI (7T) to measure ipsilateral activity patterns during active single finger presses and passive finger stimulation. We contrasted the overall activity during active and passive conditions in both the contralateral and ipsilateral hemisphere. Using multivariate pattern analysis, we also analyzed how strongly different conditions activated finger-specific circuits, i.e., the degree to which finger information is represented in these areas (Diedrichsen and Kriegeskorte 2017). This analysis allowed us to determine the extent to which representations in the contralateral and ipsilateral motor areas are driven by sensory input alone (passive condition) or by a combination of sensory input and active planning and execution processes (active condition). We further examined these representations using a fine-grained analysis across the subfields of the sensorimotor cortices.

Overall, we found that active and passive conditions recruited contralateral and ipsilateral sensorimotor areas differently. Whereas contralateral finger representations were equally strong for active and passive conditions, the corresponding ipsilateral finger representations around the central sulcus were stronger for the active than the passive condition. Our results demonstrate that motor areas in ipsilateral and contralateral hemispheres are differentially recruited during active and passive finger presses. This differential recruitment of contralateral and ipsilateral motor areas points to a difference in neurophysiological origin of movement representation.

## METHODS

*Participants.* Seven volunteers participated in the experiment. The average age was 26.1 yr (SD = 2.5 yr), and the sample included four women and three men. All participants were right-handed and gave written informed consent to all procedures and data usage before the experiment started. The experimental procedures were approved by the Ethics Committee of University College London and Oxford University.

*Apparatus.* Participants placed their two hands on an MRI-compatible keyboard (Fig. 1*A*), which was positioned on their lap, secured with a foam pillow. The keyboard had 10 elongated keys, with a groove for each fingertip. Force applied during finger press execution was measured with force transducers mounted underneath each key. The keys were not movable, and therefore finger presses were not associated with overt movements. Nonetheless, these isometric presses still involved voluntary activation of muscles, as well as
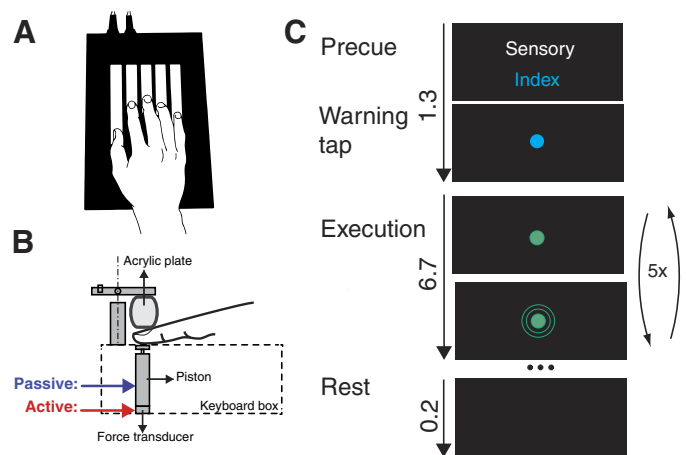


Fig. 1. Apparatus and experimental design. *A*: keyboard used in the task. The left hand was positioned on a mirror-symmetric keyboard. *B*: an adjustable foam pillow was sitting on the top of each finger, preventing any overt finger motion. In the active condition, participants pressed one of the keys and the force applied was recorded through the force transducer. In the passive condition, the force was applied to the finger via a pneumatic piston. *C*: each trial started with a cue denoting which condition and finger are implicated in the trial. This was followed by a warning press to the finger, after which each participant either received 5 finger presses (passive condition) or pressed the key 5 times (active condition). Each trial lasted for a total of 8.2 s. Both active and passive conditions involved only the right hand.

sensory feedback from the pressure on the fingertip. To generate a sensory stimulation protocol that was matched as closely as possible to the sensory input during active finger presses, we applied isometric force presses through pneumatic pistons embedded in each key of the keyboard. Upward movement of the finger was prevented by a stiff foam pad that held the fingers securely in place (Fig. 1*B*). The force to the fingertip in the passive condition was closely matched to that in the active condition by generating force pulses at the same interpress interval and with the same average peak force as those produced during the active condition. The mean peak force was 4.3 N in the active and 4.5 N in the passive condition. Therefore, the two conditions differed mainly in terms of the motor command (i.e., the efference) and were matched as closely as possible in terms of sensory afference. It is of course never possible to exactly match sensory feedback across active and passive conditions, because the efferent outflow itself will alter the incoming sensory information (Blakemore et al. 1999). Therefore, our conclusions on the source of representation did not rely on a direct comparison of passive and active conditions in a single region, but rather on a difference in their relative weighting across the two hemispheres (i.e., passive vs. active responses in contra- vs. ipsilateral sensorimotor regions).

*Experimental design.* We employed a slow event-related design, randomly intermixing active and passive conditions in each imaging run. Every trial lasted for 8.2 s, during which participants either performed five isometric presses with one of the fingers (active condition) or had a finger stimulated five times (passive condition). Both conditions involved only the right hand. Each trial was divided into the instruction phase (1.3 s) and the execution phase (6.7 s). First, the instructional cue was presented on the screen, specifying which finger was to be pressed or stimulated (e.g., Sensory/Index, Fig. 1*C*). Next, the fixation circle appeared in blue and a warning press was applied to the finger that was to be pressed or stimulated. Afterward, the central circle turned green, which was a "go" cue for participants to perform the five presses in the active condition or to have force applied to their finger five times. For every press with the correct finger, the central fixation circle expanded with green circles, whereas in the rare case of an incorrect press, the surrounding circles turned red. To control for visual feedback and predictability of presses, the visual display in the passive condition was the same as in the active

condition. Each run contained 3 repetitions of each of 10 conditions (5 fingers in passive/active tasks), and there were 7 or 8 imaging runs per participant. Thus the number of repetitions was equal across all conditions for each participant. Five rest phases of 13–16 s each were randomly interspersed in each imaging run to obtain a reliable estimate of baseline activation. We ensured that our participants performed the task nearly perfectly. Three of seven participants never pressed the key with an incorrect finger throughout the entire session, and the mean error rate across all participants was 1.3% of trials. Even in these cases, typically only one of the five presses performed in the trial was incorrect. Because of near-perfect performance and for consistency across participants, we have included all the trials in the analysis.

*Image acquisition.* Data was acquired on a 7-Tesla Siemens Magnetom scanner with a 32-channel head coil. An anatomical T1-weighted scan was acquired using a magnetization-prepared rapid gradient echo sequence (MPRAGE) with voxel size of 0.7 mm isotropic (field of view = 224 × 224 × 180 mm). Functional data were acquired in seven to eight runs (depending on the participant) using a two-dimensional (2-D) echo-planar imaging sequence [GRAPPA 2; repetition time (TR) = 3.0 s, echo time (TE) = 25 ms]. We acquired 47 slices with isotropic voxel size of 1.4 mm.

*First-level analysis.* Functional data were analyzed using SPM12 and custom-written MATLAB code. Differences in acquisition timing of slices were corrected for by aligning all slices to the middle slice of each volume. Functional images were corrected for geometric distortions using field map data (Hutton et al. 2002) and aligned to the first image of the first run, resulting in correction for head movements during the scan (3 translations: *x*, *y*, *z* directions and 3 rotations: pitch, roll, and yaw). Finally, the data were coregistered to the anatomical scan. No smoothing or normalization to an atlas template was performed at this stage.

Preprocessed data were analyzed using a general linear model (GLM). Because participants performed the active finger tapping task almost perfectly (average error rate = 1.3 ± 1.7% of trials), we included all of the trials in the analysis. For each trial type, we defined one regressor per imaging run, resulting in 10 regressors per run (5 fingers in passive/active conditions). The regressor was a boxcar function that started with the beginning of the trial and lasted for the trial duration. This function was convolved with a hemodynamic response function, with a time to peak of 4.5 s, manually adjusted to best fit the average time series. The analysis resulted in one activation estimate (beta image) for each of the 10 conditions per run. We calculated average percent signal change for the passive and active conditions (averaged across all fingers) as the mean evoked response relative to the baseline in each run, averaged across runs.

*Surface-based analysis and searchlight approach.* To carefully characterize activation patterns across different cortical areas, we obtained a reconstruction of individual subjects' cortical surfaces using FreeSurfer (Dale et al. 1999). All individual surfaces were aligned to the symmetrized atlas template of FreeSurfer (using xhemireg; Fischl et al. 1999) via spherical registration.

To detect finger-specific representations for the active and passive conditions across the cortex (see *Multivariate analysis*), we used a surface-based searchlight approach (Oosterhof et al. 2011). For each surface node, we selected a surrounding circular region of 120 voxels (i.e., in 3-D volume), which on average resulted in a searchlight radius of 6.5 mm. To avoid contamination of signals across the central sulcus, we excluded all voxels that contained gray matter from the other side. We extracted the activation estimates (betas) of selected voxels from the first-level analysis and then computed the dissimilarity between activity patters for the passive and active finger pairs (see below). The resulting distance was assigned to the center of the searchlight sphere. By moving the searchlight across the cortical surface, we obtained a map of distances for active and passive condition patterns, representing how well each patch of cortex represented individual finger active and passive conditions.

*Regions of interest and cross section.* To compare finger representations across different subfields of the sensorimotor cortex, we defined seven regions of interest (ROIs). The ROIs were defined using Brodmann maps derived from postmortem histology, aligned to the cortical surface atlas (Fischl et al. 2008). Each cortical node was assigned to the region that had (across analyzed brains) the highest probability. Primary motor cortex (M1), or Brodmann area 4, was split into anterior (BA4a) and posterior (BA4p) components. ROIs for primary somatosensory cortex (S1) were Brodmann areas 3a, 3b, 1, and 2. Additionally, the premotor cortex was defined as the lateral aspect of Brodmann area 6 (BA6). To exclude mouth and leg representations in all these areas, we included only cortical nodes within 2.5 cm above and below the hand knob, the point of greatest curvature in the central sulcus (Yousry et al. 1997).

We performed the analysis on percent signal change and distance estimates (see *Multivariate analysis*) for cortical surface patches in a cross section across the surface sheet, running from the rostral end of BA6 to the posterior end of BA2. For the pattern component modeling analysis (described below), we used all voxels within each ROI and further joined BA4a and BA4p into BA4, and BA3a and BA3b into BA3.

*Multivariate analysis.* The overall activation across fingers does not provide insight into finger-specific processes (i.e., finger representations; Diedrichsen et al. 2013). Although finger representations can be visualized in terms of their rough somatotopic arrangement on the cortical surface (Indovina and Sanes 2001; Wiestler et al. 2011), a fuller description can be obtained by taking into account the entire fine-grained activity pattern for each finger (Ejaz et al. 2015). We therefore calculated distances between activation patterns for different fingers, separately for each subject. We first standardized the beta image for each voxel by dividing it by the standard deviation of its residual, as obtained from the first-level GLM. Such univariate prewhitening has been shown to increase the reliability of distance estimates compared with nonstandardized images (Walther et al. 2016). For active and passive conditions separately, we then calculated the cross-validated squared Mahalanobis distance (crossnobis estimator: Diedrichsen and Kriegeskorte 2017; Nili et al. 2014; Walther et al. 2016) between each finger pair. Because the expected value of this estimator is zero if the two conditions only differ by measurement noise, the crossnobis estimate can be used to test whether an area "represents" a certain parameter by testing it against zero (Diedrichsen et al. 2016).

*Pattern component analysis.* To quantify the correspondence between active and passive activity patterns, we used pattern component modeling (PCM; Diedrichsen et al. 2017). A naive way to assess the correlation would be to simply correlate corresponding finger patterns, after subtracting the mean pattern, for the passive and active condition. However, the raw correlations severely underestimate the true correlation between patterns as the correlations are lowered by measurement noise. Even cross-validated correlations are severely biased (see *example 2* in Diedrichsen et al. 2017). Instead, we can use PCM to test between different models on the strength of the correlation between the finger-specific patterns in the active and passive condition: a "null" model where active and passive conditions are unrelated, a "flexible correlation" model where the two conditions share some correlation, and a "perfect correlation" model in which the passive finger-specific patterns are simply a scaled version of the active patterns. We compared these models by calculating for each subject the log-Bayes factor of the flexible and perfect model against the null model. Subsequent group inferences were performed using parametric statistics (*t*-test) on the individual log-Bayes factors.

*Statistical analyses.* To statistically assess how activity or distances differ between conditions in either hemisphere, we performed a condition × ROI ANOVA, followed by post hoc *t*-tests on distance estimates of passive and active conditions in each region individually. To directly contrast the distance estimates of the two conditions across the two hemispheres, we conducted a hemisphere × condition ANOVA. We

further quantified the spatial distribution of distances across regions of the two hemispheres using a hemisphere × ROI ANOVA on estimates of distances in the active condition. To statistically assess the correspondence between active and passive patterns, we contrasted the obtained correlation estimates against zero using one-sample $t$-tests and conducted a model type × ROI ANOVA on log-Bayes factors of the flexible and perfect correlation models. Our ANOVAs were followed by post hoc $t$-tests, with the use of Bonferroni correction for multiple comparisons for adjusting the significance value. Given the small sample size ($N = 7$), we replicated each test using nonparametric statistics (rank-sum test; not reported), which yielded qualitatively similar results. All of the plots presenting results are group averages per condition ($N = 7$): the cross-sectional plots in Figs. 2 and 3 for each surface node, the matrices in Fig. 4 providing a group average across seven subjects, and in Fig. 5 for each of the dots in the bar plot (so 7 values per ROI).

## RESULTS

*Contralateral finger representations are equally strong in active and passive conditions.* Before looking at the contribution of sensory and motor processes to the ipsilateral representations, we carefully quantified the passive and active finger representations in the contralateral hemisphere. As a first proxy for contralateral recruitment during the two conditions, we investigated the overall BOLD activation across sensorimotor regions. The sensory input was similar in both tasks, but the active condition additionally required planning and initiation of the press. These additional motor demands were predicted to evoke higher levels of activation in the active compared with the passive task. Figure 2A shows the percent signal change on

the flattened contralateral cortical surface related to the active and passive condition. Both conditions evoke activity in highly overlapping cortical patches. For statistical evaluation, we used a series of anatomically defined ROIs, running from premotor cortex (BA6) posterior into BA2 (separated by dotted lines), and tested the evoked activity of each region against zero with a one-sample $t$-test. Significance at $P < 0.001$ was reached in all subfields for both passive and active conditions (Fig. 2B). To examine differences between active and passive conditions, we performed a condition × ROI ANOVA. Both the main effects of condition and ROI were significant [condition: $F_{(1,6)} = 23.791$, $P = 0.0028$; ROI: $F_{(1,6)} = 4.833$, $P = 9.0e^{-4}$], as was the interaction between them [$F_{(1,6)} = 8.19$, $P = 1.3e^{-5}$]. Post hoc $t$-tests comparing activation during passive and active conditions within each ROI revealed that the active condition elicited higher activation than the passive condition in every region (Bonferroni-corrected significance level: $P = 0.0071$; Fig. 2B).

Next, we evaluated how strong representations for different fingers were in each of these ROIs, independent of the overall activity. It is possible to observe large activation without any representation of individual fingers (implying the activation is induced by processes not specifically related to finger control) or to observe lower activation with very clear finger representation. For a region to perform a specific function, a clear representation is more important than high activation (Diedrichsen and Kriegeskorte 2017). We evaluated the strength of representation using the cross-validated squared Mahalanobis distance estimate (crossnobis; Diedrichsen et al. 2016) between activity patterns of individual fingers separately for active presses and passive finger
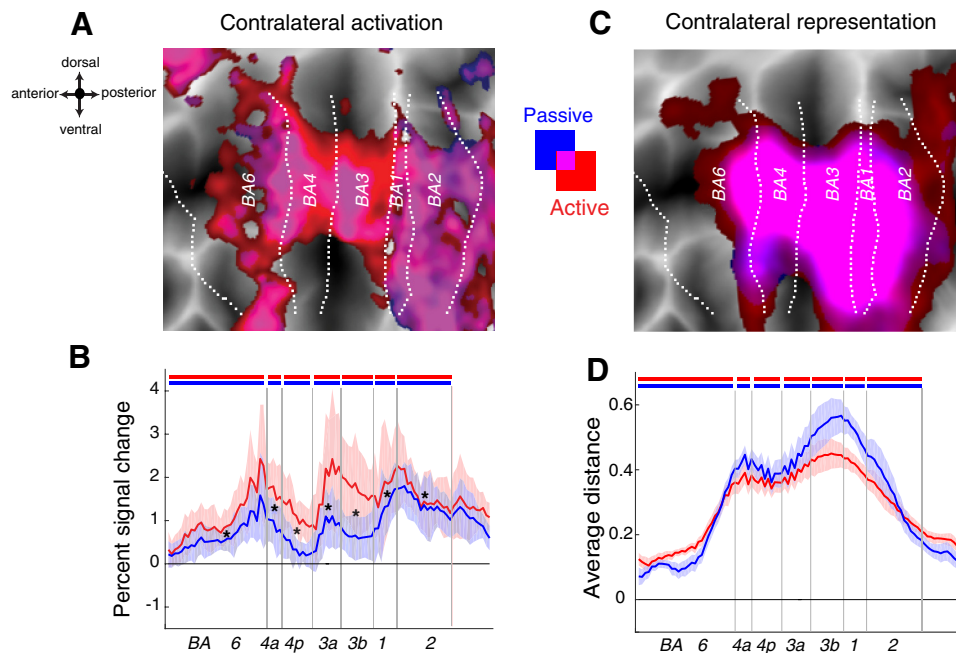


Fig. 2. Average contralateral evoked activation and distances between finger patterns during active and passive tasks across subfields of sensorimotor cortex. *A*: evoked activity for the active (red) and passive (blue) conditions on the flattened contralateral cortical surface. The two conditions activated similar cortical areas, with the overlap indicated by purple areas. Regions of interest (ROIs) were defined on the basis of a probabilistic cytoarchitectonic atlas (Fischl et al. 2008), with each node assigned the area of the highest probability. Borders between regions are indicated with white dotted lines. *B*: percent signal change for active and passive tasks was sampled in a cross section from anterior (BA6) to posterior (BA2), along a rectangular strip with a width of 26 mm. Horizontal red and blue bars indicate significant activation during the active and passive tasks, respectively. *$P < 0.0071$, significant differences between the activation for active and passive tasks (Bonferroni correction). *C*: average distance between finger patterns for the active (red) and passive (blue) tasks on the flattened contralateral cortical surface. The two conditions evoked similar distances, which is indicated by the purple overlap. *D*: distances in the contralateral hemisphere were significantly higher than 0 for both tasks, as indicated by the red and blue bars. There was no difference in distances between the two conditions in any ROI. Shaded areas in *B* and *D* reflect the standard error of the group mean ($N = 7$).

stimulation. As expected, we found strong finger representations for both passive and active conditions (Fig. 2*C*), confirmed by a *t*-test on distance estimates of each condition across all cortical sensorimotor regions combined [passive: $t_{(6)} = 13.82$, $P = 8.93e^{-6}$; active: $t_{(6)} = 9.76$, $P = 6.65e^{-5}$]. Distances were particularly large in the depths of the central sulcus, peaking in area 3b, and decreased anteriorly in premotor area (BA6) and posteriorly in BA2 (Fig. 2*D*). We quantified this observation statistically by performing a condition × ROI ANOVA on the distance estimates. The main effect of condition was not significant [$F_{(1,6)} = 3.183$, $P = 0.125$], but both the main effect ROI and the interaction between the ROI and condition were significant [ROI: $F_{(1,6)} = 37.288$, $P = 5.1e^{-14}$; interaction: $F_{(6,36)} = 12.183$, $P = 1.9e^{-7}$]. Post hoc *t*-tests on the effect of condition within each region revealed a trend for larger distances in the passive compared with the active condition in BA3b and BA1, but this difference did not reach significance after Bonferroni correction.

In summary, we found that both active and passive conditions activated the finger-specific representations to the same extent in contralateral M1 and S1. In contrast, the average overall activity was significantly higher in the active condition. This means that the additional neuronal processes in the active condition were not finger specific, but instead increased activity in a general fashion for all fingers.

*Ipsilateral finger representations are stronger in active than passive condition.* Having quantified the amount of passive and active digit representations in the contralateral hemisphere, we next turned to the ipsilateral hemisphere. We again first quantified the overall percent signal change of elicited activity. Consistent with previous research (Diedrichsen et al. 2013; Verstynen et al. 2005), we found significant BOLD modulation across ipsilateral ROIs during the active condition, as con-

firmed by a one-way ANOVA with the main effect of region [$F_{(6,36)} = 16.26$, $P = 5.9e^{-9}$]. Activation in the depth of the sulcus was suppressed below resting baseline (Fig. 3*B*), and this suppressive effect was significant in areas 4p and 3a [BA4p: $t_{(6)} = -4.89$, $P = 0.0027$; BA3a: $t_{(6)} = -4.28$, $P = 0.005$]. Only premotor (BA6) and parietal areas (BA2) exhibited significant increases in BOLD signal [BA6: $t_{(6)} = 6.57$, $P = 5.94e^{-4}$; BA2: $t_{(6)} = 4.51$, $P = 0.004$].

To quantify the activation and deactivation profiles across both active and passive conditions, we used a condition × ROI ANOVA. The main effect of condition was not significant [$F_{(1,6)} = 0.095$, $P = 0.769$], but there was a significant main effect of ROI [$F_{(1,6)} = 19.55$, $P = 5.4e^{-10}$] and a significant interaction between the two factors [$F_{(6,36)} = 8.13$, $P = 1.4e^{-5}$]. Post hoc *t*-tests demonstrated that this interaction was driven by higher activity in the premotor cortex during the active condition [$t_{(6)} = 4.23$, $P = 0.006$], which is in line with its bilateral involvement during action preparation (Cisek et al. 2003). Other areas showed no significant difference in activity between the two conditions. Thus regions located in the depth of the central sulcus in the ipsilateral hemisphere were significantly suppressed during both passive and active conditions.

We have previously found that despite the suppression of BOLD activity, the ipsilateral hemisphere contains information about individual finger movements (Diedrichsen et al. 2013). In the present study, we asked whether the ipsilateral hemisphere represents individual fingers only during active movement or also during passive finger stimulation. We first examined individual finger representations during the active condition. The average distance among active finger presses was higher than zero in every region [all $t_{(6)} > 2.721$, $P < 0.034$; Fig. 3*D*], replicating our prior results (Diedrichsen et al.
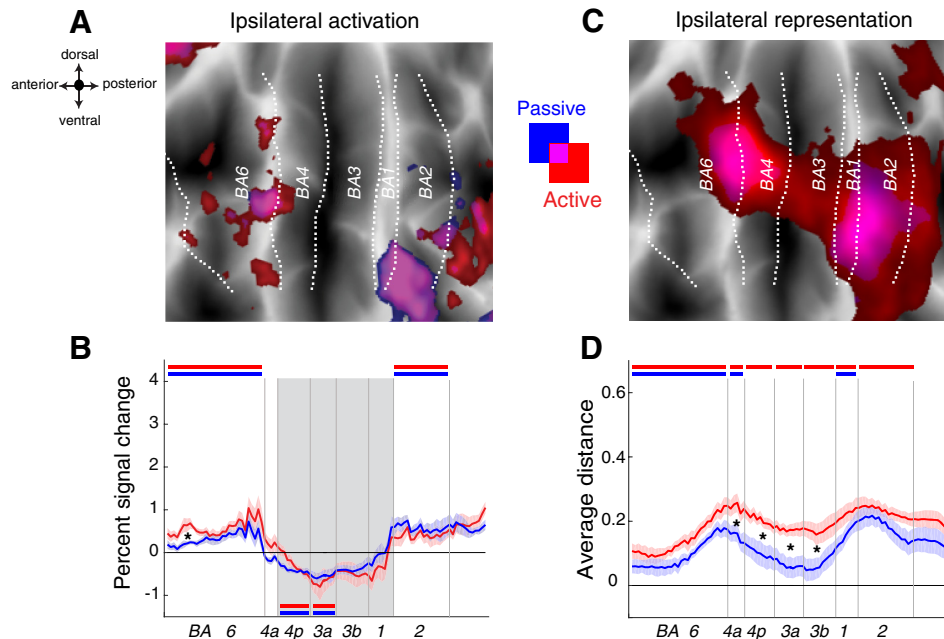


Fig. 3. Average ipsilateral evoked activation and distances between finger patterns during active and passive tasks across subfields of sensorimotor cortex. *A*: evoked activity above resting baseline for the two conditions on the flattened ipsilateral hemisphere. *B*: ipsilateral hemisphere showed suppression of activity below resting baseline around the central sulcus for both conditions, indicated with gray background. BA6 displayed more activation for the active than passive condition, but all other areas responded similarly for the two conditions. *C*: average passive and active distances in the ipsilateral hemisphere. The active condition elicited higher distances than the passive condition, which is reflected in the predominately red areas, especially in the depth of the central sulcus. *D*: ipsilateral hemisphere displayed higher distances for the active than the passive task. This difference was significant in areas BA4a, 4p, 3a, and 3b (*$P < 0.0071$). Shaded areas in *B* and *D* reflects the standard error of the group mean ($N = 7$).

2013). Next, we tested whether the ipsilateral hemisphere represents individual fingers in the passive condition to the same extent as during active movement (similar to the contralateral hemisphere). The main effect of condition on the distance estimates was significant [$F_{(1,6)} = 24.36$, $P = 0.0026$], and post hoc $t$-tests revealed that the average distance was lower in the passive than in the active task in the depth of the sulcus (Fig. 3$D$). Subfields 4p, 3a, and 3b, all of which showed significant distances during active finger presses, did not show finger representation for passive finger stimulation, as confirmed by one-sample $t$-tests against zero (Fig. 3$D$). These findings suggest that ipsilateral representations in these areas are driven by processes involved in the active generation of movement, but not by the sensory input arising from passive stimulation.

Last, we quantified whether the relative amount of finger representation across the passive and active tasks differs across the two hemispheres. This test is critical to determine whether the source of contralateral and ipsilateral finger information is identical or different. A hemisphere × condition ANOVA combined across all regions revealed a clear interaction effect [$F_{(1,6)} = 64.481$, $P = 2.0e^{-4}$], demonstrating that the relative magnitude of finger-specific representation during the active and passive conditions differs significantly across the two hemispheres. This can also be observed in the representational dissimilarity matrices (Fig. 4), which show the distances between digits during active and passive conditions for the contra- and ipsilateral M1. Whereas the contralateral sensorimotor circuit represents individual finger presses and stimulation to the same extent (or, if anything, more for the passive condition), finger representation on the ipsilateral side was stronger during the active condition. This demonstrates that the contribution of sensory information to the neural activation patterns is much smaller in the ipsilateral compared with the contralateral sensorimotor areas.

*Spatial distribution of active representations is different across hemispheres.* An additional important insight about ipsilateral representation can also be gained by considering the spatial distribution of representations across subfields of sensorimotor cortices. We compared the distribution of active distances across the cross section of ROIs in the contralateral
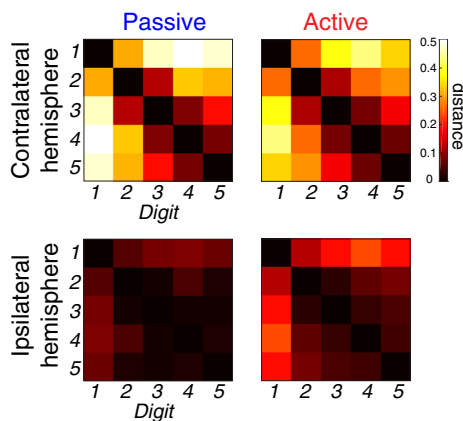


Fig. 4. Representational dissimilarity matrix for distances between patterns of digit pairs in contralateral and ipsilateral M1 (BA4a and BA4p combined) for passive and active conditions. The distances are averaged across 7 participants. The structure of dissimilarity matrix (see Ejaz et al. 2015) is preserved across hemispheres and conditions.

and ipsilateral hemisphere (i.e., the profile of red lines in Fig. 2$D$ vs. Fig. 3$D$). Our results showed that the ipsilateral profile of distances for the active condition is not just a scaled-down version of the contralateral distances. For example, contralateral distances peaked in area 3b, but ipsilateral hemisphere showed lower distances in 3b than in areas 1 and 2. To quantify this effect, we performed a hemisphere × ROI ANOVA on the distance estimates in the active condition. Both main effects were significant [hemisphere: $F_{(1,6)} = 35.827$, $P = 0.001$; ROI: $F_{(6,36)} = 20.272$, $P = 3.33e^{-10}$], but importantly, the interaction between them was significant, as well [$F_{(6,36)} = 17.236$, $P = 2.83e^{-9}$]. This suggests that the ipsilateral hemisphere has a unique profile across areas, with relatively stronger finger-specific representations in premotor and parietal areas.

*Correlation of activity patterns during active and passive conditions.* Finally, we examined to what degree active and passive conditions activate the same or different finger-specific circuits. On one extreme, individual finger presses and individual finger stimulation could evoke the same responses in the same voxels. In the other extreme, the two conditions could activate completely different voxels or the same voxels to a different extent. Using PCM, we can determine the degree to which finger-specific patterns of activity were shared across the two conditions. When estimating the correlation between active and passive conditions (corrected for the measurement noise, see METHODS) on the contralateral hemisphere, we obtained an average value of 0.84 between across all areas of interest (Fig. 5$A$, solid line). Also in the ipsilateral hemisphere, consistently positive correlations (average $r = 0.66$) were found (Fig. 5$A$, dashed line).

These results clearly show that the passive and active conditions engage overlapping finger-specific circuits on the contralateral side, and to a lesser extent on the ipsilateral side. However, the problem is that correlation coefficients underestimate the true correlation (Diedrichsen et al. 2017) such that the lower correlation coefficient on the ipsilateral side likely reflects a lower signal-to-noise ratio. To test whether the data could be explained by a true correlation of $r = 1$ between active and passive patterns, we compared two PCM models: a "perfect correlation" model that constrained the correlation between passive and active patterns to 1, and a "flexible correlation" model in which the correlation was estimated in a cross-validated fashion across subjects. Evidence for these two models was expressed relative to a "null" model, which assumes that the correlation between active and passive patterns is 0. On the contralateral side, both flexible and perfect correlation models were a better descriptor of our data than the null model (Fig. 5$B$): the flexible correlation model had a log-Bayes factor of 357 [one-sample $t$-test against 0: $t_{(6)} = 10.684$, $P = 3.41e^{-16}$], whereas the perfect correlation model had a log-Bayes factor of 344 [$t_{(6)} = 10.188$, $P = 2.53e^{-16}$]. The two models performed indistinguishably in all contralateral ROIs [all $t_{(6)} < 2.12$, $P > 0.078$].

On the ipsilateral hemisphere, both models had lower log-Bayes factors; the flexible correlation model had an average log-Bayes factor of 54.2 across regions, whereas the perfect correlation model average log-Bayes factor was 52.9. Specifically in area BA3, where evidence for both models was the highest in the contralateral hemisphere, the two models on the ipsilateral hemisphere did not perform better than the null model [flexible model: $t_{(6)} = 1.45$, $P =$
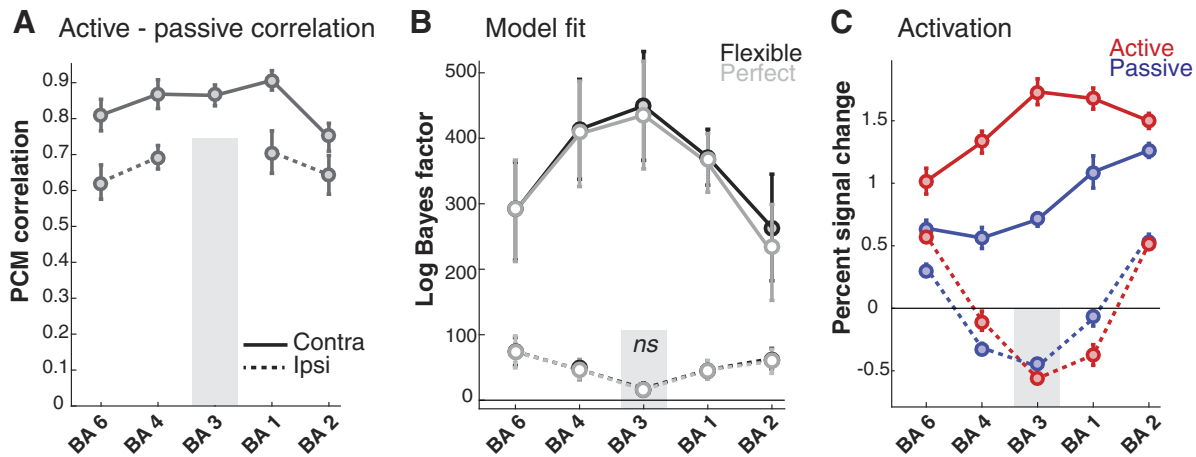
Fig. 5. Correlation between finger-specific activity patterns in the active and passive conditions. *A*: correlation coefficients estimated using pattern component modeling (PCM) for contralateral (solid line) and ipsilateral (dashed line) hemispheres. Note that for ipsilateral area 3b, there was not enough evidence for a finger-specific representation in the passive condition to reliably estimate a correlation coefficient. *B*: performance of the model with correlation between active and passive patterns unconstrained (flexible correlation model) and the model where the correlation is constrained to be 1 (perfect correlation model); both are expressed relative to a null model (no correlation between active and passive patterns). Although a log-Bayes factor of 1 is considered positive evidence and a log-Bayes factor of 3 as strong model evidence (Kass and Raftery 1995), our log-Bayes factors are likely inflated due to residual dependence between voxels after prewhitening. Therefore, the critical test is whether the group log-Bayes factors are significantly different from 0 in a frequentist (*t*) test. ns, Not significant. *C*: percent signal change in active (red) and passive (blue) conditions for contralateral (solid) and ipsilateral (dashed) hemispheres. Error bars are standard error of the group mean (*N* = 7).

0.098; perfect correlation model: $t_{(6)} = 1.54$, $P = 0.086$]. This is caused by the absence of a significant finger representation in this area in the passive condition (see Fig. 3*D*), which makes the estimation of a correlation impossible. Additionally, this area displayed the lowest elicited activation during the passive and active conditions (Fig. 5*C*). Together, our results demonstrate that in all areas in which both active and passive conditions elicit reliable finger-specific activity patterns, these representations are highly related.

## DISCUSSION

In this study, we used active finger presses and passive finger stimulation to investigate the origin of finger representations in ipsilateral sensorimotor cortex. We first provided a detailed characterization of the nature of contralateral representations. We found that finger-specific representations were equally strong across active and passive conditions despite BOLD activations being larger for the active condition. We expanded on these results in two ways. First, we quantified finger representations across the subfields of the sensorimotor cortex and report that representations were most pronounced in BA3a, 3b, and BA1. Second, we demonstrated that finger-specific activity patterns were highly correlated between active and passive conditions. Altogether, our results demonstrate that passive finger stimulation drives contralateral finger-specific motor circuits as strongly as active finger presses. Although this may be surprising in some ways, it aligns with the importance of sensory inputs in dexterous manipulation (Pruszynski et al. 2016). These findings are therefore expected under the hypothesis that the main function of primary motor cortex is feedback control (Scott 2004).

Having established the nature of contralateral sensorimotor finger representations, we then examined the extent to which the ipsilateral motor areas are recruited during active and passive conditions. Overall, ipsilateral representations were weaker than those in the contralateral hemisphere. Critically, however, whereas contralateral representations were equally

strong for both active and passive conditions, ipsilateral sensorimotor representations were significantly stronger for the active condition. There was no reliable finger representation during passive stimulation in ipsilateral areas 4p, 3a, and 3b. The difference between hemispheres became also clear when we investigated the spatial distribution of finger representations: in the contralateral hemisphere, finger representations were strongest along the central sulcus, whereas on the ipsilateral side, they were strongest in premotor and parietal areas. These data provide clear evidence that finger-specific representation in contralateral and ipsilateral hemispheres differ qualitatively, likely reflecting the difference in the functional role of these representations.

Our data therefore clearly argue against the idea that ipsilateral representations are caused by a passive spillover from the homologous areas though transcallosal connections (e.g., M1-M1; Asanuma and Okuda 1962), because such a fixed information transmission should have resulted in the same active-to-passive ratio of information in both hemispheres. At the very least, our results indicate that the information transmission between hemisphere is strongly modulated by the behavioral context (active vs. passive). Similarly, our results confirm that the process that leads to global suppression of the BOLD signal in the ipsilateral hemisphere (supposedly through interhemispheric inhibition; Gerloff et al. 2006) is qualitatively different from the mechanism that causes the finger-specific ipsilateral activity patterns. Although the overall ipsilateral suppression in BA 3 and 4 was equivalent across active and passive conditions, the strength of the finger representations showed substantial differences. Furthermore, we have shown in previous work that the ipsilateral patterns are caused by an activation of the corresponding finger representations for the other hand, not by a suppression of these circuits (Diedrichsen et al. 2013). Together, evidence suggests that ipsilateral representations are not passive copies of their contralateral homologous counterparts.

Although other possible explanations exist, the most likely interpretation of the whole pattern of results is that ipsilateral representations are more related to the planning and initiation of actions but less to the ongoing feedback control of movements. In favor of this interpretation, there was very little ipsilateral finger-specific information in the passive condition in ipsilateral primary somatosensory areas. If the ipsilateral hemisphere had a direct role in feedback control of the movement, we would have expected a clear representation of sensory information, as observed for the contralateral hemisphere. Second, the finger-specific representations in the ipsilateral hemisphere was most pronounced in premotor and parietal areas, which are thought to be involved in motor planning (this pattern of results was also observed in the ipsilateral superior parietal lobule and supplementary motor areas; not shown in RESULTS). The function of the ipsilateral representations to movement planning (rather than control) is also more consistent with research in nonhuman primates demonstrating that the ipsilateral hemisphere has limited capacity to cause upper limb movements (Kuypers et al. 1962) and therefore most likely plays a modulatory or indirect role in active control (Soteropoulos et al. 2011).

Interestingly, however, ipsilateral premotor and parietal areas also displayed significant finger representations in the passive conditions. This raises the alternative hypothesis that the ipsilateral finger representations may reflect attentional signals. Given that participants knew which finger would be stimulated, they may have allocated spatial attention to the specific finger, causing finger-specific activity patterns to occur. Alternatively, participants may have internally prepared an action with the corresponding finger.

Is it possible that the differences in finger representations across active and passive conditions are caused by participants allocating more attention to the finger in the active condition? We think that this explanation is unlikely, because the biggest relative difference between conditions was found in the ipsilateral M1/S1, whereas the difference in contra- and ipsilateral premotor areas was much less pronounced. If anything, attentional effects should be expressed more in these higher order areas and should also be found in the contralateral sensorimotor cortex (Johansen-Berg and Matthews 2002; Rushworth et al. 2003).

It is also possible that the finger representations in ipsilateral primary sensorimotor areas are a pure epiphenomenon without any functional relevance. Namely, the presence of a detailed representation during the active condition (as observed with fMRI or electrophysiology) does not automatically imply that the activity plays any causal role. For example, bilateral representations in primary sensorimotor regions could arise from covert planning of candidate responses with either hand (Cisek and Kalaska 2010). The ipsilateral representations would then be suppressed when the choice of hand is made, without contributing in any way to motor performance. Although there is some evidence that disruption of ipsilateral motor circuits impedes the quality and skill of motor execution (Chen et al. 1997; Johansen-Berg et al. 2002), the observed deficits are rather subtle (Noskin et al. 2008; Xu et al. 2017). Even if it turns out that ipsilateral representation is not essential to ensure normal motor control, it is still possible that this activity subserves other functions. For example, it has been suggested that bilateral representations of motor plans may promote transfer of motor learning across hands (Wiestler et al. 2014). Furthermore, the representation could provide a redundant code that could obtain a functional role when the corresponding regions in the opposite hemispheres are disrupted (Li et al. 2016). Thus, in the case of case of brain injury, the ipsilateral hemisphere may play a compensatory role.

In conclusion, we have provided a detailed characterization of the nature of ipsilateral sensorimotor representations during active presses and passive finger stimulation. Our results suggest that the ipsilateral hemisphere does not receive the sensory input critical for dexterous feedback control, and instead may primarily be involved in planning-related processes. Therefore, our study provides important constraints on the role that the ipsilateral hemisphere can play in the control of movement in health and disease.

## DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

## AUTHOR CONTRIBUTIONS

G.P., J.O., and E.N. performed experiments; E.B., G.P., and J.D. analyzed data; E.B., E.N., and J.D. interpreted results of experiments; E.B. prepared figures; E.B. drafted manuscript; E.B., E.N., and J.D. edited and revised manuscript; E.B., G.P., J.O., E.N., and J.D. approved final version of manuscript.

## REFERENCES

**Asanuma H, Okuda O.** Effects of transcallosal volleys on pyramidal tract cell activity of cat. *J Neurophysiol* 25: 198–208, 1962. doi:10.1152/jn.1962.25.2.198.

**Augurelle AS, Smith AM, Lejeune T, Thonnard JL.** Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand-held objects. *J Neurophysiol* 89: 665–671, 2003. doi:10.1152/jn.00249.2002.

**Blakemore SJ, Frith CD, Wolpert DM.** Spatio-temporal prediction modulates the perception of self-produced stimuli. *J Cogn Neurosci* 11: 551–559, 1999. doi:10.1162/089892999563607.

**Brinkman J, Kuypers HG.** Cerebral control of contralateral and ipsilateral arm, hand and finger movements in the split-brain rhesus monkey. *Brain* 96: 653–674, 1973. doi:10.1093/brain/96.4.653.

**Chen R, Gerloff C, Hallett M, Cohen LG.** Involvement of the ipsilateral motor cortex in finger movements of different complexities. *Ann Neurol* 41: 247–254, 1997. doi:10.1002/ana.410410216.

**Cisek P, Crammond DJ, Kalaska JF.** Neural activity in primary motor and dorsal premotor cortex in reaching tasks with the contralateral versus ipsilateral arm. *J Neurophysiol* 89: 922–942, 2003. doi:10.1152/jn.00607.2002.

**Cisek P, Kalaska JF.** Neural mechanisms for interacting with a world full of action choices. *Annu Rev Neurosci* 33: 269–298, 2010. doi:10.1146/annurev.neuro.051508.135409.

**Cramer SC, Finklestein SP, Schaechter JD, Bush G, Rosen BR.** Activation of distinct motor cortex regions during ipsilateral and contralateral finger movements. *J Neurophysiol* 81: 383–387, 1999. doi:10.1152/jn.1999.81.1.383.

**Dale AM, Fischl B, Sereno MI.** Cortical surface-based analysis. I. Segmentation and surface reconstruction. *Neuroimage* 9: 179–194, 1999. doi:10.1006/nimg.1998.0395.

**Diedrichsen J, Kriegeskorte N.** Representational models: a common framework for understanding encoding, pattern-component, and representational-similarity analysis. *PLoS Comput Biol* 13: e1005508, 2017. doi:10.1371/journal.pcbi.1005508.

**Diedrichsen J, Provost S, Zareamoghaddam H.** On the distribution of cross-validated Mahalanobis distances (Preprint). *arXiv* 1607.01371, 2016.

**Diedrichsen J, Wiestler T, Krakauer JW.** Two distinct ipsilateral cortical representations for individuated finger movements. *Cereb Cortex* 23: 1362–1377, 2013. doi:10.1093/cercor/bhs120.

**Diedrichsen J, Yokoi A, Arbuckle SA.** Pattern component modeling: a flexible approach for understanding the representational structure of brain activity patterns. *Neuroimage* 180: 119–133, 2017. doi:10.1016/j.neuroimage.2017.08.051.

**Ejaz N, Hamada M, Diedrichsen J.** Hand use predicts the structure of representations in sensorimotor cortex. *Nat Neurosci* 18: 1034–1040, 2015. doi:10.1038/nn.4038.

**Fischl B, Rajendran N, Busa E, Augustinack J, Hinds O, Yeo BT, Mohlberg H, Amunts K, Zilles K.** Cortical folding patterns and predicting cytoarchitecture. *Cereb Cortex* 18: 1973–1980, 2008. doi:10.1093/cercor/bhm225.

**Fischl B, Sereno MI, Tootell RB, Dale AM.** High-resolution intersubject averaging and a coordinate system for the cortical surface. *Hum Brain Mapp* 8: 272–284, 1999. doi:10.1002/(SICI)1097-0193(1999)8:4<272::AID-HBM10>3.0.CO;2-4

**Fujiwara Y, Matsumoto R, Nakae T, Usami K, Matsuhashi M, Kikuchi T, Yoshida K, Kunieda T, Miyamoto S, Mima T, Ikeda A, Osu R.** Neural pattern similarity between contra- and ipsilateral movements in high-frequency band of human electrocorticograms. *Neuroimage* 147: 302–313, 2017. doi:10.1016/j.neuroimage.2016.11.058.

**Gerloff C, Bushara K, Sailer A, Wassermann EM, Chen R, Matsuoka T, Waldvogel D, Wittenberg GF, Ishii K, Cohen LG, Hallett M.** Multimodal imaging of brain reorganization in motor areas of the contralesional hemisphere of well recovered patients after capsular stroke. *Brain* 129: 791–808, 2006. doi:10.1093/brain/awh713.

**Hutton C, Bork A, Josephs O, Deichmann R, Ashburner J, Turner R.** Image distortion correction in fMRI: A quantitative evaluation. *Neuroimage* 16: 217–240, 2002. doi:10.1006/nimg.2001.1054.

**Indovina I, Sanes JN.** On somatotopic representation centers for finger movements in human primary motor cortex and supplementary motor area. *Neuroimage* 13: 1027–1034, 2001. doi:10.1006/nimg.2001.0776.

**Johansen-Berg H, Matthews PM.** Attention to movement modulates activity in sensori-motor areas, including primary motor cortex. *Exp Brain Res* 142: 13–24, 2002. doi:10.1007/s00221-001-0905-8.

**Johansen-Berg H, Rushworth MF, Bogdanovic MD, Kischka U, Wimalaratna S, Matthews PM.** The role of ipsilateral premotor cortex in hand movement after stroke. *Proc Natl Acad Sci USA* 99: 14518–14523, 2002. doi:10.1073/pnas.222536799.

**Kass RE, Raftery A.** Bayes factors. *J Am Stat Assoc* 90: 773–795, 1995. doi:10.1080/01621459.1995.10476572.

**Kuypers HG, Fleming WR, Farinholt JW.** Subcorticospinal projections in the rhesus monkey. *J Comp Neurol* 118: 107–137, 1962. doi:10.1002/cne.901180109.

**Li N, Daie K, Svoboda K, Druckmann S.** Robust neuronal dynamics in premotor cortex during motor planning. *Nature* 532: 459–464, 2016. [Erratum in *Nature* 537: 122, 2016.] doi:10.1038/nature17643.

**Nili H, Wingfield C, Walther A, Su L, Marslen-Wilson W, Kriegeskorte N.** A toolbox for representational similarity analysis. *PLoS Comput Biol* 10: e1003553, 2014. doi:10.1371/journal.pcbi.1003553.

**Noskin O, Krakauer JW, Lazar RM, Festa JR, Handy C, O'Brien KA, Marshall RS.** Ipsilateral motor dysfunction from unilateral stroke: implications for the functional neuroanatomy of hemiparesis. *J Neurol Neurosurg Psychiatry* 79: 401–406, 2008. doi:10.1136/jnnp.2007.118463.

**Oosterhof NN, Wiestler T, Downing PE, Diedrichsen J.** A comparison of volume-based and surface-based multi-voxel pattern analysis. *Neuroimage* 56: 593–600, 2011. doi:10.1016/j.neuroimage.2010.04.270.

**Pruszynski JA, Johansson RS, Flanagan JR.** A rapid tactile-motor reflex automatically guides reaching toward handheld objects. *Curr Biol* 26: 788–792, 2016. doi:10.1016/j.cub.2016.01.027.

**Rushworth MF, Johansen-Berg H, Göbel SM, Devlin JT.** The left parietal and premotor cortices: motor attention and selection. *Neuroimage* 20, *Suppl* 1: S89–S100, 2003. doi:10.1016/j.neuroimage.2003.09.011.

**Scherer R, Zanos SP, Miller KJ, Rao RP, Ojemann JG.** Classification of contralateral and ipsilateral finger movements for electrocorticographic brain-computer interfaces. *Neurosurg Focus* 27: E12, 2009. doi:10.3171/2009.4.FOCUS0981.

**Scott SH.** Optimal feedback control and the neural basis of volitional motor control. *Nat Rev Neurosci* 5: 532–546, 2004. doi:10.1038/nrn1427.

**Soteropoulos DS, Edgley SA, Baker SN.** Lack of evidence for direct corticospinal contributions to control of the ipsilateral forelimb in monkey. *J Neurosci* 31: 11208–11219, 2011. doi:10.1523/JNEUROSCI.0257-11.2011.

**Verstynen T, Diedrichsen J, Albert N, Aparicio P, Ivry RB.** Ipsilateral motor cortex activity during unimanual hand movements relates to task complexity. *J Neurophysiol* 93: 1209–1222, 2005. doi:10.1152/jn.00720.2004.

**Walther A, Nili H, Ejaz N, Alink A, Kriegeskorte N, Diedrichsen J.** Reliability of dissimilarity measures for multi-voxel pattern analysis. *Neuroimage* 137: 188–200, 2016. doi:10.1016/j.neuroimage.2015.12.012.

**Wiestler T, McGonigle DJ, Diedrichsen J.** Integration of sensory and motor representations of single fingers in the human cerebellum. *J Neurophysiol* 105: 3042–3053, 2011. doi:10.1152/jn.00106.2011.

**Wiestler T, Waters-Metenier S, Diedrichsen J.** Effector-independent motor sequence representations exist in extrinsic and intrinsic reference frames. *J Neurosci* 34: 5054–5064, 2014. doi:10.1523/JNEUROSCI.5363-13.2014.

**Xu J, Ejaz N, Hertler B, Branscheidt M, Widmer M, Faria AV, Harran MD, Cortes JC, Kim N, Celnik PA, Kitago T, Luft AR, Krakauer JW, Diedrichsen J.** Separable systems for recovery of finger strength and control after stroke. *J Neurophysiol* 118: 1151–1163, 2017. doi:10.1152/jn.00123.2017.

**Yousry TA, Schmid UD, Alkadhi H, Schmidt D, Peraud A, Buettner A, Winkler P.** Localization of the motor hand area to a knob on the precentral gyrus. A new landmark. *Brain* 120: 141–157, 1997. doi:10.1093/brain/120.1.141.