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Supplemental Information

A Rapid Tactile-Motor Reflex Automatically Guides Reaching toward Handheld Objects

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FIGURE S1

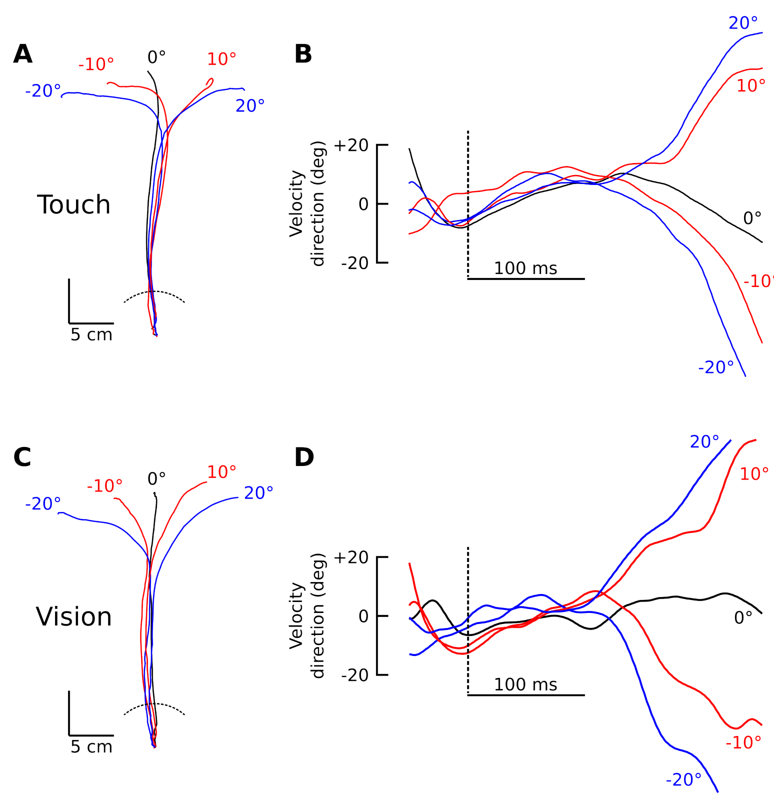

Figure S1 (related to Figure 2). Single trial data for Experiment 1.
(**A,B**) Same format as Fig. 2A,B. Each trace represents a single touch trial from Participant #2. Trials taken in order from near the end of the experiment.
(**C,D**) Same format but for vision trials.

FIGURE S2

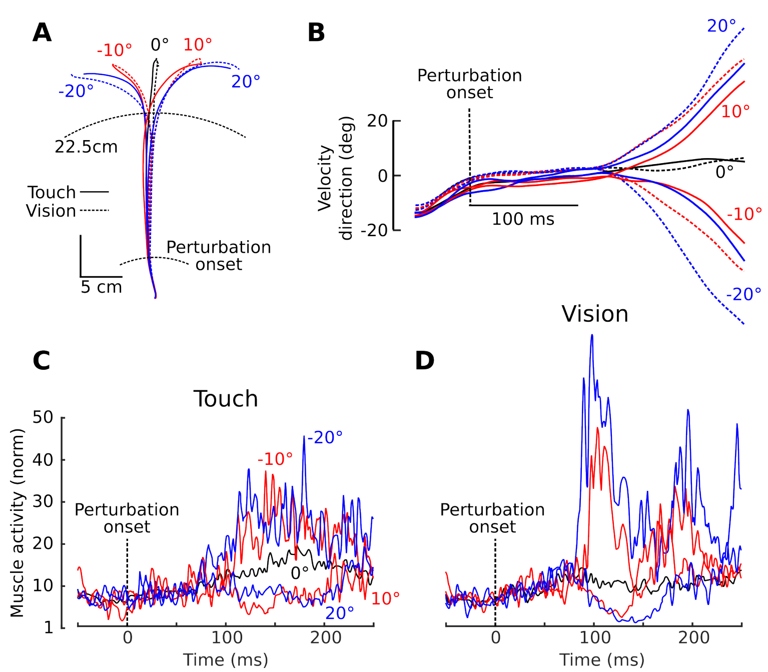

Figure S2 (related to Figure 2). Results for representative participant in Experiment 1.
(**A,B**) Same format as Fig. 2A,B but for a representative participant (#2).
(**C,D**) Same format as Fig. 3A,B but for a representative participant (#2).

FIGURE S3

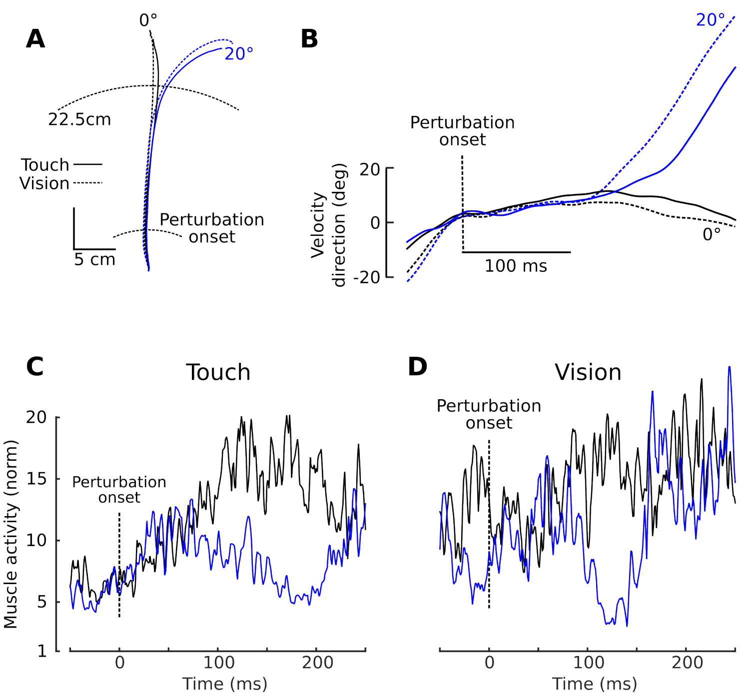

Figure S3 (related to Figure 4). Results for representative participant in Experiment 2.
(**A**) Same format as Fig. 2A but for a representative participant (#2) in Experiment 2.
(**B**) Same format as Fig. 4A but for a representative participant (#2).
(**C,D**) Same format as Fig. 4C but for a representative participant (#2).

SUPPLEMENTAL EXPERIMENTAL PROCEDURES

Participants

A total of 12 healthy right-handed individuals (19-34 years old) participated in two experiments. Participants provided written informed consent in accordance with the Declaration of Helsinki. The ethics committee of Umeå University approved the study.

Experimental procedures

Participants stood at a table (90 cm high) and made right-handed reaches from a central start location to a spherical target (diameter = 4 cm) located 30 cm in front of them (Fig. 1A). Their goal was to touch the target with their right index finger. The target was mounted on the distal end of a rod, the proximal end of which was connected to a vertically oriented shaft of a rotational motor (Fig. 1A,B). On a subset of trials, the motor could rotate the rod such that the participant needed to adjust their hand trajectory to successfully touch the displaced target. Target movements were triggered when the distance between the finger position and the start position first exceeded 5 cm. The duration of the target movement was always 50 ms. Participants could initiate a reach whenever they liked after keeping their index finger at the start position for 1-1.5 s (as indicated by an auditory cue). Participants were instructed to reach at a consistent speed and received auditory feedback if their reach time, defined as the time required for the finger to go from 5 cm to 22.5 cm relative to the start position, was not between 100 and 300 ms. Participants reliably met this constraint.

In the present experiments, we manipulated the magnitude and direction of target displacements (Fig. 1C) and, critically, the modality of sensory inputs upon which the participant could make corrective responses.

Experiment 1: Corrective responses to perturbations of varying direction and magnitude

Participants (n = 12) made reaching movements guided by either vision or touch. In vision trials, participants could see the target throughout the duration of the trial. In touch trials, participants had their vision occluded during the main portion of the reach by shutter glasses (PLATO, Translucent Tech., Toronto, Canada), but lightly held their left thumb on a raised edge attached to the near end of the rod. The edge (width at top = 0.5 mm; height = 8 mm; length = 28 mm) was aligned with the long-axis of the rod and centered on the rotational axis of the motor. The shutter glasses were open at the start of the trial allowing participants to prepare their movement while seeing the target at its unperturbed location. The shutter closed when the participant's right index finger contacted the start position but reopened when the distance between the finger and the start position exceeded 22.5 cm, which allowed participants to make terminal reach corrections based on vision (if needed).

For both vision and touch trials, half the trials were unperturbed so that participants reached straight to the presented target (0°). In the other half of trials, the target moved either left- or rightwards at one of two different magnitudes (i.e. ±10°, ±20°) with equal probability (Fig. 1C). Participants performed a total of 160 perturbed trials (2 sensory conditions x 4 target displacements x 20 repeats) and 160 unperturbed trials (2 sensory conditions x 80 repeats). These trials were grouped in 8 blocks of 40 trials, each based on a single sensory condition. Each block included 20 unperturbed trials and 5 perturbed trials for each direction and magnitude. Blocks were randomized across the experimental sessions and counterbalanced across individuals. Within each block, the various target displacements were randomly interleaved such that the participant could not predict the presence, direction or magnitude of a target displacement.

Note that a control experiment, where participants performed the touch trials of Experiment 1 but touched the motor housing rather than the edge, showed that general auditory and/or vibratory cues from the device could not be used to guide corrective responses. That is, participants were unable to reliably reach to the goal target on perturbation trials when touching the motor housing.

Experiment 2: Corrective responses when final target position is fully predictable

This experiment was run in the same session as Experiment 1. Participants (n = 12) made reaching movements guided by either vision or touch. Half the trials were unperturbed and, in the other half of trials, the target moved to the right at one magnitude (i.e. +20°). Participants performed 50 perturbed trials (2 sensory conditions x 1 target displacement x 25 repeats) and 50 unperturbed trials (25 per sensory condition). These trials were grouped in 2 blocks of 50 trials, each based on a single sensory condition. Each block included 25 unperturbed trials and 25 perturbed trials. Blocks were counterbalanced across individuals. Within each block, the perturbation trials were randomly interleaved such that the participant could not predict the presence of a target displacement but could perfectly predict the final location of the target on perturbation trials because there was only one possible target displacement.

Data analysis

We measured the position of the participant's right index finger in three dimensions at 120 Hz with a miniature electromagnetic position-angle sensor (FASTRAK; Polhemus, Colchester, VT) glued to the nail. We acquired muscle activity using electromyography (bandwidth 20–450 Hz) using bipolar electrodes (DE-2.1, Delsys, Boston, MA) placed on the skin above the bellies of two shoulder flexors (pectoralis major, biceps long head) and two shoulder extensors (posterior deltoid, triceps long head) of the right arm. We focused our analysis on the pectoralis major muscle. Similar results were evident for the biceps. Signals from the extensor muscles gave limited information since their activity was markedly inhibited during the reaching movement around the time of target displacement.

Kinematics and muscle activity were digitized and collected by the same system at a sampling rate of 1000 Hz (S/C Zoom, Umea, Sweden). All incoming data was filtered (3rd-order, two-pass, Butterworth with passpand 20-450 Hz) and temporally aligned on the time when the right index finger first passed 5 cm from the start position, which was the trigger for onset of object rotation and target movement in perturbation trials. We analyzed the trajectory of the finger motion in the horizontal plane. Preliminary analyses showed no obvious effect of sensory condition or type of target displacement on hand elevation. To analyze how hand kinematics evolved over time as a function of target displacement and sensory condition, we calculated the direction of the velocity vector by numerical differentiation of the finger position signals in the horizontal plane.

Muscle activity was full-wave rectified and normalized to the mean background activity when the participant held their right index finger at the start position (500 ms window before they received the cue that they could begin reaching). To quantify muscle activity during the fast corrective responses, we analyzed mean activity between 75 and 100 ms after perturbation onset. We chose this epoch because responses at these latencies are automatic, that is, faster than standard measures of voluntary reaction time. The effect of sensory condition and target displacement on the muscle activity was assessed using a repeated-measures ANOVA.

We used the receiver-operator characteristic (ROC) technique to determine the time point when kinematics or muscle activity first differed as a function of target displacement for each sensory condition. For each time step (1 ms), we generated an ROC curve to calculate the probability that an ideal observer could discriminate between kinematics or muscle activity for target displacements of equal magnitude but opposite direction (Exp. 1) or between the perturbed (+20°) and unperturbed (0°) trials (Exp. 2). Areas under the ROC curve with values of 0 and 1 represent perfect discrimination, whereas a value of 0.5 represents chance performance. For kinematic data, we estimated the timing of the initial separation by first calculating when the ROC data remained above a threshold of 0.75 or below 0.25 for at least 5 consecutive time steps and then looking back in time for the first data sample that fell on the other side of 0.5 (i.e. < 0.5 if threshold = 0.75; > 0.5 if threshold = 0.25). We used the same approach for muscle activity data but with thresholds of 0.4 and 0.6 to account for relatively noisy nature of single-trial muscle activity. Because such quantitative methods are sensitive to the signal-to-noise ratio of the underlying signals [S1], we confirmed that our findings were qualitatively similar across a range of thresholds and that the outputs of our quantitative method matched manual inspection of the underlying data. We compared our estimates of initial separation times using a repeated-measures ANOVA with sensory condition and target displacement as factors (Exp. 1) or with a paired t-test between sensory conditions (Exp. 2). All statistical tests were deemed significant if $p < 0.05$.

SUPPLEMENTAL REFERENCES

S1. Oostwoud Wijdenes, L., Brenner, E., and Smeets, J. B. J. (2014). Analysis of methods to determine the latency of online movement adjustments. Behav. Res. Methods *46*, 131–139.