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Supplementary Information for
Motor learning without movement.

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This PDF file includes:

Supplementary Information Text

Extended Methods. The text used for conveying instructions to participants in Experiments 1-5 is shown here. During the experiments, the background color of the screen was a warm black, so most of the text was shown in light colors. For the sake of legibility, we have changed any white text to black and used a highlighted background to indicate when a word was shown in another color (i.e., the color of the highlight). To make these sections easier to refer to in the main text, we have abbreviated "Experiment" to "E".

E1 Instructions.

Baseline.

You will see one target.

Hold the cursor in the circle at the center of the screen to start a trial.

When the target turns `green`, move your hand `straight through` it.

The target will turn `gray` when you have moved far enough.

Then, the robot will automatically move your hand back to the center circle.

Always try to make `straight` hand movements.

No-feedback.

The cursor will now be hidden while you reach to the target.

Continue making `straight` hand movements through the target when it turns `green`.

No-movement.

On some trials, the target will turn `magenta` after turning `green`.

Do not move on these `stop` trials.

Instead, you will see the cursor moving by itself through the target.

When the target stays `green`, make a `straight` hand movement through the target.

Test block.

Great job! For the remainder, there will be a mixture of trials.

Sometimes, the cursor will be hidden. Other times, the cursor will move at an angle relative to the "real" hand position.

Even through you cannot see it, always try to `move your hand straight through the target when the target` is `green`.

Remember, do not move if the target turns `magenta`.

There will be periodic breaks.

Break.

Take a break.

As a reminder: when the target is green, try to move your hand (not the displayed cursor) straight through the target.

Do not move if the target turns magenta.

E2-5 Instructions. The text of these instructions was accompanied by corresponding animations.

Baseline (Movie S1).

You will see one target.

Hold the cursor in the circle at the center of the screen to start a trial.

When the target turns green, move your hand straight through it.

The target will turn gray when you have moved far enough.

Then, the mouse cursor will teleport next to the center.

Always try to make straight hand movements.

No-feedback (Movie S2).

The cursor will now be hidden while you reach to the target.

Continue making straight mouse movements through the target when it turns green.

The animation below shows how you should try to move your mouse, although your mouse pointer will be hidden on these trials.

No-movement (Movie S3).

On some trials, the target will turn magenta after turning green.

Do not move on these stop trials.

Instead, you will see the cursor moving by itself through the target.

When the target stays green, make a straight mouse movement through the target.

Test block (Movie S4).

Great job! For the remainder, there will be a mixture of trials.

Sometimes, the cursor will be hidden. Other times, the cursor will move at an angle relative to the "real" mouse position.

Even through you cannot see it, always try to move the real mouse straight through the target when the target is green.

Remember, do not move if the target turns magenta.

There will be periodic breaks.

Break (Movie S5).
Take a break.

As a reminder: when the target is green, try to move your hand (not the displayed cursor) straight through the target.

Do not move if the target turns magenta.

Move through the target reminder (Movie S6).
Make reaches through the green target.

Movement time reminder (Movie S7).
Please move quickly through the target.

Reaction time reminder (Movie S8).
Please start the reach sooner.

Withhold movement reminder (Movie S9).
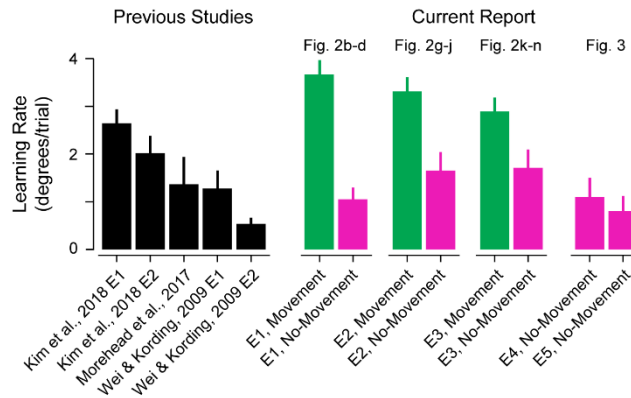Do not move when the target is magenta.

Fig. S1. Learning rates reported in the literature and observed in the current study. Learning rates for motor adaptation observed in previous studies are shown at left in black, and learning rates observed in each experiment in the current report are shown at the right, with data from Movement triplets shown in green and data from No-Movement triplets shown in magenta. Data are shown as mean ± SEM, and are shown for rotational/error clamp perturbations of 15°, with the exception of Wei & Körding, 2009 E2, where an 11° perturbation was applied. Papers referred to and their corresponding reference numbers: Kim et al., 2018 (1); Morehead et al., 2017 (2); Wei & Körding, 2009 (3). "E1, Movement" and "E1, No-Movement" show data from the in-lab experiment where participants saw 15° rotated feedback on Movement trials (*i.e.*, Experiment 1, **Fig. 2c-e**), "E2, Movement" and "E2, No-Movement" show data from the online experiment where participants saw 0-15° rotated feedback on Movement trials (*i.e.*, Experiment 2, **Fig. 2f-h**). "E3, Movement" and "E3, No-Movement" show data from the online experiment where participants saw 0-15° error-clamed feedback (*i.e.*, Experiment 3, **Fig. 2i-k**). "E4, No-Movement" shows data from the online experiments where participants saw feedback rotated by 0° on Movement trials but saw 15° perturbations on No-Movement trials (*i.e.*, Experiment 4, **Fig. 3**, left sub-panels). "E5, No-Movement" shows data from the online experiments where participants saw 0° error-clamped feedback on Movement trials but saw 0-15° perturbations on No-Movement trials (*i.e.*, Experiment 5, **Fig. 3**, right sub-panels). Abbreviations: E, experiment.
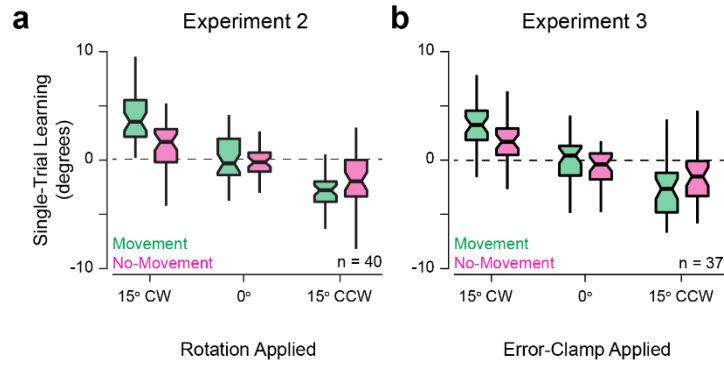
Fig. S2. Summary statistics of data collected in Experiments 2 and 3. As statistical comparisons were conducted using the estimated marginal means (EMMs) from linear mixed models, figures showing the EMMs are included in the main text of the paper. For completeness, we have included boxplots showing summary statistics for participantwise single-trial learning (STL) measurements under each experimental condition. (**a**) Boxplots (center: median, notches: 95% confidence-interval of the median, box edges: 1st and 3rd quartiles, whiskers: most extreme value within 1.5*interquartile range of the median) showing STL across Movement (green) and No-Movement (magenta) triplets for participants in Experiment 2. (**b**) As in (**a**), but for participants in Experiment 3.

Table S1. Pairwise post-hoc comparisons between estimated marginal means in **Fig. 2h** (Experiment 2).

Group 1		Group 2		Est. Diff.	t	df	FDR-adjusted p	Cohen's d
Trial Type	Rotation	Trial Type	Rotation					
M	0°	M	15° CW	-3.67°	-9.14	2227	* 6.39×10^{-19}	-0.61
M	0°	M	15° CCW	3.09°	7.81	2220	* 2.60×10^{-14}	0.52
M	15° CW	M	15° CCW	6.76°	17.08	2223	* 1.31×10^{-60}	1.13
No-M	0°	No-M	15° CW	-1.88°	-3.92	2225	* 0.0001	-0.31
No-M	0°	No-M	15° CCW	1.75°	3.56	2229	* 0.0005	0.29
No-M	15° CW	No-M	15° CCW	3.64°	7.41	2231	* 3.86×10^{-13}	0.61
M	0°	No-M	0°	0.41°	0.93	2240	0.35	--
M	15° CW	No-M	15° CW	2.20°	4.98	2238	* 1.25×10^{-6}	0.37
M	15° CCW	No-M	15° CCW	-0.93°	-2.06	2239	* 0.04	-0.15

Note. Abbreviations: M – Movement; No-M – No-Movement; Est. Diff. – Estimated Differences in degrees. Note that degrees of freedom pertain to the inputs to the LMM and are estimated using the Kenward-Roger approach. Statistically significant p-values are indicated with asterisks. * $p < 0.05$.

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Table S2. Pairwise post-hoc comparisons between estimated marginal means in **Fig. 2m** (Experiment 3)

Group 1		Group 2		Est. Diff.	t	df	FDR-adjusted p	Cohen's d
Trial Type	Rotation	Trial Type	Rotation					
M	0°	M	15° CW	3.54°	-7.55	1827	* 3.08×10^{-13}	-0.56
M	0°	M	15° CCW	2.57°	5.57	1828	* 8.84×10^{-8}	0.41
M	15° CW	M	15° CCW	6.11°	13.14	1828	* 8.51×10^{-37}	0.97
No-M	0°	No-M	15° CW	-1.81°	-3.21	1830	* 0.002	-0.29
No-M	0°	No-M	15° CCW	1.29°	2.25	1832	* 0.03	0.20
No-M	15° CW	No-M	15° CCW	3.10°	5.46	1833	* 1.24×10^{-7}	0.49
M	0°	No-M	0°	0.08°	0.16	1846	0.87	--
M	15° CW	No-M	15° CW	1.81°	3.49	1846	* 0.0009	0.29
M	15° CCW	No-M	15° CCW	-1.19°	-2.28	1846	* 0.03	-0.19

Note. Abbreviations: M – Movement; No-M – No-Movement; Est. Diff. – Estimated Differences in degrees. Note that degrees of freedom pertain to the inputs to the model and are estimated using the Kenward-Roger approach. Statistically significant p-values are indicated with asterisks. * $p < 0.05$.

Table S3. Pairwise post-hoc comparisons between estimated marginal means in Fig. 3

Group 1		Group 2		Est. Diff.	t	df	FDR-adjusted p	Cohen's d
Trial Type	Rotation	Trial Type	Rotation					
		Experiment 4						
No-M	15° CCW	No-M	15° CW	2.45°	4.80	557	* 2.07 x 10^{-6}	0.40
		Experiment 5						
No-M	15° CCW	No-M	15° CW	2.37°	4.32	805	* 0.0001	0.37
No-M	15° CW	No-M	0°	1.36°	2.48	801	* 0.020	0.21
No-M	15° CCW	No-M	0°	1.01°	1.83	800	0.068	--

Note. Abbreviations: No-M – No-Movement; Est. Diff. – Estimated Differences in degrees. Note that degrees of freedom pertain to the inputs to the model and are estimated using the Kenward-Roger approach. Statistically significant p-values are indicated with asterisks. * p < 0.05.

Movie S1 (separate file). Baseline instructions. A movie showing the appearance of the initial, baseline instructions in Experiments 2-5. The accompanying, explanatory animation is also shown. In the animation, the white circle on the right side of the frame represents the starting location, and the grey circle on the left represents the target location. A black pointer on top of a white, circular cursor represent the participant's mouse location on an ideal trial, on which the target turns green and the participant moves the mouse straight through the center of the target.

Movie S2 (separate file). No-feedback instructions. A movie showing the appearance of the instructions about trials without cursor feedback in Experiments 2-5. The accompanying, explanatory animation is also shown. In the animation, the white circle on the right side of the frame represents the starting location, and the grey circle on the left represents the target location. A black pointer represents the participant's mouse location on an ideal trial, on which the target turns green and the participant moves the mouse straight through the center of the target.

Movie S3 (separate file). No-Movement instructions. A movie showing the appearance of the instructions about staying still on No-Movement trials in Experiments 2-5. The accompanying, explanatory animation is also shown. In the animation, the white circle on the right side of the frame represents the starting location, and the grey circle on the left represents the target location. A black pointer represents the participant's mouse location and a small, white circle represents the animated cursor movement on an exemplar trial. In the example trial, the target turns green before quickly turning magenta, and the mouse pointer remains stationary in the starting location while the cursor moves through the target.

Movie S4 (separate file). Test block instructions. A movie showing the appearance of the instructions to be followed during the test block in Experiments 2-5. The accompanying, explanatory animation is also shown. In the animation, the white circle on the right side of the frame represents the starting location, and the grey circle on the left represents the target location. A black pointer represents the participant's mouse location and a small, white circle represents the cursor movement on an example trial. In the example trial, the target turns green, and the mouse pointer moves through the center of the target. The cursor is shown at a location rotated 15° clockwise of the mouse pointer/error-clamped to travel 15° clockwise of the target center.

Movie S5 (separate file). Break instructions. A movie showing the appearance of the break notification and refresher instructions in Experiments 2-5. The accompanying, explanatory animation is also shown. In the animation, the white circle on the right side of the frame represents the starting location, and the grey circle on the left represents the target location. A black pointer represents the participant's mouse location and a small, white circle represents the cursor movement on an example trial. In the example trial, the target turns green, and the mouse pointer moves through the center of the target. The cursor is shown at a location rotated 15° clockwise of the mouse pointer/error-clamped to travel 15° clockwise of the target center.

Movie S6 (separate file). Move toward the target reminder. A movie showing the appearance of reminder instructions about moving towards the target in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green. Then, the participant moves the cursor about 45° clockwise of the target. After the cursor passes the target distance, a 4-s time-out is initiated, and the text "Make reaches toward the green target" is shown during the time-out.

Movie S7 (separate file). Move quickly through the target reminder. A movie showing the appearance of reminder instructions about moving quickly through the target in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green. Then, the participant moves the cursor about 45° counterclockwise

of the target, but does not meet the movement time requirement (<400 ms). After the cursor passes the target distance, a 4-s time-out is initiated, and the text "Please move quickly through the target" is shown during the time-out.

Movie S8 (separate file). Reaction time reminder. A movie showing the appearance of reminder instructions about reacting quickly in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot is the cursor. After a delay, the target turns green. Then, the participant moves the cursor through the target, but does not meet the reaction time requirement (<800 ms). After the cursor passes the target distance, a 4-s time-out is initiated, and the text "Please start the reach sooner" is shown during the time-out.

Movie S9 (separate file). Reminder to withhold movement on No-Movement trails. A movie showing the visual feedback, reminder, and time-out that occurred on an instance where a participant moved on a No-Movement trial in the online experiment. This warning and timeout were shown if movement was detected on a No-Movement trial in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green and then magenta. The participant moves (not visible in the movie, as the cursor feedback was not tied to participant movement), triggering the appearance of the warning message and the onset of a 4-s time-out. After the time-out period ends, the warning message is hidden and the start and target locations are displayed.

Movie S10 (separate file). No-Movement trial 15° counterclockwise perturbation. A movie of the visual stimuli shown on a No-Movement trial with a 15° counterclockwise perturbation in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green and then magenta. The cursor is then seen moving 15° counterclockwise of the target center. This cursor movement was pre-programmed and occurred only if the participant was stationary in the starting location.

Movie S11 (separate file). No-Movement trial 0° perturbation. A movie of the visual stimuli shown on a No-Movement trial with a 0° perturbation in Experiments 2-3. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green and then magenta. The cursor is then seen moving directly to the center of the target. This cursor movement was pre-programmed and occurred only if the participant was stationary in the starting location.

Movie S12 (separate file). No-Movement trial 15° clockwise perturbation. A movie of the visual stimuli shown on a No-Movement trial with a 15° clockwise perturbation in Experiments 2-5. The larger white circle at the center of the movie is the central starting location, and the grey circle in the top right of the movie is the target location. The smaller dot that appears near the center of the screen is the cursor. Once it appears, the participant moves to the starting location. After a delay, the target turns green and then magenta. The cursor is then seen moving 15° clockwise of the target center. This cursor movement was pre-programmed and occurred only if the participant was stationary in the starting location.

SI References

1. H. E. Kim, J. R. Morehead, D. E. Parvin, R. Moazzezi, R. B. Ivry, Invariant errors reveal limitations in motor correction rather than constraints on error sensitivity. *Communications Biology* **1**, 1–7 (2018).

2. J. R. Morehead, J. A. Taylor, D. E. Parvin, R. B. Ivry, Characteristics of Implicit Sensorimotor Adaptation Revealed by Task-irrelevant Clamped Feedback. *J Cogn Neurosci* **29**, 1061–1074 (2017).

3. K. Wei, K. Körding, Relevance of Error: What Drives Motor Adaptation? *Journal of Neurophysiology* **101**, 655–664 (2009).