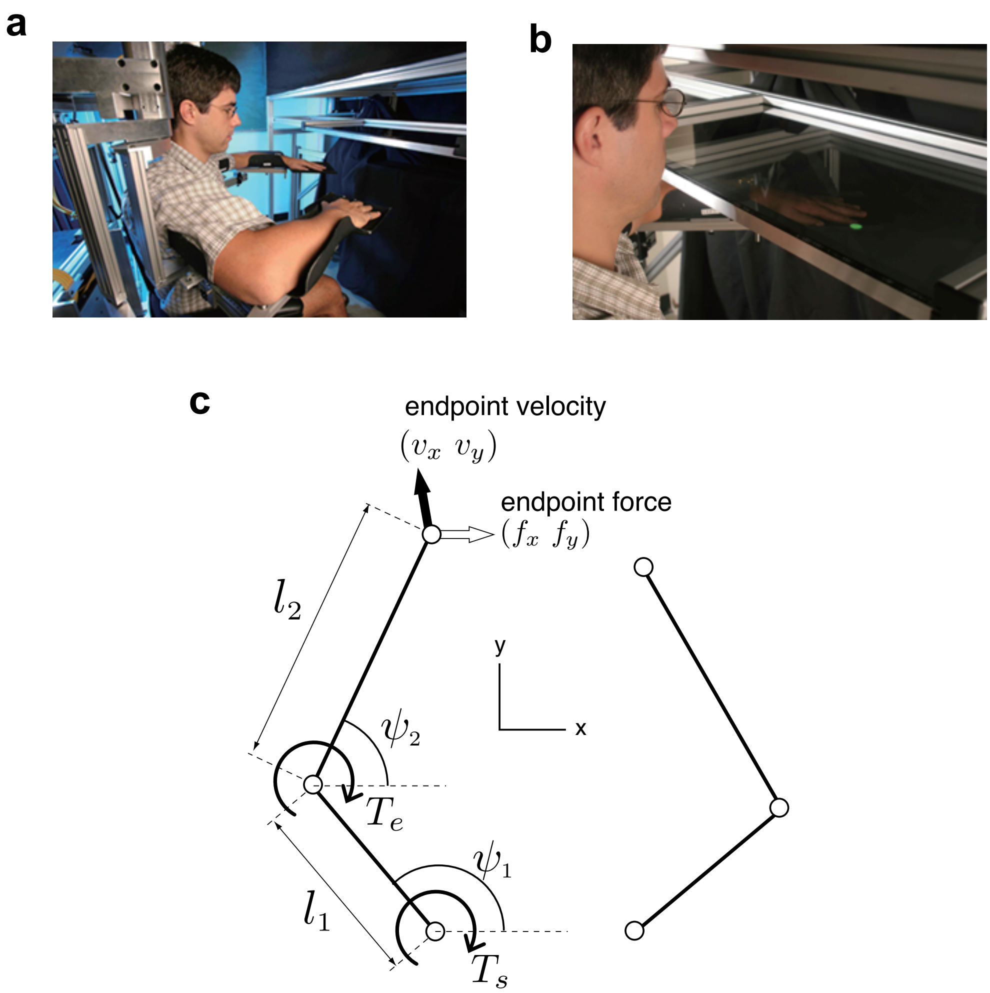


Supplementary Figure 1: (**a**) Subject wearing the robotic exoskeleton. (**b**) Target presentation on a screen using a virtual reality system. (**c**) An endpoint force (f_x, f_y) vector was mimicked by applying shoulder (T_s) and elbow (T_e) joint torques using the exoskeleton. $\mathbf{v} = (v_x, v_y)$ is the endpoint velocity. l_1 (l_2) and φ_1 (φ_2) are, respectively, the length and angle (relative to x-axis) of the upper-arm (forearm).

Supplementary Methods

Subjects and experimental device

Experiments were composed of several sessions lasting ∼45 min each. A total of 27 subjects participated following informed consent. All subjects were right-handed, aged 20-39, had no cognitive or motor disorders, and were paid for their time. Our experimental device consisted of planar robotic exoskeleton that could apply mechanical loads directly to the shoulder and elbow joints (BKIN Technologies Ltd., Kingston, Canada; Scott, 1999). Fiberglass braces fixed to a fully adjustable linkage were attached to the upper and lower segments of each arm. This permitted flexion and extension movements of the shoulder and elbow with the arm abducted into the horizontal plane (Supplementary Figure 1a).

On certain trials we imposed a hand-based velocity-dependent force field to the left arm (see below for force field). This perturbation would result in a large lateral displacement in the absence of any predictive compensation. The robotic device was coupled to a virtual reality system such that start, finger tip, and target positions were projected as small circles on a semi-transparent mirror through which subjects could see their entire limb (Singh and Scott, 2003).

The starting position (1cm diameter) of the left and right hands were equally separated from the midline by 6-8cm giving shoulder and elbow angles of 33-42deg and 90deg, respectively. The target position for each hand was 10 cm forward from the start position. Targets could appear for the left hand alone (unimanual) or for both hands (bimanual) after a 1.5±0.25s hold time at the starting position. Target condition was pre-cued by one or two vertically long ellipse(s) (0.3×8.0cm) appearing at the starting target(s) for unimanual and bimanual trials. Subjects were required to reach with a peak hand velocity of 0.4±0.06 m s^{-1}. Peak velocities above or below this 15% threshold were indicated by the white target changing to red or blue, respectively. Accurate performance was signaled by a switch to green. Before data collection, subjects performed 30 to 40 unloaded practice trials to familiarize themselves with the task.

Force field generated by robotic exoskeleton

Two torque motors (Kollmorgen U12CBL, Radford, Virginia) attached to the linkage for each arm could apply loads to each joint independently. Motor positions measured by resolvers attached to the motors, were converted to encoder-equivalent units and sent to a motor control card (mini-PMAC, Delta Tau, Chatsworth, California) in the host computer, which computed joint positions and velocities and controlled the magnitude of the torque applied by the motors. Target lights were presented in the plane of the task using an overhead projector and a screen positioned above a semi-transparent mirror (Supplementary Figure 1b).

Using this robotic exoskeleton, we mimicked a velocity-dependent endpoint force field (f_x, f_y) using the two torque motors as follows (Supplementary Figure 1c):

$$\begin{pmatrix} T_s \\ T_e \end{pmatrix} = \begin{pmatrix} l_1 \sin\varphi_1 + l_2 \sin\varphi_2 & -(l_1 \cos\varphi_1 + l_2 \cos\varphi_2) \\ l_2 \sin\varphi_2 & -l_2 \cos\varphi_2 \end{pmatrix} \begin{pmatrix} f_x \\ f_y \end{pmatrix},$$

where the T_s and T_e are the shoulder and elbow joint torques, respectively.

In Experiments 1 and 2 for the left arm, the force field was $f_x = 10v_y, f_y = -10v_y$ where the v_y is y-component of the endpoint (hand) velocity (m s^{-1}) and force is in Newtons. In Experiment 3, two purely rotatory force fields were used: $f_x = 10v_y, f_y = -10v_x$ where the v_x is the x-component of the hand velocity for the rightward force field and $f_x = -10v_y, f_y = -10v_x$ for the leftward force field.

Experiment 1

Eight subjects completed two counter-balanced sessions where they trained with the perturbing force field during either unimanual reaches or bimanual reaches. Both sessions began with 20 unloaded unimanual and bimanual movements for a pre-perturbation baseline. Subjects then performed 40 reaches with the force field in either the unimanual or bimanual condition; *note that the force perturbation was applied only to their left arm.* Force-field training was followed by 120 trials where the perturbation was randomly removed once per 12 trials, i.e. 'catch trials'. Both sessions had unimanual and bimanual catch trials, but bimanual reaching only occurred during catch trials in the unimanual session (and vice versa). This design allowed us to compare transfer from unimanual training to bimanual reaches (and vice versa). The session ended with 20 repeated catch trials for the same movement context as performed during the learning phase to observe the washout of learning, i.e. unimanual washout during the unimanual session and bimanual washout during the bimanual session.

Experiment 2

Eight subjects completed two counter-balanced sessions similar to the 20 baseline trials, 40 training trials, and 120 test/random-catch trials of Experiment 1. As before, perturbations were applied only to their left arm. Subjects then had two successive blocks of catch trials. The first block involved the movement context *not used* during training whereas the second block involved the movement context *used* during training, i.e. 10 repeated bimanual (or unimanual) catch trials followed by 10 repeated unimanual (or bimanual) catch trials for the unimanual (or bimanual) training sessions.

Control experiment of Exp1 and Exp2

This experiment aimed to investigate if the results (i.e. partial transfer and partial elimination of motor learning) could arise from pairing two arbitrary motor acts. Eight subjects learned the force field during unimanual movements (left arm) paired with right ankle flexion. Sufficient practice was undertaken so that the subject moved the left arm and right foot synchronously. Foot movements were monitored with a magnetic position sensor (Polhemus, USA). Then two kinds of catch trials and washout trials (reaching+foot and reaching only) were conducted as in Exp 2.

Experiment 3

Ten subjects completed two sessions in counter-balanced order: ‘combined’ and ‘unimanual-only’. In the ‘combined’ session, subjects reached with unimanual and bimanual movements in alternation.

Subjects began with 20 baseline trials of both movement types followed by 80 training trials where rightward and leftward force fields were also alternated on each trial. Thereby, the force field during unimanual reaching was always opposite the force field during bimanual reaching. As before, the forces were applied to the left arm only. In the following 120 trials, unimanual and bimanual catch trials were intervened once per 12 trials. The session ended with 20 repeated catch trials for each movement type. Subjects were not given any explicit information on the direction of the force fields.

In the 'unimanual-only' condition, subjects performed only unimanual reaches. Following 20 baseline trials, subjects were exposed to the opposing fields in alternating trials, 80 total. Force field direction was pre-cued by the target color (blue, rightwards; red, leftwards). The session ended with 20 repeated catch trials for each target color.

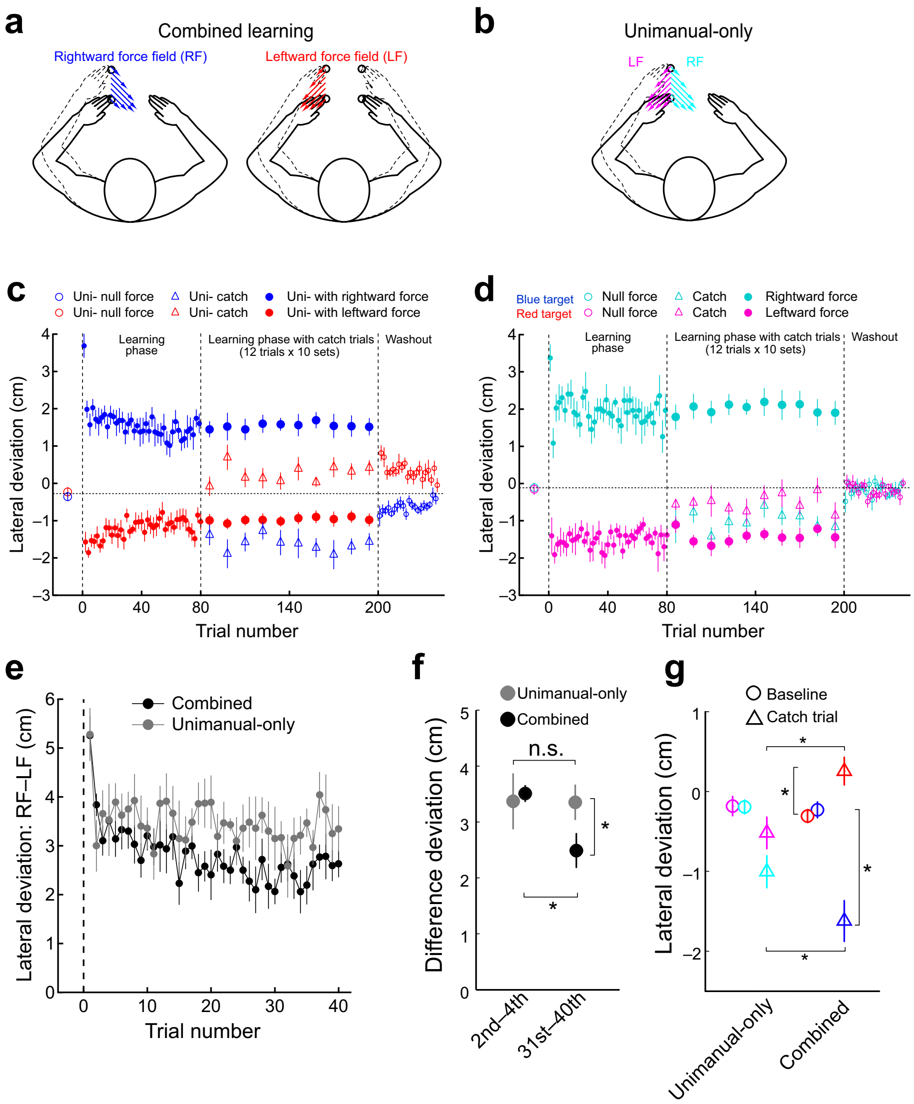
Data Analysis

The angular position and velocity data of the motor resolvers were collected at 1000 Hz. Signals were re-sampled at 100Hz then filtered with a 4th order zero-phase-shift Butterworth filter (effective cut-off frequency of 8 Hz). Finger position and velocity was calculated from this angular data. We quantified movement performance as the lateral deviation of the hand at its peak velocity relative to a line connecting the start and target positions.

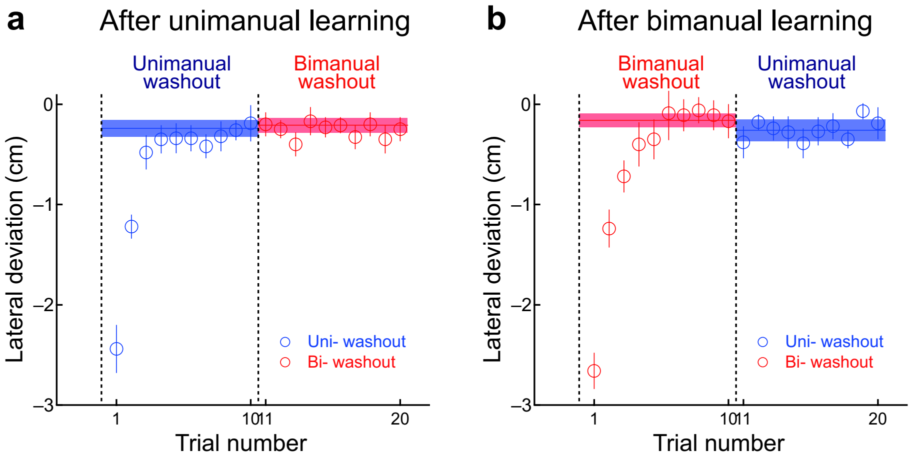
References

1. Scott, S. H. Apparatus for measuring and perturbing shoulder and elbow joint positions and torques during reaching. *J. Neurosci. Meth.* **89**, 119-127 (1999).

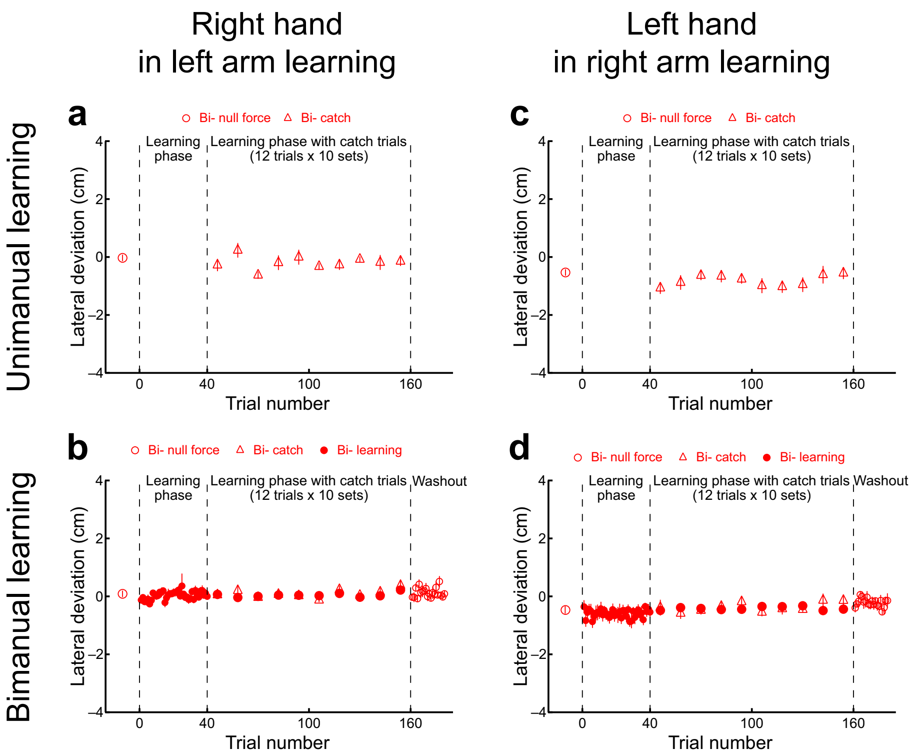
2. Singh, K. & Scott, S. H. A motor learning strategy reflects neural circuitry for limb control. *Nat. Neurosci.* **6**, 399-403 (2003).



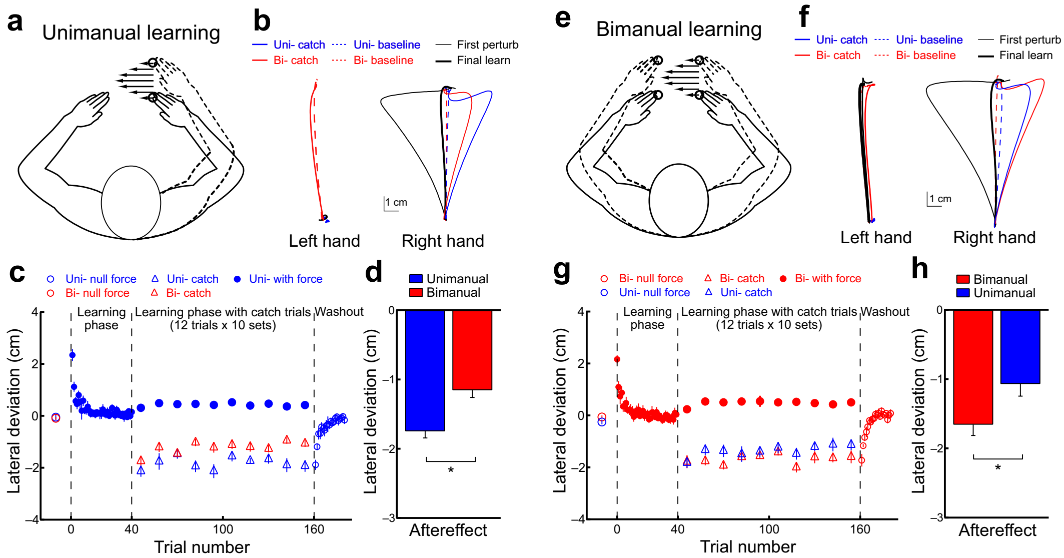
Supplementary Figure 7: Simultaneous learning of two different force fields predicted from the partial overlap model. (**a**) Subjects were asked to learn rightward (blue) and leftward (red) velocity-dependent force fields presented alternately ('combined' learning). (**b**) They were also asked to learn the force fields presented alternately only for unimanual reaches ('unimanual-only' learning). (**c, d**) Measured changes in the lateral hand deviation (mean±s.e.m. of each trial during learning and washout phase and of each set of 12 trials during learning phase with catch trials across all subjects) for combined (**c**) and unimanual-only (**d**) conditions. Positive value indicates rightward hand deviation. (**e**) Change in the difference of lateral hand deviations between two force fields during learning phase (mean±s.e.m.). (**f, g**) Comparison of the learning effect (**f**) and the aftereffect (**g**) between combined and unimanual-only conditions. The values are mean±s.e.m. $^*P < 0.05$



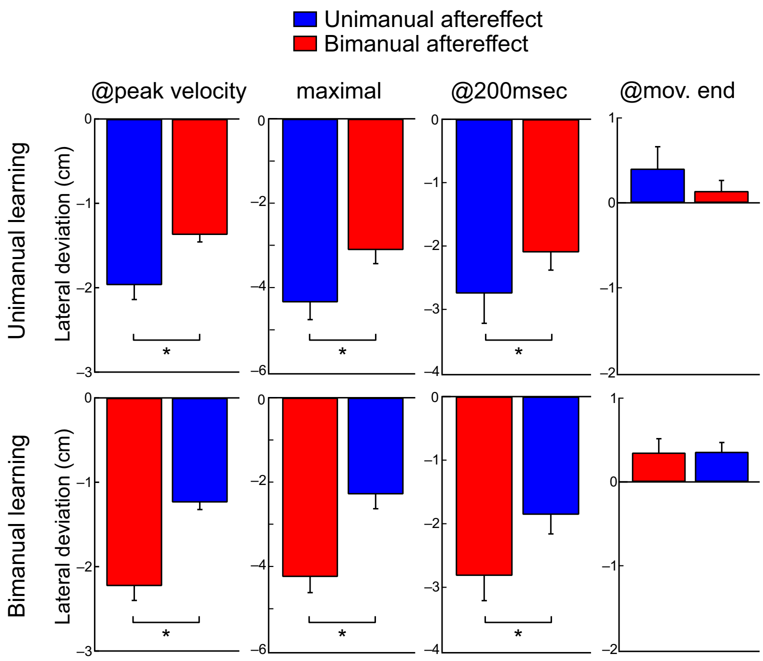
Supplementary Figure 6: (**a**) There was no substantial re-expression of aftereffects in the 1st bimanual catch trial conducted after 10 repeated unimanual catch trials when the subjects were trained unimanually. (**b**) Similarly, there was no substantial re-expression of aftereffects in the 1st unimanual catch trial conducted after 10 repeated bimanual catch trials when the subjects were trained bimanually. The values are mean±s.e.m. of each trial across all subjects.



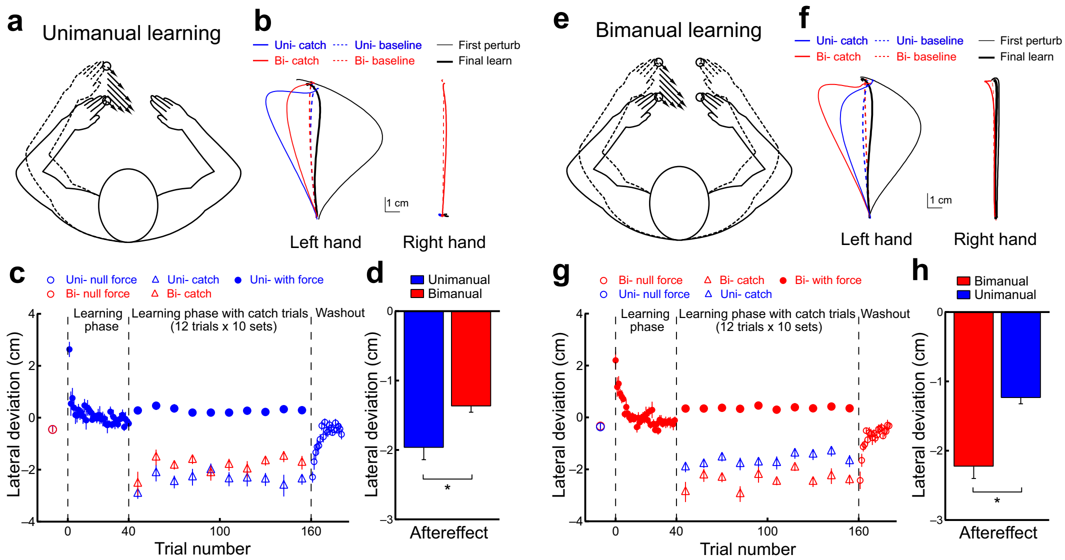
Supplementary Figure 5: Changes in the lateral deviation of the opposite hand; the right hand for left arm learning (**a**, unimanual; **b**, bimanual) and the left hand for the right arm learning (**c**, unimanual; **d**, bimanual). The values are mean±s.e.m. of each trial (learning and washout phases) and for each block consisting of 12 trials (learning phase with catch trials) across all subjects.



Supplementary Figure 4: (**a, e**) Subjects learned a velocity-dependent force field applied to the right arm either during unimanual (**a**) or bimanual (**e**) reaching movements. Black arrows denote the approximate size and direction of the force field applied to the limbs during movement. (**b, f**) Left and right hand paths obtained during unimanual (**b**) and bimanual (**f**) learning condition. Each diagram shows the mean hand paths for baseline unloaded reaching, initial and final hand trajectory when the load was applied, and aftereffects observed during catch trials. (**c, g**) Change in the lateral hand deviation with trials for unimanual (**c**) and bimanual (**g**) learning session. Positive value indicates hand deviation to the left. The values are mean±s.e.m. of each trial (learning and washout phases) and for each block consisting of 12 trials (learning phase with catch trials) across all subjects. (**d, h**) Summary of the aftereffects during catch trials for unimanual (**d**) and bimanual (**h**) learning session. There were significant differences in the lateral hand deviation between unimanual and bimanual aftereffects (*$P < 0.05$). Error bars indicate s.e.m.



Supplementary Figure 3: The aftereffects were compared between unimanual and bimanual movements with four different measures: the lateral hand deviation at the peak velocity (column 1: these are identical to the results shown in Fig.1 in main text and in Supplementary Fig.2), the maximal lateral hand deviation (column 2), and the lateral hand deviation at 200ms after the movement onset (column 3). The values are mean±s.e.m. These measures did not alter the results: the aftereffects were significantly ($^*P < 0.05$) larger for unimanual (bimanual) movement after bimanual (unimanual) learning. Since the subjects were required to touch the target by visual feedback, the movement end error was not appropriate for the evaluation. In fact, there were no significant differences in the movement end error between unimanual and bimanual catch trials (column 4). It should be also noted that the movement end errors were within the range of the target radius (0.5cm).



Supplementary Figure 2: (**a, e**) Subjects learned a velocity-dependent force field applied to the left arm either during unimanual (**a**) or bimanual (**e**) reaching movements. Black arrows denote the approximate size and direction of the force field applied to the limbs during movement. (**b, f**) Left and right hand paths obtained during unimanual (**b**) and bimanual (**f**) learning condition. Each diagram shows the mean hand paths for baseline unloaded reaching, initial and final hand trajectory when the load was applied, and aftereffects observed during catch trials. (**c, g**) Change in the lateral hand deviation with trials for unimanual (**c**) and bimanual (**g**) learning session. Positive value indicates hand deviation to the left. The values are mean±s.e.m. of each trial (learning and washout phases) and for each block consisting of 12 trials (learning phase with catch trials) across all subjects. (**d, h**) Summary of the aftereffects during catch trials for unimanual (**d**) and bimanual (**h**) learning session. There were significant differences in the lateral hand deviation between unimanual and bimanual aftereffects (*$P < 0.05$). Error bars indicate s.e.m.

Supplementary Information

Whole results of Experiment 1

Supplementary Figure 2 shows the result of Exp.1 for bimanual learning and unimanual learning.

Evaluation of motor adaptation; other measures

Throughout the present paper, we used the lateral hand deviation at peak velocity to evaluate the degree of motor adaptation. However, our results were robust to the particular measures employed including the maximal lateral deviation and lateral deviation at 200ms post-movement onset (Supplementary Figure 3, column1-3). Movement end error is frequently used for the evaluation, but it is not appropriate in the current experimental setting. This is because the subjects were always required to touch the target by visual feedback. In fact, there were no significant differences in the movement end error (the error when the movement velocity was closest to zero) between unimanual and bimanual catch trials (Supplementary Figure 3, column4).

Task variation: Right arm adaptation for Experiment 1

We replicated Experiment 1 to illustrate that the results can be observed for different loads and when the load is applied to the right limbs. Eight subjects performed Experiment 1 using the same leftward force field as in Experiment 3 (Supplementary Figure 4a, e). As in the case of the left arm, aftereffects of the right arm after unimanual learning were significantly smaller during the bimanual reaching than the unimanual reaching ($66.2 \pm 13.5\%$; $F_{1,7} = 44.84$, $P < 0.001$; Supplementary Figure 4b-d). This pattern was reversed when the subjects learned the force field bimanually ($64.1 \pm 21.9\%$; $F_{1,7} = 17.96$, $P < 0.01$; Supplementary Figure 4f-h). Hence, the result that the learning effect was not fully transferred between unimanual and bimanual movements was not dependent on the arm or load tested.

Movement of the opposite arm

Supplementary Figure 5 shows the lateral hand deviation of the non-perturbed arm in Experiment 1 (e.g., the right arm when subjects were trained with left arm). There were no apparent aftereffects, indicating the learning was specific to the trained limb.

The reversal order of two blocks of washout trials for Experiment 2

In Experiment 2, the training and two washout blocks had the following order: uni-bi-uni or bi-uni-bi. Seven subjects performed a variant of Experiment 2: uni-uni-bi or bi-bi-uni. In this case, the re-expressed aftereffects observed in the 1st trial of the 2nd washout in Experiment 2 (Fig.2 in the main text) were never observed (Supplementary Figure 6).

Task variation: Different force field for Experiment 3

We examined whether the *type* of force field influenced the results. Eight subjects performed Experiment 3 using the force field from Experiment 1 and 2 ($f_x = 10v_y, f_y = -10v_y$) and its reflection about y axis ($f_x = -10v_y, f_y = -10v_y$), which caused both a lateral deviation and forward resistance (Supplementary Figure 7a,b). Although the two force fields were not orthogonal (i.e. not completely conflicting), subjects could have partial adaptation by 'combined' learning (Supplementary Figure 7c, e-g) and negligible adaptation during 'unimanual-only' (Supplementary Figure 7d-g).