Supplemental Information

Rapid Automatic Motor Encoding

of Competing Reach Options

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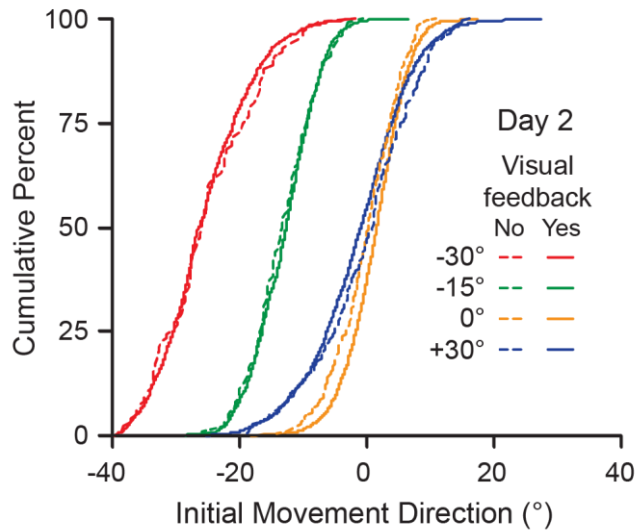
Figure S1: Initial movement directions with and without visual feedback after adaptation (Day 2), Related to Figure 2. Cumulative distributions of initial movement directions (i.e., handle direction at 30% of the target distance) from post-adaptation (Day 2) one-target trials with (solid lines) and without (dashed lines) visual feedback of the cursor controlled by the hand. The distributions include all data from all participants. Note that the initial directions with and without visual feedback are very similar for all four targets shown.
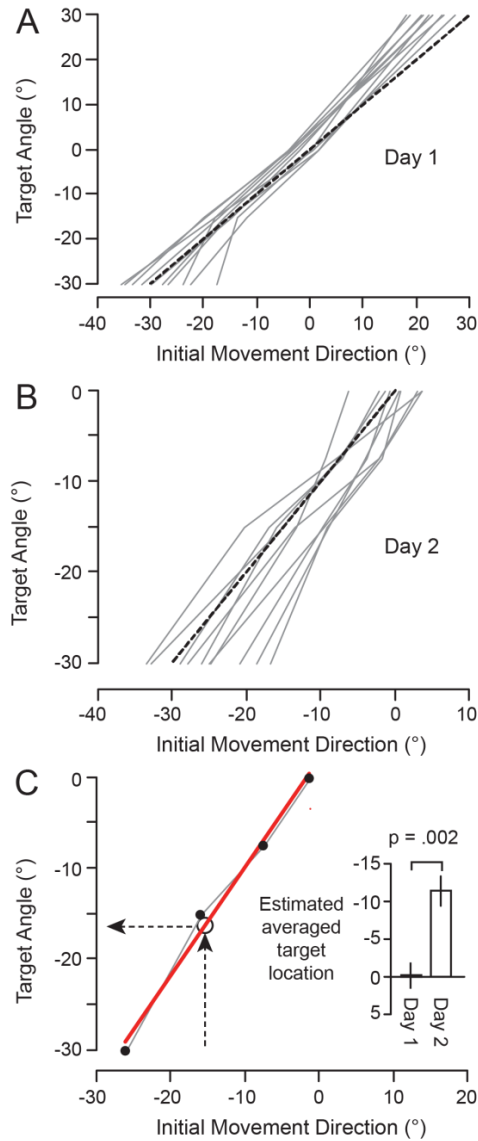
Figure S2: Estimation of target direction under the assumptions of visual averaging, Related to Figure 3. (A) Each grey line shows the mapping between target angle and initial reach direction (i.e., handle direction at 30% of the target distance) based on Day 1 one-target trials for each participant. **(B)** Corresponding mappings, for each participant, on Day 2. The dashed lines in A and B are unity lines. **(C)** Target direction estimation procedure. For each participant, a linear regression line was fit through the data points (red line), allowing us to estimate the averaged target position that the participant was putatively aiming for—assuming visual averaging—given their initial movement direction on -30/+30° two-target trials. Example in C is from Day 2. The inset in C (at right) shows the mean estimated angle of the target on Days 1 and 2, based on participant medians. The error bars represent ± 1 SE.

Supplemental Experimental Procedures

Maintenance of visuomotor adaptation during non-visual feedback trials

In our experiment, it was critical to maintain adaptation during the post-adaptation phase (on Day 2) in one- and two-target trials without visual feedback of the cursor controlled by the hand. With this goal in mind, we provided visual feedback of the cursor in the majority of one-target trials. Figure S1 shows cumulative distributions of initial hand directions—combining data from all trials and participants—from Day 2 one-target trials (to the -30, -15, 0 and +30° targets) with and without visual feedback. The fact that initial hand directions were highly similar with and without visual feedback indicates that we were successful in maintaining adaptation effects during trials without visual feedback.

Assessing the 'visual averaging' hypothesis

As shown in Fig. 3A, we observed a significant counterclockwise rotation of the initial movement direction in -30/+30° two-target trials on Day 2, relative to Day 1. Although this finding provides support for the motor, and not visual, averaging hypothesis, it is nevertheless possible that the learned visuomotor rotations may have had a small overall influence on movement directions on Day 2 that could influence these results. Thus, the test performed in our main paper may not provide a completely fair assessment of the null, visual averaging hypothesis.

A more direct way to evaluate the visual averaging hypothesis is to estimate the averaged target position that participants putatively aimed towards in -30/+30° two-target trials without cursor feedback on Days 1 and 2. Because this averaged visual-perceptual target position should be completely independent of the visuomotor rotations learned by participants (as only the motor, not visual, space was adapted on Day 2), the visual averaging hypothesis predicts that its position should not vary across testing days. To determine the averaged target position that participants putatively aimed towards we computed, for each individual, the median initial direction in Day 1 one-target trials involving the -30, -15, 0, and +30° targets and in Day 2 one-target trials involving the -30, -15, -7.5 and 0° targets (importantly, all trials in which movements were directed approximately to the target).

The grey lines in Figs. S2A and B show, for each participant, the mapping between their median movement directions and the target angles on Days 1 and 2, respectively. For each participant and day, we fit a linear regression line through the 4 data points (see Fig. S2C, which show the Day 2 data points from a single participant), allowing us to estimate the averaged target location (horizontal arrow) that a participant was ostensibly aiming for—under the assumption of the visual averaging hypothesis—given their initial movement direction (vertical dashed arrow). Note that this approach compensates for any possible effects of the visuomotor rotations applied (to the 0 and +30° one-target trials with visual feedback) on Day 2. The linear regressions provided good fits for all participants on each day (the 20 r^2 values, 10 participants x 2 days, ranged from 0.976 to 0.999).

The inset in Fig. S2C shows the average estimated angle, based on participant medians, of the target in -30/+30° two-target trials on Days 1 and 2, derived from the regression analyses described above. As can be clearly observed, the target angle on Day 2 was rotated counterclockwise relative to Day 1, which was centered approximately at 0°. A paired t-test confirmed that the estimated target angle on Day 2 (M = -11.41°; SE = 1.90°) was significantly less (t_9 = -4.20; p = 0.002) than on Day 1 (M = -0.17°; SE = 1.69°). These findings further argue against the visual averaging hypothesis and suggest that the reaches executed under target uncertainty are related to the learned movement vectors, and not visual directions, associated with each potential target.

Relation of current findings to previous work
In a previous paper (Stewart et al., 2014), we compared the motor versus visual encoding of potential targets by using an obstacle to dissociate target and reach directions (see also Pearce and Moran, 2012). There were three possible target locations: straight ahead (0°), right (+30°), and left (-30°). An obstacle was positioned on the right side of the workspace such that initial direction of reaches to the +30° target were straight ahead while the initial directions of reaches to the other two targets were unaffected. We found that when required to launch a reach movement towards the -30° and +30° potential targets, participants' initial reach directions were deflected to the left of midline. Although this result is consistent with the idea that competing visual targets are directly mapped onto corresponding movements required to attain those

4

targets (i.e., a motor encoding of the potential targets), we now recognize a limitation to this study that precludes a definitive conclusion. Specifically, because reaches launched towards two potential targets are far more variable in their initial directions than single-target movements (Chapman et al., 2010; Gallivan and Chapman, 2014; Ghez et al., 1997; Stewart et al., 2013; Stewart et al., 2014), it is plausible that participants, on two-target trials, shifted the distribution of their initial movement directions away from the obstacle's position (i.e., leftward) in order to provide a reasonable margin of safety for avoiding collision (Chapman and Goodale, 2008; Hamilton and Wolpert, 2002; Sabes and Jordan, 1997; Sabes et al., 1998). In this previous study (Stewart et al., 2014), there was also a 750 ms delay between target presentation and the go cue, which may have facilitated the implementation of a cognitive strategy to avoid the obstacle (Fernandez-Ruiz et al., 2011; Haith et al., 2015). For these reasons, we view the current set of results as particularly compelling evidence for the notion that the brain, when presented with multiple competing targets, automatically maps those potential targets onto associated motor representations in cortex.

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