

Running head: PREPARATION TIME CONSTRAINTS CAN ASSAY IMPLICIT  
VISUOMOTOR ADAPTATION

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Estimating the implicit component of visuomotor rotation learning by constraining movement preparation time.

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*Keywords:* implicit learning, explicit learning, compensatory strategies, motor learning, visuomotor rotation

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### **Abstract**

24           When sensory feedback is perturbed, accurate movement is restored by a combination of  
25 implicit processes and deliberate re-aiming to strategically compensate for errors. Here, we  
26 directly compare two methods used previously to dissociate implicit from explicit learning on a  
27 trial-by-trial basis: 1) asking participants to report the direction that they aim their movements,  
28 and contrasting this with the directions of the target and the movement that they actually produce,  
29 2) manipulating movement preparation time. By instructing participants to re-aim without a  
30 sensory perturbation, we show that re-aiming is possible even with the shortest possible  
31 preparation times, particularly when targets are narrowly distributed. Nonetheless, re-aiming is  
32 effortful and comes at the cost of increased variability, so we tested whether constraining  
33 preparation time is sufficient to suppress strategic re-aiming during adaptation to visuomotor  
34 rotation with a broad target distribution. The rate and extent of error reduction under preparation  
35 time constraints were similar to estimates of implicit learning obtained from self-report without  
36 time pressure, suggesting that participants chose not to apply a re-aiming strategy to correct  
37 visual errors under time pressure. Surprisingly, participants who reported aiming directions  
38 showed less implicit learning according to an alternative measure, obtained during trials  
39 performed without visual feedback. This suggests that the process of reporting can affect the  
40 extent or persistence of implicit learning. The data extend existing evidence that restricting  
41 preparation time can suppress explicit re-aiming, and provide an estimate of implicit visuomotor  
42 rotation learning that does not require participants to report their aiming directions.

### **New and Noteworthy**

44           During sensorimotor adaptation, implicit, error-driven learning can be isolated from  
45 explicit strategy-driven re-aiming by subtracting self-reported aiming directions from movement  
46 directions, or by restricting movement preparation time. Here, we compared the two methods.  
47 Restricting preparation times did not eliminate re-aiming, but was sufficient to suppress re-  
48 aiming during adaptation with widely-distributed targets. The self-report method produced a  
49 discrepancy in implicit learning estimated by subtracting aiming directions, and implicit learning  
50 measured in no-feedback trials.

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### Introduction

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55 When we move, perturbations to our body or the environment can elicit discrepancies

56 between predicted and actual outcomes. We readily adapt our movements to compensate when

57 such discrepancies are systematic, and this process is commonly termed sensorimotor adaptation.

58 Sensorimotor adaptation was traditionally thought to occur largely via implicit mechanisms

59 involving updating of an internal model (Wolpert et al. 1995) in order to compensate for sensory

60 prediction errors (i.e. mismatches between predicted and observed behaviour). It has long been

61 recognized, however, that explicit processes can influence the behavioural response to

62 sensorimotor perturbation (e.g., Keisler and Shadmehr 2010; Mazzoni and Krakauer 2006;

63 Redding and Wallace 1996; Uhlarik 1973). For example, if a rotation of visual feedback results

64 in a participant noticing systematic reaching errors to one side of a target, she might deliberately

65 aim to the opposite side of the target to compensate. One way to disentangle such strategic re-

66 aiming from implicit learning is to require participants to report their aiming directions

67 throughout adaptation, and then to infer implicit adaptation by subtracting verbally reported

68 aiming directions from actual movement directions (Bond and Taylor 2015; Brudner et al. 2016;

69 McDougale et al. 2015; Taylor et al. 2014). This method also provides a measure of explicit re-

70 aiming, which is estimated as the difference between the reported aiming direction and the target

71 direction. Studies using this approach suggest that explicit re-aiming dominates the rapid initial

72 error reduction typically seen in most sensorimotor adaptation studies, but then contributes

73 progressively less to behaviour as an implicit *remapping* between motor commands and expected

74 sensory outcomes develops with extended exposure to perturbation.

75 The capacity to decompose sensorimotor adaptation into implicit and explicit components

76 represents an important advance in the understanding of how the brain responds to systematic

77 discrepancies between desired and actual motor behaviour (Taylor et al. 2014). In particular, the

78 demonstration that explicit re-aiming dominates the initial error reduction phase of sensorimotor

79 adaptation presents challenges for those interested in assessing the rate of implicit remapping. A

80 method of disentangling explicit and implicit processes that relies upon subject reports of aiming

81 directions may have limitations, however. Firstly, the approach requires faithful reports of

intended aiming directions from study participants, which may be imprecise, difficult to obtain in

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82 some contexts, and time-consuming. Secondly, the instruction to report aiming directions results  
83 in faster error reduction than occurs in the absence of such instructions (Taylor et al. 2014),  
84 presumably because the reporting requirement alerts participants to the benefits of re-aiming to  
85 achieve task success. This raises the question of whether the reporting procedure might also  
86 impact implicit processes, because the reduced task errors that accompany explicit strategy use  
87 might affect the rate or extent of implicit adaptation via reward or reinforcement-related  
88 processes (Reichenthal et al. 2016).

89 An alternative approach to probe implicit processes in sensorimotor adaptation is to  
90 suppress the expression of explicit processes. This can be done either by employing dual-task  
91 paradigms to limit attentional resources that can be devoted to explicit re-aiming (Galea 2010;  
92 Keisler and Shadmehr 2010; Malone and Bastian ; Taylor and Thoroughman 2007; Taylor and  
93 Thoroughman 2008), or by restricting the amount of time available to prepare a movement  
94 (Fernandez-Ruiz et al. 2011; Haith et al. 2015). Restricting preparation time appears to be a  
95 particularly promising approach, as there is a relationship between preparation time and  
96 movement accuracy even without a sensorimotor perturbation (Georgopoulos and Massey 1987b;  
97 Marinovic et al. 2017). Furthermore, there is a time cost of explicitly preparing movements  
98 toward locations that are offset from the physical location of a target (Georgopoulos and Massey  
99 1987b). In one such approach, Haith et al. (2015) carefully controlled movement preparation  
100 time to dissociate learning resulting from explicit and implicit processes during adaptation to a  
101 visuomotor rotation. They showed significantly slower error reduction when they restricted  
102 movement preparation time by suddenly shifting target position in 20% of trials approximately  
103 300ms before the imperative to move (Haith et al. 2015). The data suggest that explicit re-aiming  
104 was suppressed by the preparation time constraint. The approach also has the benefit that it  
105 provides a within-subject contrast between presumed implicit remapping (from errors on the  
106 short preparation trials) and combined implicit and explicit adaptation (from errors on the long  
107 preparation trials). However, some aspects of this approach merit further consideration. First, it  
108 is unclear whether 300 ms is sufficiently brief to prevent entirely strategy use during adaptation.  
109 Second, the switch in target location might introduce an additional processing demand, and may  
110 not be desirable in some experimental designs. More generally, it is unknown whether assays of  
111 implicit sensorimotor adaptation obtained via preparation time manipulation differ from those

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112 obtained via reporting procedures. Here, we compared implicit learning assayed by restricting  
113 movement preparation time to implicit learning assayed via reporting procedures.

114         The first aim of the study was to determine the extent to which the capacity to explicitly  
115 re-aim is suppressed by reducing the amount of time available to prepare movement. We asked  
116 people to explicitly re-aim 30° clockwise or counter-clockwise to targets, under increasing time  
117 pressure, but in the absence of a perturbation. We expected that there would be a minimum time  
118 for movement preparation below which people would be unable to aim accurately to one side of  
119 a target. However, we also wondered whether advance knowledge of the approximate location of  
120 potential targets would influence the capacity to re-aim. To this end, voluntary re-aiming was  
121 performed either to a narrow (0-35° range) (Experiment 1A) or uniform 360° distribution of  
122 target directions (Experiment 1B). We predicted that people would be able to re-aim with shorter  
123 preparation times when targets were distributed narrowly. We found that participants could re-  
124 aim by 30° even at the shortest preparation times tested with a narrow target distribution, but at  
125 the expense of increased movement variability. For a broad 360° target distribution, participants  
126 could at least partially re-aim whenever movement time was sufficient to produce directionally  
127 tuned movements (i.e., as opposed to randomly directed movements), but at more dramatic cost  
128 to movement variability. Thus, the motor system is capable of systematic re-aiming to one side  
129 of a target irrespective of time constraints. However, we noted that participants found re-aiming  
130 at short preparation times extremely effortful. Given this, the purpose of Experiment 2 was to  
131 determine whether people would choose to re-aim under time pressure in order to improve  
132 performance on a visuomotor rotation task.

133         In Experiment 2, we compared adaptation to a 30° visuomotor rotation with a 360° target  
134 distribution under three alternative conditions. Separate groups of participants were either  
135 allowed: (1) a short time to prepare movement, (2) a longer time to prepare movement, but also  
136 asked to report their aiming direction, or (3) a longer time to prepare movement, without  
137 reporting aiming direction. If people chose not to re-aim reaches to counter the visuomotor  
138 rotation when preparation time was constrained, then we expected the rate of error reduction in  
139 this condition to resemble the rate of implicit adaptation estimated from the self-report procedure.  
140 We were also interested in the effects of the three different conditions on an alternative measure  
141 of implicit adaptation obtained from reaches made in the absence of visual feedback. We found

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142 that the rate and extent of error compensation with short preparation time closely matched  
143 implicit error compensation, as estimated from subtracting movement directions from self-  
144 reported aiming directions. This suggests that restriction of preparation time can suppress  
145 explicit re-aiming, and provide an estimate of implicit learning that does not require participants  
146 to report their aiming directions. Surprisingly, in the post-perturbation no-feedback trials, less  
147 implicit learning was shown in participants who reported aiming directions than participants who  
148 did not report aiming directions. This raises the possibility that the reporting procedure itself  
149 increased engagement of explicit learning, which inadvertently reduced engagement of implicit  
150 learning.

151

### 152 **Method**

#### 153 **Participants**

154 A total of 74 participants completed this study (Experiment 1A: n=14, mean age = 19.93,  
155 range = 17-42 years, 12 females, 2 left-handed; Experiment 1B: n=14, mean age = 19.07, SD =  
156 3.53, range = 17-31 years, 11 females, 2 left-handed; Experiment 2: n=36, 30 females, 2 left  
157 handed, mean age =19.85, SD = 1.82). In Experiment 2, 36 people were initially assigned either  
158 to a short preparation time condition or a long preparation time condition in which they had to  
159 report aiming direction. Subsequently, in order to test whether differences in post-perturbation  
160 estimates of implicit learning were due to the preparation time conditions or the reporting  
161 procedure, a further 10 people were recruited to a long preparation time condition without  
162 reporting (mean age 21, SD=4.7, range=18 to 34 years, all right-handed). For all experiments,  
163 the participants were randomly assigned either to clockwise or counter-clockwise visuomotor  
164 rotation conditions in equal proportions. All participants were naïve to visuomotor rotation and  
165 force-field adaptation tasks.

#### 166 **Apparatus and General Trial Structure**

167 Participants completed the task using the vBOT planar robotic manipulandum, which has  
168 a low-mass, two-link carbon fibre arm and measures position with optical encoders sampled at  
169 1,000 Hz (Howard et al. 2009). Participants were seated on a height-adjustable chair at their ideal  
170 height for viewing the screen for the duration of the experiment. Visual feedback was presented

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171 on a horizontal plane on a 27" LCD computer monitor (ASUS, VG278H, set at 60Hz refresh rate)  
172 mounted above the vBOT and projected to the subject via a mirror in a darkened room,  
173 preventing direct vision of their hand. The mirror allowed the visual feedback of the target (a 0.5  
174 cm radius circle), the starting location (a 0.5 cm radius circle), and hand cursor (0.25 cm radius)  
175 to be presented in the plane of movement, with a black background. The start circle was aligned  
176 10cm to the right of the participant's mid-sagittal plane at approximately mid-sternum level.

### 177 **General Trial Structure**

178 Participants made centre-out reaching movements by moving the robot arm from the start  
179 circle to the target. Targets appeared in random order at one of eight locations 9cm away from  
180 the start circle—target locations were clustered either in a small range (Experiment 1A:  
181 17.5°,12.5°,7.5°,2.5°,-2.5°,-7.5°,-12.5°,-17.5° from straight ahead), or distributed uniformly  
182 throughout 360° (Experiment 1B & Experiment 2: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°).  
183 At the start of each trial, the central start circle was displayed. If participants failed to move the  
184 hand to within 1cm of the start circle after 1 second, the robotic manipulandum passively moved  
185 the participant's hand to the start circle (using a simulated 2 dimensional spring with the spring  
186 constant magnitude increasing linearly over time). A trial was initiated when the cursor remained  
187 within the home location at a speed below 0.1 cm/s for 200 ms. We used a timed-response  
188 paradigm (Ghez et al. 1989; Haith et al. 2015; Marinovic et al. 2014; Marinovic et al. 2008;  
189 Schouten and Bekker 1967) to manipulate movement preparation time. Across all conditions, a  
190 sequence of three tones spaced 500 ms apart was presented at a clearly audible volume via  
191 external speakers. Participants were instructed to time the onset of their movements with the  
192 onset of the third tone (see Figure 1). They were instructed not to stop on the target, but to slice  
193 through it. Movement initiation was defined online as when hand speed exceeded 2cm/s. Targets  
194 appeared at 1000ms, 250ms, 200ms, 150ms, or 100ms, minus a display latency ( $27.6 \pm 1.8$  ms),  
195 prior to the third tone. Thus target direction information became available 972.4, 222.4, 172.4,  
196 122.4, or 72.4 ms before the desired initiation time. When movements were initiated 50 ms later  
197 than the third tone, the trial was aborted: the screen was blanked and a "Too Late" on-screen  
198 error signal appeared. Similarly, when movements were initiated more than 100 ms before the  
199 desired initiation time, the trial was aborted: the screen was blanked and a "Too Soon" on-screen  
200 error signal appeared. No visual feedback about movements was available when trials were

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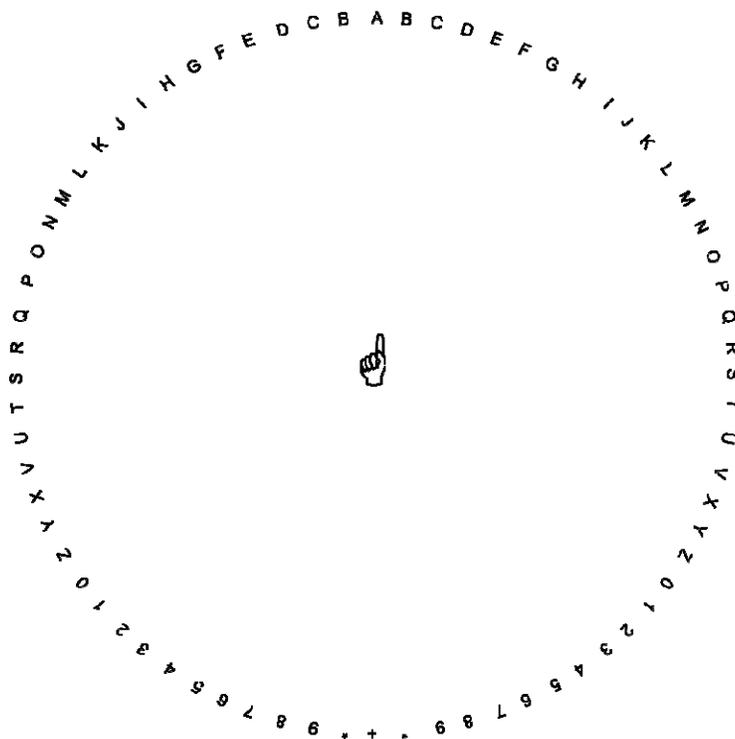
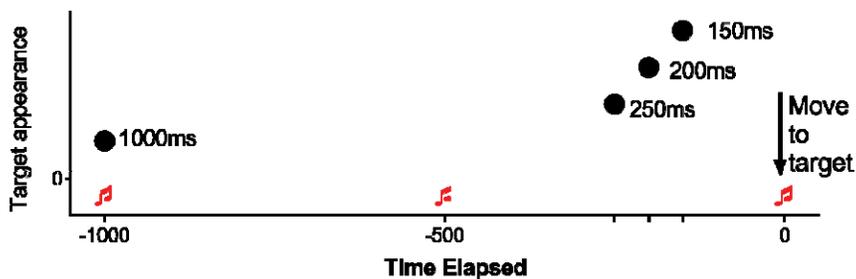
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201 aborted. Thus, all movements recorded and analysed were made according to the following “hard  
202 cut-off” times: within 1022.4, 272.4, 222.4, 172.4, 122.4 ms after target presentation.

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204 Figure 1. Top panel: A schematic representing the timed-response paradigm. Three tones spaced  
205 500 ms apart were presented, and participants were instructed to time the onset of their  
206 movements with the onset of the third tone. Targets appeared at different latencies prior to the  
207 third tone (Experiment 1a: 1000ms, 250ms, 200ms, 150ms, or 100ms; Experiment 1b: 1000ms,  
208 250ms, 200ms, 150ms; Experiment 2: Long preparation time condition: 1000ms, short  
209 preparation time condition: 250ms). Note that these latencies were minus a display latency of  
210  $27.6 \pm 1.8$  ms. Bottom panel: Experiment 2 landmark layout for the LongReport conditions.

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211           **Experiment 1.** The aim was to test re-aiming performance under progressively shorter  
212 preparation times, to determine whether restricting movement preparation can prevent strategic  
213 re-aiming. This paradigm of asking participants to re-aim by a specified angle relative to a visual  
214 target is similar to that used by Georgopoulos and Massey (1987a). In each trial, participants  
215 encountered one of eight targets which either spanned a small range of 35° (-17.5°, -  
216 12.5°...17.5°) in Experiment 1A, or a distribution of 360° (0°, 45° ... 360°) in Experiment 1B.  
217 Targets were presented in random order. In all trials, thirty-six “landmarks” were presented on-  
218 screen as white circles spaced 10° apart throughout the 360° range, 10 cm from the start circle. In  
219 the re-aiming condition, half of the participants were instructed to re-aim to the third landmark  
220 located clockwise from the target, and half were instructed to re-aim to the third landmark  
221 counter-clockwise to the target (i.e., 30° either side of the target). All participants completed the  
222 aiming condition before the re-aiming condition in blocks of 48 trials for each preparation time  
223 condition. The preparation times were progressively shortened, such that the trial schedule was:  
224 1000ms aiming, 1000ms re-aiming, 250ms aiming, 250ms re-aiming, 200ms aiming, 200ms re-  
225 aiming, 150ms aiming, 150ms re-aiming, 100ms aiming, 100ms re-aiming. The 100ms condition  
226 was not included in Experiment 1B because most participants could not initiate target-directed  
227 movements prior to the deadline.

228           **Experiment 2.** To examine whether shortening preparation time can provide a sufficient  
229 assay of implicit learning, we compared adaptation behaviour with short preparation time to an  
230 estimate of implicit learning obtained by subtracting self-reported aiming direction from the  
231 actual direction of hand movement (Bond and Taylor 2015; Brudner et al. 2016; McDougle et al.  
232 2015; Taylor et al. 2014). Participants were assigned either to a 250ms preparation time  
233 condition (Short), or one of two 1000ms preparation time conditions. In the LongReport  
234 condition, they had to verbally report aiming directions by stating which of 72 landmarks spaced  
235 5° apart most closely corresponded to the direction that they were aiming towards (Bond and  
236 Taylor 2015; Taylor et al. 2014). Previous studies exclusively used numerical landmarks (Bond  
237 and Taylor 2015; Brudner et al. 2016; Morehead et al. 2015; Taylor et al. 2014), which allowed  
238 the use of mental addition or subtraction strategies in some participants (Bond and Taylor 2015).  
239 We thus avoided using only number landmarks. Landmarks consisted of the letters A to Z, the  
240 numbers 1-9, and the symbol “\*” (reported as “star”). For ease of reporting, multiple-syllable

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241 characters (i.e., W) were not used. Landmarks rotated with the target, such that the same  
242 landmarks would always appear in the same location relative to the target, because rotating  
243 landmarks are more sensitive to explicit processes than fixed-location landmarks (Bond and  
244 Taylor 2015). Because of this, only a subset of the possible landmark values (A, B...G, \*, 1,  
245 2, ...9) were actually used by participants when reporting their aiming directions. Participants  
246 were allowed to report their aiming direction at any time between target appearance and  
247 movement completion. Verbal reports of aiming directions were recorded online by the  
248 experimenter. To estimate implicit learning, these self-reported aiming directions were  
249 subtracted from actual movement directions. A third control group (LongNoReport) had a  
250 1000ms preparation time, but did not have to report aiming directions. We did not apply the  
251 reporting manipulation to the Short condition, as piloting showed that it was extremely difficult  
252 to report the aiming direction when the target appeared 250 ms prior to the imperative signal to  
253 move.

254         Prior to the start of the experiment, participants were given no information about the  
255 nature of the rotation; they were only told that a disturbance of the cursor would be present in  
256 some trials, which may increase task difficulty. Participants in all conditions first completed a  
257 **pre-rotation** block of 6 cycles (48 trials) with veridical feedback of their movement trajectories  
258 to familiarize them with the task. LongReport participants began to verbally report their aiming  
259 direction in last 24 trials in the pre-rotation block to familiarize them with the reporting  
260 procedure. The pre-rotation block was followed by a **rotation** block (60 cycles, i.e., 480 trials)  
261 with either a 30° clockwise or counterclockwise rotation of visual feedback relative to the centre  
262 of the start circle. Halfway through this block, participants were given a 30 second break. The  
263 rotation block was followed by a **no-feedback** block of 6 cycles (i.e., 48 trials), where visual  
264 feedback of the cursor position was hidden immediately after the cursor left the start circle.  
265 Crucially, before commencing this block, participants were explicitly instructed that there was no  
266 longer any disturbance of visual feedback, and that they should aim straight towards the target  
267 (Heuer and Hegele 2008; Taylor et al. 2014). The no-feedback block therefore provides an  
268 alternative assay of implicit remapping. Finally, participants completed a **washout** block of 6  
269 cycles (48 trials) where unrotated visual feedback was available to enable participants to return  
270 movements back to the unadapted state. Landmarks were removed from the no-feedback block

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271 and the washout block, and participants were no longer required to report aiming direction in  
272 these blocks. The same preparation time constraints were maintained throughout the entire  
273 experiment for each group.

### 274 **Data analysis**

275 Movement onset time was taken as the time at which hand speed first exceeded 2 cm/s.  
276 Movement direction was quantified 100ms after movement onset, prior to the potential influence  
277 of online corrections. For Experiment 2, data from the counterclockwise rotation group were  
278 sign-transformed to allow us to collapse the dataset with data from the clockwise rotation group.  
279 Negatively signed angles indicate that the deviation in hand direction relative to the target was  
280 opposite to the direction of the rotation (i.e., to reduce visual error).

281 **Experiment 1:** To determine which of the preparation times was sufficiently short to  
282 suppress strategic re-aiming, we first quantified movement directions relative to the target as  
283 mean vectors and variability of movement directions as mean vector lengths, denoted as  $r$  for all  
284 preparation times tested using circular statistics. In the aiming condition, mean vectors values  
285 close to zero suggest that movement directions were close to the target. In the re-aiming  
286 condition, values close to  $30^\circ$  indicate that movement directions were close to the instructed re-  
287 aiming direction. Longer mean vectors indicate less variable movement directions, with a value  
288 of 1 indicating all directions aligned, and a value of 0 indicating an absence of directional tuning  
289 (i.e. a uniform distribution throughout all possible directions). We then compared movement  
290 directions and variability for the aiming conditions to the re-aiming conditions. When directional  
291 data is normally distributed, one can use the Hotelling's Paired Test, which is the equivalent of  
292 the paired t-test for circular statistics (Zar 2010). However, as aiming directions were not  
293 normally distributed, we used a non-parametric alternative (Moore's paired sample second order  
294 tests) to determine whether mean vectors differed reliably between aiming and re-aiming  
295 conditions (Zar 2010). Similarly, mean vector lengths typically show skewed distributions close  
296 to 1, and thus Wilcoxon-Rank analyses were used to compare variability between the aiming and  
297 re-aiming conditions. Circular statistics analyses were conducted with the software Oriana. For  
298 Experiment 1a (narrow target distribution), we also tested whether participants re-aimed by  
299 moving towards the middle of a (hypothetical) re-aiming target distribution by measuring the  
300 errors made to each target, for the two shortest preparation time conditions (100 ms & 150 ms).

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301 If re-aiming errors were smallest at the central 0° target and largest at the surrounding targets,  
302 then this would suggest that participants adopted a strategy to re-aim to the middle of the  
303 hypothetical re-aiming target distribution by initiating movements prior to full integration of  
304 target direction information.

305 **Experiment 2.** Prior to statistical analyses, movements further than 90° clockwise or  
306 counterclockwise away from the target (i.e., outside of a 180° range) were deemed as outliers,  
307 and were discarded from the analysis. This procedure excluded a small proportion of trials  
308 (Short: 4.00%, LongReport: 0.58%, LongNoReport: 0.39%). We evaluated whether the direction  
309 of hand movement relative to the target, under reduced movement preparation time conditions,  
310 was similar to the estimate of implicit learning obtained by subtracting self-reported aiming  
311 directions from actual movement directions (Taylor et al. 2014). To this end, we recoded verbal  
312 reports of landmarks into angular aiming directions, and then estimated implicit learning by  
313 subtracting reported aiming directions from actual movement directions. Trials were averaged in  
314 cycles of eight (one trial for each target angle) for statistical analysis. To compare adaptation  
315 behaviour between conditions, ANOVAs with the within-subjects factor Cycle and two between-  
316 subjects factors of Condition and Rotation Direction (clockwise, counterclockwise) were run on  
317 relevant cycles. For the early adaptation phase, the relevant cycles were cycles 1-30 of the  
318 adaptation block. For the late adaptation phase, the relevant cycles were cycles 31-60 of the  
319 adaptation block. For the no-feedback block, the relevant cycles were all 6 cycles of the no-  
320 feedback block. For the washout block, the relevant cycles were all 6 cycles of the washout  
321 block. For all ANOVAs, when Mauchly's test of sphericity was statistically significant, the  
322 Greenhouse-Geisser correction was used to adjust degrees of freedom.

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**Results**

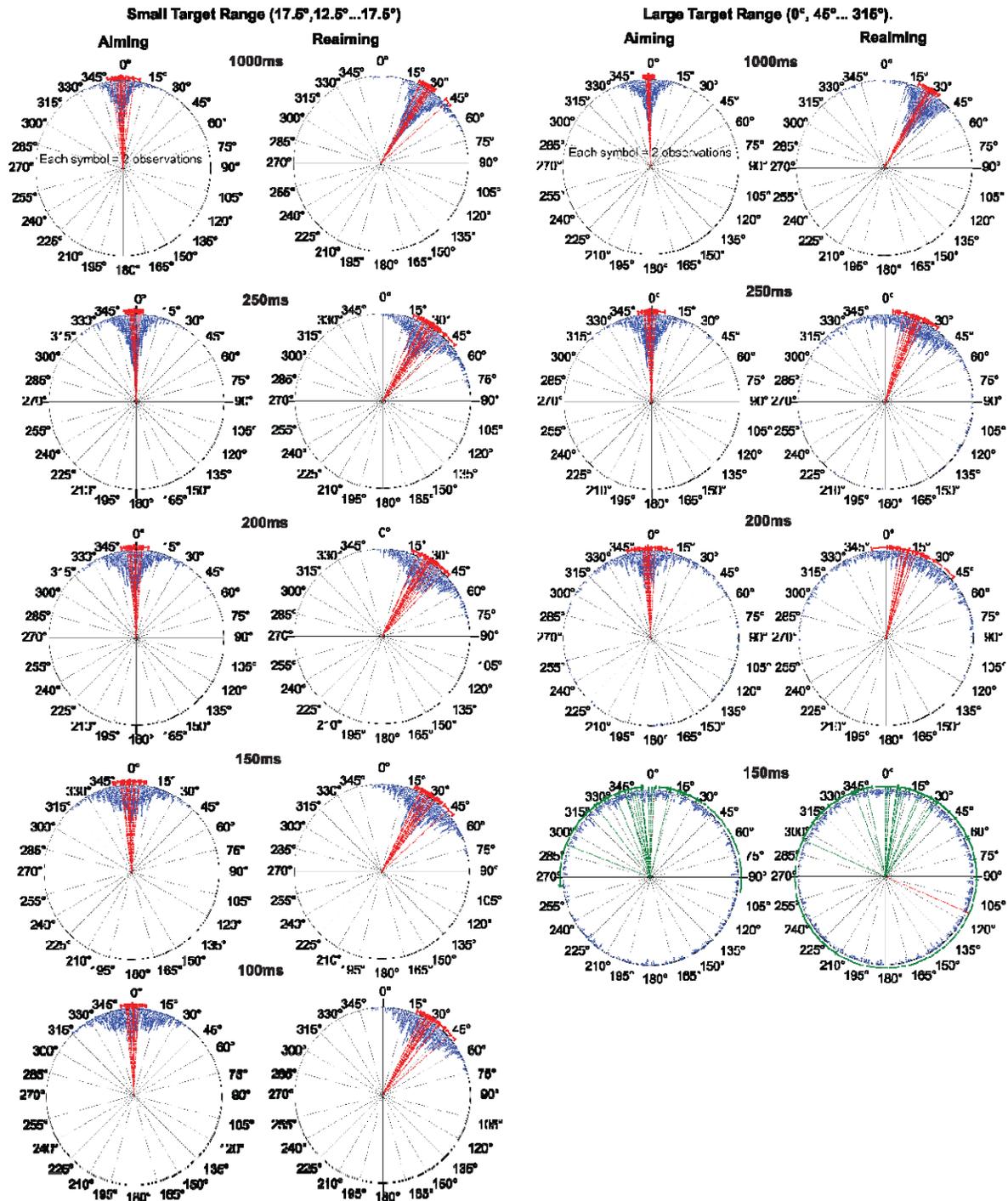
325 **Experiment 1: Re-aiming away from a target at very short preparation times**

326 Movement directions for all trials pooled across all subjects are shown in Figure 2 for  
327 Experiment 1A (small target range) and for Experiment 1B (large target range). With the small  
328 target range, movement directions were close to the target directions when aiming, and  
329 approximated the required 30° offset when re-aiming, even with the shortest preparation time  
330 condition of 100ms (i.e., hard initiation cut-off of 122.4ms). Rao's tests run for each participant's  
331 dataset within each preparation time condition indicated that movement directions were  
332 directionally tuned for all conditions, even for the shortest 100ms preparation time condition (all  
333  $p < .0001$ ). With the large target range, re-aiming movements were directed progressively closer to  
334 the original target (i.e., further from the instructed 30° offset) as preparation times were  
335 shortened. Rao's tests run for each participant's dataset within each preparation time condition  
336 indicated that movement directions were not directionally tuned for 5 of the 13 participants who  
337 completed the 150ms aiming condition and 10 of the 13 participants who completed the 150ms  
338 re-aiming conditions.

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341 *Figure 2. Movement directions for the narrow target range (-17.5° to 17.5°) and large target range (0° to 360°) plotted relative*  
342 *to target direction at 0°, in the aiming and re-aiming conditions. Data from participants in the counterclockwise re-aiming*  
343 *condition were normalized to the clockwise direction and collapsed with data from participants in the clockwise re-aiming*  
344 *condition. Symbols represent movement directions in individual trials for all participants across the preparation time conditions*  
345 *(1000ms, 250ms, 200ms, 150ms to 100 ms). Note that the hard cut-off times for movement initiation in these conditions were:*

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346 1022.4, 272.4, 222.4, 172.4, 122.4 ms after target appearance. Red vectors represent individual mean vectors for each  
 347 participant, and error bars represent the mean and 95% confidence intervals of mean movement direction for each participant.  
 348 Green vectors represent individual mean vectors that were not significantly directionally tuned according to a Rayleigh's test.

349  
 350

351 Table 1.

352 *Statistical analyses comparing aiming and re-aiming accuracy (assessed via mean movement*  
 353 *direction) and variability (assessed via vector length—longer vectors indicate less variability),*  
 354 *as the amount of time available to prepare movements was progressively shortened.*

<b>Movement Preparation Time</b>	Direction Variability (vector length)	Mean Vector Angle	Movement Time (mean+/- SEM)	Direction Variability (vector length)	Mean Vector Angle	Movement Time (mean+/-SEM)
<b>Exp. 1A:</b> Small target range: -17.5 ° to 17.5 °			<b>Exp. 1B:</b> Large target range: 0, 45°,... 315°			
1000 ms	Aiming: 0.99 Re-aiming: 0.99 z = -.32, p = 0.759	Aiming: 358.5° Re-aiming: 32.3° 2.00, p < 0.001	Aiming: 268+/- 18 ms Re-aiming: 262+/-22 ms	Aiming: 0.99 Re-aiming: 0.98 z = -2.98, p = 0.003	Aiming: 358.3° Re-aiming: 30.1° 1.48, p < 0.01	Aiming: 352+/- 19ms Re-aiming: 322+/-14ms
250 ms	Aiming: 0.99 Re-aiming: 0.97 z = -3.21, p = 0.001	Aiming: 358.2° Re-aiming: 32.6° 2.00, p < 0.001	Aiming: 262+/- 20ms Re-aiming: 278+/-16 ms	Aiming: 0.97 Re-aiming: 0.88 z = -3.41, p = 0.001	Aiming: 358.4° Re-aiming: 20.1° 1.97, p < 0.01	Aiming: 235+/- 18ms Re-aiming: 250+/-22ms
200 ms	Aiming: 0.98 Re-aiming: 0.97 z = -2.52, p = 0.012	Aiming: 358.4° Re-aiming: 32.2° 2.00, p < 0.001	Aiming 261+/- 18 ms Re-aiming= 253+/-16 ms	Aiming: 0.89 Re-aiming: 0.66 z = -3.35, p = 0.001	Aiming: 357.8° Re-aiming: 14.6° 1.81, p < 0.01	Aiming: 218+/- 17ms Re-aiming: 233+/-17ms
150 ms	Aiming: 0.97 Re-aiming: 0.96 z = -.79, p = 0.432	Aiming: 358.8° Re-aiming: 32.2° 1.99, p < 0.001	Aiming: 260+/- 15 ms Re-aiming: 251+/-14 ms	Aiming: 0.46 Re-aiming: 0.27 z = 3.11, p = 0.002	Aiming: 354.3° Re-aiming: 351.9° 1.54, p < 0.01	Aiming: 236+/- 18 Re-aiming: 235+/-18
100ms	Aiming: 0.97 Re-aiming: 0.96 z = -2.61, p = 0.009	Aiming: 358.5° Re-aiming: 32.4° 2.00, p < 0.001	Aiming: 262+/-18 ms, Re-aiming: 258+/-16 ms	n/a	n/a	n/a

355

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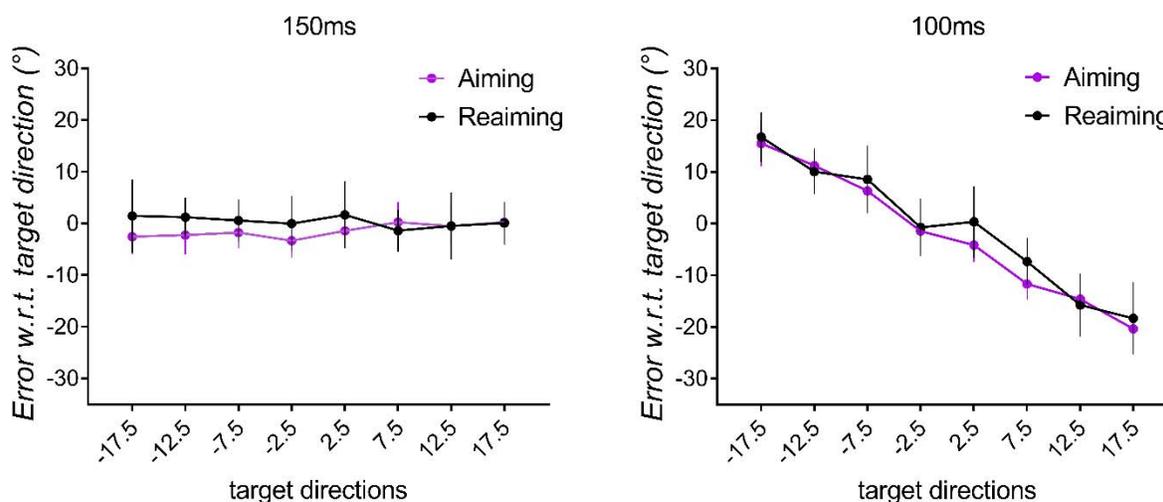
356 Table 1 summarizes statistical comparisons between aiming and re-aiming across  
357 preparation times for both the narrow target distribution (Experiment 1A) and the full 360° target  
358 distribution (Experiment 1b). For both target distributions, movement directions were more  
359 variable (shorter vector lengths) when re-aiming away from the target than when aiming to the  
360 target across all preparation times. When errors were averaged across all targets in the narrow  
361 range (Experiment 1a), it appears that participants could re-aim away from the target in all  
362 preparation times tested (even when movements were initiated within 122.4 ms of target  
363 preparation). That is, mean vector angles were on average approximately 30° away from the  
364 target across all preparation times tested. We were surprised at this apparent success in re-  
365 aiming, since Haith et al (2016) showed that directionally tuned movements to a unique target  
366 require approximately 130 ms, and the process of re-aiming (and preparing movements to a  
367 direction offset by 30° to the target) should require at least some additional processing (Haith et  
368 al. 2016). We therefore examined errors for each target in the distribution individually, to search  
369 for evidence that participants might have been able to achieve task success by aiming toward the  
370 middle of the re-aiming target distribution (i.e. 30° away from the central visual target  
371 distribution). In this case, movement could be initiated prior to integration of target direction  
372 information, but average errors collapsed across targets would be close to zero.

373 Figure 3 shows clear evidence that subjects adopted such a strategy for the shortest  
374 preparation time condition, under both aiming and re-aiming conditions. Errors were similar for  
375 all targets in the 150ms preparation time condition, indicating that there were no large inherent  
376 biases in reaching performance. There were no statistically significant differences in error size  
377 across targets ( $F(7,91) = 1.10$ ,  $p = 0.39$ , partial  $\eta$ -squared = 0.08) or conditions ( $F(1,13) = 1.1$ ,  $p$   
378 = 0.3, partial  $\eta$ -squared = 0.08), nor an interaction between target and condition ( $F(7,91) = 1.2$ ,  $p$   
379 = 0.3, partial  $\eta$ -squared = 0.09). By contrast, with 100ms preparation time (122.4 ms hard cut-  
380 off), errors were systematically larger in absolute terms as the angle from the centre of the  
381 distribution increased for the aiming condition (main effect of target  $F(7,91) = 199$ ,  $p < 0.001$ ,  
382 partial  $\eta$ -squared = 0.94). The signs of errors indicate that participants made reaching movements  
383 that were biased towards the central target. The pattern of errors for aiming and re-aiming  
384 conditions were similar for the aiming and re-aiming conditions, with no statistically significant  
385 main effect of condition ( $F(1,13) = 0.6$ ,  $p = 0.45$ , partial  $\eta$ -squared = 0.04) or interaction between

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386 condition and target ( $F(7,91) = 1.6$ ,  $p = 0.15$ , partial  $\eta$ -squared = 0.11). Note that errors from the  
387 required (re-aiming) target are plotted and analysed, rather than errors relative to the presented  
388 target. Critically, the similarity in error directions and magnitudes for the aiming and re-aiming  
389 conditions, across all preparation time conditions, suggests that if participants had sufficient time  
390 to aim towards the target, then they also had time to re-aim to one side of the target by a  
391 specified angle. Although this process of re-aiming must require some additional processing, our  
392 data suggest that such processing is extremely rapid, to the point that we were not able to detect a  
393 time-cost for re-aiming under the conditions of our experiment. The data also suggest that people  
394 are able to apply a re-aiming strategy to an anticipated target location when there is insufficient  
395 time to adequately process visual information related to the actual target. This indicates that the  
396 approach of restricting strategic re-aiming through preparation time constraints might be  
397 especially problematic for single or dual target paradigms.



398

399 *Figure 3. Movement errors for each target direction from  $-17.5^{\circ}$  to  $17.5^{\circ}$  with respect to (w.r.t) the required*  
400 *reaching direction (i.e., presented target or re-aiming target depending on condition). Data from participants in the*  
401 *counterclockwise re-aiming condition were normalized to the clockwise direction and collapsed with data from*  
402 *participants in the clockwise re-aiming condition. Separate plots are shown for the 150ms to 100 ms preparation*  
403 *time conditions. Note that the hard cut-off times for movement initiation in these conditions were 172.4 and 122.4*  
404 *ms after target appearance. Values are group mean errors and error bars represent 95% confidence intervals.*

405 In Experiment 1b, which involved the broad target distribution, participants were less  
406 accurate at re-aiming away from the target ( $20.1^{\circ}$ ) with 250ms preparation, although re-aiming  
407 away from the target was still possible with 200 ms ( $14.6^{\circ}$ ) and 150ms ( $7.7^{\circ}$ ) preparation. This

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408 confirms that voluntary re-aiming is not absolutely prevented by shortening movement  
409 preparation time, irrespective of whether potential targets lie within a narrow or large angular  
410 range. Self-reports from our participants indicated, however, that re-aiming was extremely  
411 effortful at short preparation times, especially when targets were distributed around the circle.  
412 Moreover, the accuracy cost of re-aiming was dramatically greater when targets were distributed  
413 around the circle. Given this, in Experiment 2, we considered whether participants would choose  
414 to re-aim under time pressure in order to improve performance in a visuomotor rotation task. For  
415 this experiment, targets were radially arranged throughout the circle ( $0^\circ$ ,  $45^\circ$ ... $315^\circ$ ) and  
416 movement preparation time was restricted to 250ms. We decided to use 250ms as an arbitrary  
417 trade-off between a sufficient time to allow accurate aiming to the presented target, and  
418 sufficient time-pressure to make re-aiming effortful.  
419

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420 **Experiment 2: Suppressing strategic re-aiming with short preparation time constraints**  
421 **reduces the rate and extent of error compensation.**

422 Figure 4 shows the group mean, cycle-averaged, movement directions across different  
423 phases of the experiment. To evaluate whether the discrepancy between the measures of implicit  
424 learning (i.e., implicit learning estimated from subtracting aiming directions from movement  
425 directions and implicit learning estimated from the no-feedback trials) is related to the process of  
426 reporting explicit aiming angles or the preparation time constraints, we compared this data to 10  
427 additional task-naïve participants (5 counterclockwise, 5 clockwise) who completed the  
428 visuomotor rotation task with the same 1000ms preparation time constraints via the same timed-  
429 response paradigm, but who did not report aiming directions and had no visual landmarks  
430 throughout the task (LongNoReport). In the baseline block (i.e., before encountering the  
431 perturbation) a counterclockwise bias was evident in the Long preparation time group, as Cycle  
432 (Cycle 1...6) x Condition (Long, Short, LongNoReport) x Rotation Direction (clockwise,  
433 counterclockwise) ANOVA revealed a significant main effect of Condition,  $F(2,30) = 4.267$ ,  $p =$   
434  $0.023$ , partial  $\eta$ -squared = 0.221. To estimate the bias, we averaged mean movement directions  
435 from baseline cycles 2-6 (baseline cycle 1 was not included as participants were still  
436 familiarising themselves with the vBOT at this stage). To eliminate the influence of this bias on  
437 the subsequent test phases, we subtracted the bias from mean movement directions from each  
438 subsequent cycle (i.e., the first cycle of the adaptation block to the last washout cycle). The  
439 adaptation phase was arbitrarily separated into Early (Cycle 1-30) and Late blocks (Cycle 31-60).  
440 ANOVAs were run on each block for all three conditions (LongReport, Short, LongNoReport),  
441 according to a mixed within-between effects model (Cycle x Rotation Direction x Condition  
442 [LongReport, Short, LongNoReport]). In the Early phase, there was a significant main effect of  
443 Condition,  $F(2,30) = 6.25$ ,  $p = 0.005$ , partial  $\eta$ -squared = 0.294, as well as a significant Cycles x  
444 Condition interaction,  $F(24.6,370.2) = 1.59$ ,  $p = 0.037$ , partial  $\eta$ -squared = 0.09, as less error  
445 compensation was evident with Short ( $-17.3 \pm 1.3^\circ$ ) compared to LongReport, ( $-22.4 \pm 1.3^\circ$ ,  
446  $p = .033$ ) and compared to LongNoReport ( $-24.4 \pm 1.8^\circ$ ,  $p = .009$ ). Error compensation in this early  
447 phase did not differ reliably between LongReport and LongNoReport ( $p = .75$ ). Similarly, for the  
448 Late phase, there was a significant main effect of Condition,  $F(2,30) = 4.77$ ,  $p = 0.016$ , partial  $\eta$ -  
449 squared = 0.241; as less error compensation was evident with short preparation time ( $-23.1 \pm$

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450 1.1°) compared to LongNoReport (-28.7±1°,  $p = .007$ ) and compared to LongReport (-26.7±/  
451 1.1°,  $p = .036$ ). Error compensation was also more complete for clockwise than counterclockwise  
452 rotations, as evident in significant main effect of Rotation across all phases: Early:  $F(1,30) =$   
453 21.643,  $p < 0.001$ , partial  $\eta$ -squared = 0.419, Late:  $F(1,30) = 10.96$ ,  $p = 0.002$ , partial  $\eta$ -squared  
454 = 0.268]. There were no other significant interactions.

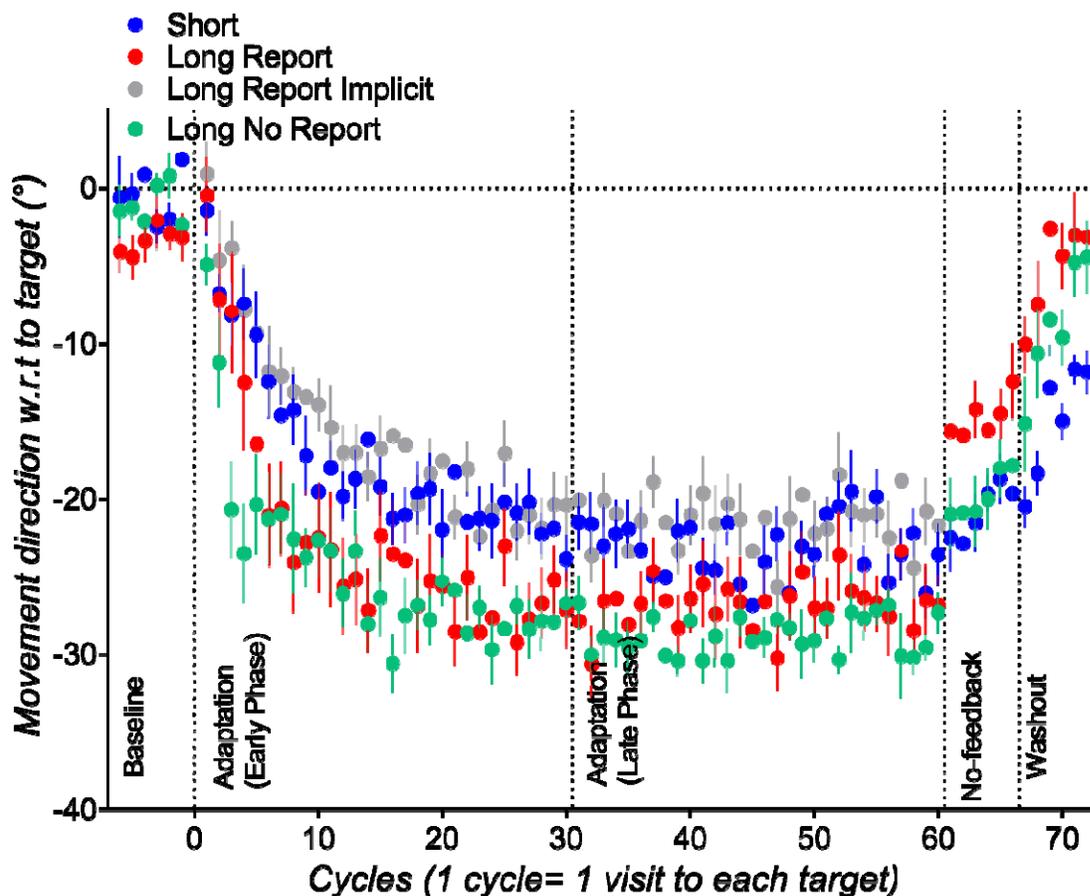
### 455 **Preparation time constraint as an assay of implicit learning**

456 The implicit component of error compensation observed for the Long preparation group  
457 was estimated by subtracting the participants' reported aiming direction from their actual  
458 movement direction, similar to previous work (Bond and Taylor 2015; Brudner et al. 2016;  
459 McDougale et al. 2015; Taylor et al. 2014). This measure of error is hereafter termed  
460 "LongImplicit", and was compared to angular errors observed between the target and movement  
461 for the short preparation time condition. There were no significant differences between  
462 LongImplicit and Short, as shown by Condition (LongImplicit, Short) x Cycle (Cycle 1...30) x  
463 Rotation Direction (CW, CCW) ANOVAs run for the early adaptation phase [main effect of  
464 Condition,  $F(1,24) = 1.33$ ,  $p = 0.26$ , partial  $\eta$ -squared = 0.05, Cycle x Condition  $F(12.6,303.9) =$   
465 1.05,  $p = 0.4$ , partial  $\eta$ -squared = 0.04 interaction], as well as the late adaptation phase  
466 [Condition,  $F(1,24) = 1.44$ ,  $p = 0.2$ , partial  $\eta$ -squared = 0.06, Cycles x Condition,  $F(11.9,287.1)$   
467 = 1.4,  $p = 0.16$ , partial  $\eta$ -squared = 0.05]. The main effect of rotation direction was statistically  
468 significant for the early adaptation phase,  $F(1,24) = 26.29$ ,  $p < 0.001$ , partial  $\eta$ -squared = 0.52 as  
469 well as for the late adaptation phase:  $F(1,24) = 11.473$ ,  $p = 0.002$ , partial  $\eta$ -squared = 0.32. There  
470 were no significant interactions. Thus, the extent and rate of implicit learning did not differ  
471 reliably between estimates based on subtracting self-reported aiming directions and restriction of  
472 preparation time.

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473

474 *Figure 4. Experiment 2 mean movement direction in every cycle, averaged across each condition. Data*  
475 *from participants who encountered counterclockwise rotations were sign-transformed to allow collapsing*  
476 *with data from participants who encountered clockwise rotations. Error bars are standard errors of the*  
477 *mean. Negative values indicate movements that were opposite from the direction of rotation, positive*  
478 *values indicate movements that were in the same direction as the rotation. Note that Long Report Implicit*  
479 *is not an additional experimental condition, but is derived from subtracting self-reported aiming*  
480 *directions from movement directions in the Long Report condition.*

481

### 482 **Difference in estimate of implicit learning from subtracting aiming directions and estimate** 483 **of implicit learning from no-feedback trials**

484 An alternative measure of implicit remapping is provided by the no-feedback trials that  
485 participants performed after the final adaptation phase block. Here, participants received no  
486 visual feedback about their movements, and were explicitly instructed that the perturbation was  
487 removed and that they should aim straight to the target (Taylor et al. 2014), (similar to Heuer and  
488 Hegele 2015). For the LongReport group (Figure 3) the measure of implicit learning obtained

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489 from this no-feedback block appears substantially lower (i.e., movements were less adapted) than  
490 the measure of implicit learning obtained by subtraction of reported aiming direction in the last  
491 adaptation cycle. In contrast, for the Short group, errors in the last adaptation cycle were similar  
492 to those in the first no-feedback cycle. To compare implicit learning (estimated by subtracting  
493 aiming direction or by shortening preparation times) to implicit learning estimated by no-  
494 feedback trials, we compared the last adaptation cycle (after subtracting aiming directions for the  
495 LongReport group) to the first no-feedback cycle for the LongReport group and the Short group,  
496 via a Condition (LongReport, Short) x Rotation Direction (CW, CCW) x Phase (last adaptation  
497 cycle, first no-feedback phase cycle) ANOVA. There was a significant Phase x Condition  
498 interaction,  $F(1, 24) = 4.36$ ,  $p = .047$ , partial eta-squared = .15. Follow-up Rotation Direction x  
499 Phase (last adaptation cycle, first no-feedback phase cycle) ANOVAs were run separately for the  
500 LongReport and the Short condition. For LongReport, implicit learning estimated by subtracting  
501 aiming direction in the last adaptation cycle ( $21.7 \pm 1.8^\circ$ ) was more than implicit learning  
502 estimated in the first no-feedback cycle ( $15.8 \pm 1.6^\circ$ ), as shown by a significant main effect of  
503 phase  $F(1, 12) = 6.94$ ,  $p = 0.022$ , partial  $\eta$ -squared = 0.37. In contrast, for the short preparation  
504 time, the last adaptation cycle ( $-23.5 \pm 1.8^\circ$ ) did not differ reliably from the first no-feedback  
505 cycle ( $-22.5 \pm 1.9^\circ$ ): the main effect of Phase was not significant ( $F(1, 12) = 0.33$ ,  $p = 0.57$ ,  
506 partial  $\eta$ -squared = 0.02), and did not interact significantly with any other factor. Thus, for the  
507 LongReport group, there was a discrepancy between the estimates of implicit learning provided  
508 by the reporting method, obtained in the presence of the rotation, and the no-feedback condition,  
509 obtained after the final movement performed under the visuomotor rotation. There was no  
510 discrepancy between implicit learning estimates for the short preparation time group, even  
511 though the final estimate of implicit learning at the end of adaptation was similar to that obtained  
512 after subtracting aiming directions for LongReport group, and despite the fact that both groups  
513 had explicit knowledge that the rotation was removed.

514 This discrepancy between the estimates of implicit learning from reporting, in the last  
515 adaptation cycle, and from no-feedback trials in which participants were instructed that the  
516 rotation was absent, was also evident in previous work using the reporting procedure (c.f. Fig 2C,  
517 Fig 5C Bond and Taylor 2015). Taylor et al. (2014) attributed the effect to trial-by-trial decay of  
518 adaptation within the first no-feedback cycle, because there was no statistically significant

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519 difference between the last adaptation trial and the first no-feedback trial (Taylor et al. 2014).  
520 Our LongReport group similarly showed no reliable difference in estimated implicit learning  
521 from the last adaptation trial to the first no-feedback trial (Trial x Rotation Direction ANOVA on  
522 the LongReport group showed a non-significant main effect of Trial  $F(1,12)=.30$ ,  $p=.59$ , partial  
523 eta-squared =.03). However, we hesitate to make inferences from this non-significant effect,  
524 because comparing trial-by-trial data in multi-target designs can be problematic: target directions  
525 were likely to differ between the last adaptation trial and the first no-feedback trial between-  
526 subjects, and directional accuracy differs between targets (Gordon et al. 1994). Moreover,  
527 movements were also less adapted on average over all six no-feedback cycles for the LongReport  
528 than the Short group, as shown by a significant main effect of Condition,  $F(1,24) = 6.91$ ,  $p =$   
529  $0.01$ , partial  $\eta$ -squared = 0.22 in a Condition x Rotation Direction x Cycle ANOVA. This  
530 suggests that the extent or persistence of implicit learning was less for the long preparation with  
531 reporting condition than the short preparation condition.

532 To evaluate whether the discrepancy between measures of implicit learning is related to  
533 the reporting procedure (i.e., the process of reporting explicit aiming angles and/or the presence  
534 of visual landmarks), we compared error compensation data from the Long Report group to the  
535 LongNoReport group. Error compensation during exposure to the rotation did not differ reliably  
536 between this LongNoReport group and the LongReport group, as Cycle x Reporting  
537 (LongNoReport, LongReport) x Rotation Direction (CW, CCW) ANOVAs run separately for the  
538 early adaptation phase (Cycles 1...31) and the late adaptation phase (Cycles 31...60) showed a  
539 non-significant main effect of reporting for the early adaptation phase [ $F(1,18) = 0.67$ ,  $p = 0.424$ ,  
540 partial  $\eta$ -squared = 0.036], and no significant interactions, as well as for the late adaptation phase,  
541  $F(1,18) = 0.843$ ,  $p = 0.371$ , partial  $\eta$ -squared = 0.045, no significant interactions]. However, the  
542 estimate of implicit learning obtained from no-feedback trials was greater for the LongNoReport  
543 group than the LongReport condition: Cycle (Cycle 1-6) x Reporting (LongNoReport,  
544 LongReport) x Rotation Direction (CW, CCW) ANOVA on the no-feedback block showed a  
545 significant main effect of reporting,  $F(1,18) = 7.32$ ,  $p = 0.015$ , partial  $\eta$ -squared = 0.289. There  
546 were no other significant interactions. The main effect of Rotation Direction was significant  
547  $F(1,18) = 16.64$ ,  $p = 0.001$ , partial  $\eta$ -squared = 0.48—similar to the adaptation phase,  
548 movements were more adapted with the clockwise direction ( $-21.0\pm 1.0^\circ$ ) than the

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549 counterclockwise direction ( $13.4 \pm 1.0^\circ$ ). Performance in the no-feedback trials did not differ  
550 significantly between the LongNoReport and the Short group—a Cycle (Cycle 1-6) x Condition  
551 (LongNoReport, Short) x Rotation Direction ANOVA showed a non-significant main effect of  
552 condition [ $F(1,18) = 0.449$ ,  $p = 0.511$ , partial  $\eta$ -squared = 0.024], and no significant interactions  
553 with condition, all  $p > 0.5$ . The main effect of rotation direction was significant  $F(1,18) = 15.98$ ,  
554  $p = 0.001$ , partial  $\eta$ -squared = 0.47.

### 555 **Discussion**

556 This study aimed to evaluate a previously established method of assaying implicit  
557 learning by restricting the time available to prepare movement (Fernandez-Ruiz et al. 2011;  
558 Haith et al. 2015). Experiment 1 showed that restricting time available to prepare movements  
559 does not prevent people from applying a deliberate strategy to re-aim to one side of a target,  
560 particularly when targets are distributed within a narrow angular range. However, Experiment 2  
561 showed that restricting movement preparation time effectively reduces strategic re-aiming during  
562 adaptation to visuomotor rotation when targets are distributed throughout  $360^\circ$ , as shown by  
563 slower and less complete error compensation compared to when movement preparation times  
564 were not shortened. Moreover, the errors made by participants when preparation time was  
565 shortened were indistinguishable from an assay of implicit learning obtained by subtracting self-  
566 reported aiming directions from movement directions (Bond and Taylor 2015; Brudner et al.  
567 2016; McDougle et al. 2015; Taylor et al. 2014). Surprisingly, despite this similarity in estimates  
568 of implicit learning obtained for the two methods during exposure to the visuomotor rotation,  
569 participants who reported aiming directions showed less implicit remapping in the post-  
570 perturbation no-feedback trials than those who did not report aiming directions. This suggests  
571 that the process of reporting aiming direction reduces the extent or persistence of implicit  
572 learning.

### 573 **Suppressing the expression of explicit learning by restricting preparation time**

574 Despite a long history of studies on implicit and explicit processes in sensorimotor  
575 adaptation (Jakobson and Goodale 1989; Uhlarik 1973), our understanding of how these  
576 processes interact to determine behaviour remains incomplete. Here, we further evaluated the  
577 method of assaying implicit learning by restricting movement preparation time (Fernandez-Ruiz

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578 et al. 2011; Haith et al. 2015). We showed that when there is intention to re-aim (i.e., when  
579 participants were explicitly instructed to re-aim) and potential targets were distributed within a  
580 small ( $35^\circ$ ) range, accurate re-aiming is possible irrespective of the time between target  
581 presentation and movement initiation. The accuracy cost of re-aiming in such conditions was  
582 modest. Moreover, for the shortest preparation time condition (movement initiation constrained  
583 to occur within 123 ms of target presentation), it appears that participants initiated movement  
584 prior to complete integration of visual information about the actual target, and were able to  
585 achieve task success by aiming or re-aiming to the centre of the (required) target distribution.  
586 When target direction (and thus re-aiming direction) was less predictable (targets distributed  
587 throughout  $0-360^\circ$ ), however, re-aiming accuracy declined with progressively shorter preparation  
588 times. Participants were still able to partially re-aim away from the target whenever they had  
589 sufficient time to produce directionally tuned movements, but at the expense of dramatically  
590 increased movement variability. Hence, compressing preparation time does not introduce an  
591 absolute limit upon the capacity for re-aiming, particularly for narrow target distributions.

592         However, during sensorimotor adaptation to a perturbation, restricting preparation time  
593 appeared to suppress re-aiming when targets were distributed about  $360^\circ$ , such that error  
594 compensation was indistinguishable from the assay of implicit learning obtained from  
595 subtracting reported aiming direction from actual movement direction. This suggests that people  
596 choose not to apply re-aiming strategies to correct for visuomotor perturbations under time  
597 pressure, presumably to avoid the increases in effort and variability associated with re-aiming  
598 under such conditions.

599         This interpretation prompts a formal definition of the distinction between implicit and  
600 explicit processes. Here, consistent with others (Huberdeau et al. 2015), we define explicit  
601 processes as those which can be deliberately engaged and disengaged. By contrast, implicit  
602 processes are automatic and difficult to deliberately disengage. We do not distinguish between  
603 explicit processes from implicit processes based on awareness of the perturbation or a re-aiming  
604 strategy, as classically defined (Reber 1967). Indeed, many of our participants in the short  
605 preparation time condition were able to accurately describe the nature of the rotation and could  
606 articulate a compensatory strategy, but found it simply too difficult to implement the strategy  
607 when preparation times were restrained.

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608           Our findings that asymptotic error levels were greater for short than long preparation time  
609 conditions differ from those of Haith et al. (2015). In their task, which involved two potential  
610 targets, participants were eventually able to reduce errors to a similar degree for the short and  
611 long preparation time targets. This discrepancy in findings probably relates to the predictability  
612 of the target locations. Targets only appeared in two locations in Haith et al. (2015), with  
613 preparation time of ~300 ms. However, our Experiment 1A shows that explicit re-aiming is  
614 possible even at 123 ms when the target direction was predictable within a small 35° range.  
615 Hence, although the target-switch protocol in Haith et al. (2015) appears to have restricted  
616 explicit processes initially, the method may not have been sufficient to suppress re-aiming by the  
617 end of the adaptation block.

### 618 **Discrepancy between different estimates of implicit learning.**

619           In Experiment 2, the extent of implicit learning inferred from aiming reports in the long  
620 preparation time condition was similar to the extent of error compensation observed for the short  
621 preparation time condition. However, for the long preparation condition, there was a difference  
622 between estimates of implicit learning obtained from reporting during exposure to the rotation,  
623 and estimates of implicit learning obtained from subsequent movements made without feedback.  
624 A discrepancy has been reported previously between measures of implicit learning measured via  
625 movement directions after subtracting aiming directions, and via movement directions in  
626 subsequent no-feedback trials (c.f. Fig 2C, Fig 5C Bond and Taylor 2015). However, we found  
627 that there was no such decay between errors in the last perturbation trials and first no-feedback  
628 trials for the short preparation time condition. Furthermore, the overall amount of implicit  
629 remapping (indicated by adapted movements in the no-feedback block despite explicit  
630 knowledge that the rotation had been removed), was less in the reporting group than in either of  
631 two groups that did not report aiming directions (i.e., the LongNoReport group and the Short  
632 group), irrespective of movement preparation time. We note that this difference might result  
633 from either the act of reporting aiming directions, and/or the presence of visual landmarks,  
634 however, as the original reporting procedure often requires the use of landmarks, we did not  
635 attempt to dissociate between the two possibilities.

636           We propose two possibilities to account for these observations. One possibility is that  
637 implicit learning is more labile (i.e., more sensitive to decay due to a change in task context or

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638 the passage of time) when it is acquired in a context in which people report their re-aiming  
639 strategies to compensate for errors. The proposal that explicit processes reduce the persistence of  
640 implicit remapping is consistent with findings in prism adaptation, where explicit knowledge of  
641 the nature of the perturbation reduces the extent of implicit remapping measured in post-  
642 perturbation no-feedback trials (Jakobson and Goodale 1989; Uhlarik 1973). One caveat to this  
643 interpretation is that, although all three groups experienced the same change in context (i.e., from  
644 having feedback of cursor position with visuomotor rotation to having no cursor feedback and  
645 explicit knowledge that the rotation had been removed), the LongReport group experienced an  
646 additional context change (i.e., from having to report aiming directions to no longer having to  
647 report aiming directions). Thus, we cannot rule out the possibility that the extent of context  
648 change, rather than sensitivity to change, was the key factor underlying a reduced estimate of  
649 implicit learning in the LongReport condition.

650 An alternative possibility that could explain our data is that people may have  
651 systematically under-reported their aiming angle (i.e., people re-aimed to a greater extent than  
652 they reported). This would result in an underestimation of explicit learning and an  
653 overestimation of implicit learning in the error compensation phase. In this case, the no-feedback  
654 trials would provide a more accurate measure of implicit learning than the reporting trials, which  
655 in turn would imply that the reporting procedure enhanced explicit learning and impaired  
656 implicit learning relative to non-reporting conditions. The possibility that the reporting procedure  
657 enhanced explicit re-aiming is supported by previous findings of faster error compensation with  
658 the reporting procedure than without (Taylor et al. 2014). Such a situation would suggest a  
659 competitive push-pull relationship between implicit and explicit processes in sensorimotor  
660 adaptation. A push-pull relationship between implicit and explicit processes has been shown for  
661 other motor learning tasks. For example, in sequence learning, disrupting explicit awareness of a  
662 sequence to be learned, by performing a concurrent verbal declarative task, improved post-task  
663 recall of implicitly acquired sequences (Brown and Robertson 2007). Similarly, in force-field  
664 adaptation, engaging a declarative verbal memory task resulted in poorer recall of a fragile,  
665 possibly explicit memory created by a fast process, and improved recall of a robust, possibly  
666 implicit memory created by a slow process (Keisler and Shadmehr 2010).

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667 By contrast, implicit adaptation to visuomotor rotation has been argued to be inflexible,  
668 such that it develops in parallel with, but independently from, explicit learning (Bond and Taylor  
669 2015). Although it is difficult to test whether self-reports of aiming direction are accurate,  
670 discrepancies between self-reported aiming directions and actual aiming directions seem possible.  
671 Georgopoulos and Massey (1987a) showed that when participants were explicitly instructed to  
672 re-aim by a specified angle, their re-aiming was in excess of the instructed angle, particularly  
673 with smaller instructed re-aiming angles of less than 35°. Thus, the question of whether implicit  
674 and explicit processes operate independently or competitively in visuomotor rotation learning  
675 warrants further attention.

### 676 **Summary**

677 This study evaluated the method of dissociating implicit and explicit learning by  
678 manipulating the amount of time available to prepare movements. The method has previously  
679 been shown to unmask implicit visuomotor rotation learning on a trial-by-trial basis (Haith et al.  
680 2015). We found that although shortening preparation time does not prevent people from  
681 voluntarily aiming to one side of a target, it appears sufficient to suppress strategic re-aiming  
682 during visuomotor adaptation when targets are distributed about a broad angular range.  
683 Estimating implicit learning by subtracting aiming directions from movement directions yielded  
684 a discrepancy between the estimate of implicit error compensation obtained during exposure to  
685 the perturbation, and the estimate of implicit learning obtained from post-perturbation trials  
686 without feedback. It is possible that the reporting procedure inadvertently increased explicit re-  
687 aiming and decreased implicit learning, which would suggest a push-pull relationship between  
688 explicit and implicit learning. In contrast, shortening movement preparation time did not result in  
689 a discrepancy between the estimate of implicit learning obtained from self-report during  
690 exposure to the perturbation, and the estimate of implicit learning obtained from trials performed  
691 subsequently without visual feedback.

692

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30

693 *References*

- 694 **Bond KM, and Taylor JA.** Flexible explicit but rigid implicit learning in a visuomotor  
695 adaptation task. *J Neurophysiol* 113: 3836-3849, 2015.
- 696 **Brown RM, and Robertson EM.** Inducing motor skill improvements with a declarative task.  
697 *Nature neuroscience* 10: 148-149, 2007.
- 698 **Brudner SN, Kethidi N, Graeupner D, Ivry RB, and Taylor JA.** Delayed feedback during  
699 sensorimotor learning selectively disrupts adaptation, but not strategy use. *J Neurophysiol* jn  
700 00066 02015, 2016.
- 701 **Fernandez-Ruiz J, Wong W, Armstrong IT, and Flanagan JR.** Relation between reaction  
702 time and reach errors during visuomotor adaptation. *Behav Brain Res* 219: 8-14, 2011.
- 703 **Galea JM.** Secondary tasks impair adaptation to step- and gradual-visual displacements. *Exp*  
704 *Brain Res* 202: 473-484, 2010.
- 705 **Georgopoulos AP, and Massey JT.** Cognitive spatial-motor processes - 1. The making of  
706 movements at various angles from a stimulus direction. *Exp Brain Res* 65: 361-370, 1987a.
- 707 **Georgopoulos AP, and Massey JT.** Cognitive spatial-motor processes. 1. The making of  
708 movements at various angles from a stimulus direction. *Exp Brain Res* 65: 361-370, 1987b.
- 709 **Ghez C, Hening W, and Favilla M.** Gradual Specification of Response Amplitude in Human  
710 Tracking Performance. *Brain Behav Evol* 33: 69-74, 1989.
- 711 **Gordon J, Ghilardi MF, and Ghez C.** Accuracy of planar reaching movements - I.  
712 Independence of direction and extent variability. *Exp Brain Res* 99: 97-111, 1994.
- 713 **Haith AM, Huberdeau DM, and Krakauer JW.** The influence of movement preparation time  
714 on the expression of visuomotor learning and savings. *The Journal of neuroscience : the official*  
715 *journal of the Society for Neuroscience* 35: 5109-5117, 2015.
- 716 **Heuer H, and Hegele M.** Adaptation to visuomotor rotations in younger and older adults.  
717 *Psychol Aging* 23: 190-202, 2008.
- 718 **Heuer H, and Hegele M.** Explicit and implicit components of visuo-motor adaptation: An  
719 analysis of individual differences. *Consciousness and cognition* 33: 156-169, 2015.
- 720 **Howard IS, Ingram JN, and Wolpert DM.** A modular planar robotic manipulandum with end-  
721 point torque control. *Journal of Neuroscience Methods* 181: 199-211, 2009.
- 722 **Huberdeau DM, Krakauer JW, and Haith AM.** Dual-process decomposition in human  
723 sensorimotor adaptation. *Curr Opin Neurobiol* 33: 71-77, 2015.
- 724 **Jakobson LS, and Goodale MA.** Trajectories of reaches to prismatically-displaced targets:  
725 evidence for "automatic" visuomotor recalibration. *Experimental brain research* 78: 575-587,  
726 1989.
- 727 **Keisler A, and Shadmehr R.** A shared resource between declarative memory and motor  
728 memory. *Journal of Neuroscience* 30: 14817-14823, 2010.
- 729 **Malone La, and Bastian AJ.** Thinking about walking: effects of conscious correction versus  
730 distraction on locomotor adaptation. *Journal of neurophysiology* 103: 1954-1962.

## PREPARATION TIME CONSTRAINTS CAN ASSAY IMPLICIT VISUOMOTOR

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31

- 731 **Marinovic W, Cheung FL, Riek S, and Tresilian JR.** The effect of attention on the release of  
732 anticipatory timing actions. *Behav Neurosci* 128: 548, 2014.
- 733 **Marinovic W, Plooy A, and Tresilian JR.** The time course of amplitude specification in brief  
734 interceptive actions. *Exp Brain Res* 188: 275-288, 2008.
- 735 **Marinovic W, Tresilian J, Chapple JL, Riek S, and Carroll T.** Unexpected acoustic  
736 stimulation during action preparation reveals gradual re-specification of movement direction.  
737 *Neuroscience* 2017.
- 738 **Mazzoni P, and Krakauer JW.** An implicit plan overrides an explicit strategy during  
739 visuomotor adaptation. *Journal of Neuroscience* 26: 3642-3645, 2006.
- 740 **McDougle SD, Bond KM, and Taylor JA.** Explicit and implicit processes constitute the fast  
741 and slow processes of sensorimotor learning. *The Journal of Neuroscience* 35: 9568-9579, 2015.
- 742 **Morehead JR, Qasim SE, Crossley MJ, and Ivry R.** Savings upon Re-Aiming in Visuomotor  
743 Adaptation. *The Journal of neuroscience : the official journal of the Society for Neuroscience* 35:  
744 14386-14396, 2015.
- 745 **Reber AS.** Implicit learning of artificial grammars. *Journal of verbal learning and verbal*  
746 *behavior* 6: 855-863, 1967.
- 747 **Redding GM, and Wallace B.** Adaptive Spatial Alignment and Strategic Perceptual-Motor  
748 Control. 22: 1996.
- 749 **Reichenthal M, Avraham G, Karniel A, and Shmuelof L.** Target size matters: Target errors  
750 contribute to the generalization of implicit visuomotor learning. *Journal of neurophysiology* jn.  
751 00830.02015, 2016.
- 752 **Schouten JF, and Bekker JAM.** Reaction time and accuracy. *Acta Psychologica* 27: 143-153,  
753 1967.
- 754 **Taylor JA, Krakauer JW, and Ivry RB.** Explicit and implicit contributions to learning in a  
755 sensorimotor adaptation task. *The Journal of neuroscience : the official journal of the Society for*  
756 *Neuroscience* 34: 3023-3032, 2014.
- 757 **Taylor JA, and Thoroughman KA.** Divided Attention Impairs Human Motor Adaptation But  
758 Not Feedback Control. *Journal of Neurophysiology* 98: 317-326, 2007.
- 759 **Taylor JA, and Thoroughman KA.** Motor adaptation scaled by the difficulty of a secondary  
760 cognitive task. *PLoS ONE* 3: 2008.
- 761 **Uhlarik JJ.** Role of cognitive factors on adaptation to prismatic displacement. *J Exp Psychol* 98:  
762 223-232, 1973.
- 763 **Wolpert DM, Ghahramani Z, and Jordan MI.** An internal model for sensorimotor integration.  
764 *Science* 269: 1880-1882, 1995.
- 765 **Zar JH.** *Biostatistical analysis*. Upper Saddle River, N.J.: Upper Saddle River, N.J. : Prentice-  
766 Hall/Pearson, 2010.
- 767  
768

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#### 769 Figure Legends

770 Figure 3. Top panel: A schematic representing the timed-response paradigm. Three tones spaced  
771 500 ms apart were presented, and participants were instructed to time the onset of their  
772 movements with the onset of the third tone. Targets appeared at different latencies prior to the  
773 third tone (Experiment 1a: 1000ms, 250ms, 200ms, 150ms, or 100ms; Experiment 1b: 1000ms,  
774 250ms, 200ms, 150ms; Experiment 2: Long preparation time condition: 1000ms, short  
775 preparation time condition: 250ms). Note that these latencies were minus a display latency of  
776  $27.6 \pm 1.8$  ms. Bottom panel: Experiment 2 landmark layout for the LongReport conditions.

777  
778 Figure 4. Movement directions for the narrow target range ( $-17.5^\circ$  to  $17.5^\circ$ ) and large target  
779 range ( $0^\circ$  to  $360^\circ$ ) plotted relative to target direction at  $0^\circ$ , in the aiming and re-aiming conditions.  
780 Data from participants in the counterclockwise re-aiming condition were normalized to the  
781 clockwise direction and collapsed with data from participants in the clockwise re-aiming  
782 condition. Symbols represent movement directions in individual trials for all participants across  
783 the preparation time conditions (1000ms, 250ms, 200ms, 150ms to 100 ms). Note that the hard  
784 cut-off times for movement initiation in these conditions were: 1022.4, 272.4, 222.4, 172.4,  
785 122.4 ms after target appearance. Red vectors represent individual mean vectors for each  
786 participant, and error bars represent the mean and 95% confidence intervals of mean movement  
787 direction for each participant. Green vectors represent individual mean vectors that were not  
788 significantly directionally tuned according to a Rayleigh's test.

789  
790 Figure 3. Movement errors for each target direction from  $-17.5^\circ$  to  $17.5^\circ$  with respect to (w.r.t)  
791 the required reaching direction (i.e., presented target or re-aiming target depending on condition).  
792 Data from participants in the counterclockwise re-aiming condition were normalized to the  
793 clockwise direction and collapsed with data from participants in the clockwise re-aiming  
794 condition. Separate plots are shown for the 150ms to 100 ms preparation time conditions. Note  
795 that the hard cut-off times for movement initiation in these conditions were 172.4 and 122.4 ms  
796 after target appearance. Values are group mean errors and error bars represent 95% confidence  
797 intervals.

798  
799 Figure 4. Experiment 2 mean movement direction in every cycle, averaged across each condition.  
800 Data from participants who encountered counterclockwise rotations were sign-transformed to  
801 allow collapsing with data from participants who encountered clockwise rotations. Error bars are  
802 standard errors of the mean. Negative values indicate movements that were opposite from the  
803 direction of rotation, positive values indicate movements that were in the same direction as the  
804 rotation. Note that Long Report Implicit is not an additional experimental condition, but is  
805 derived from subtracting self-reported aiming directions from movement directions in the Long  
806 Report condition.

807  
808



**Small Target Range (17.5°, 12.5° ... 17.5°)**

**Large Target Range (0°, 45° ... 315°)**

**Aiming**

**Reaiming**

**Aiming**

**Reaiming**

**1000ms**

**1000ms**

**250ms**

**250ms**

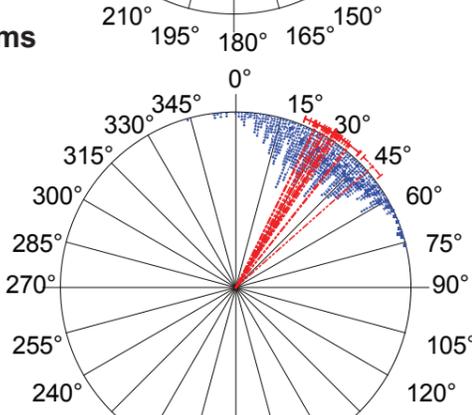
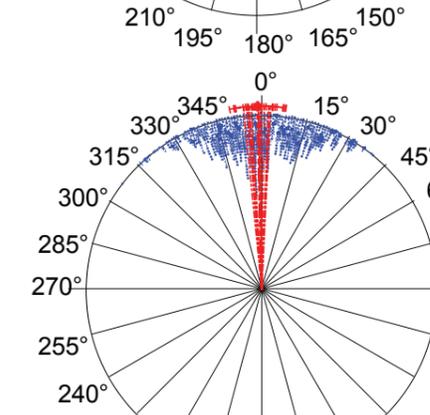
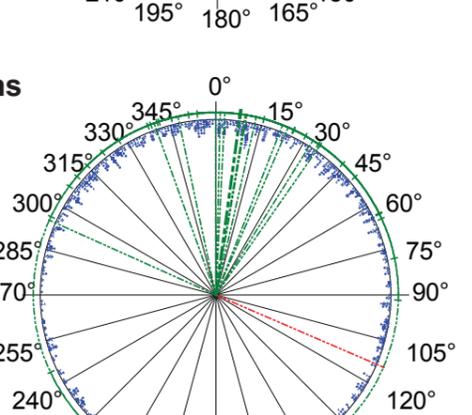
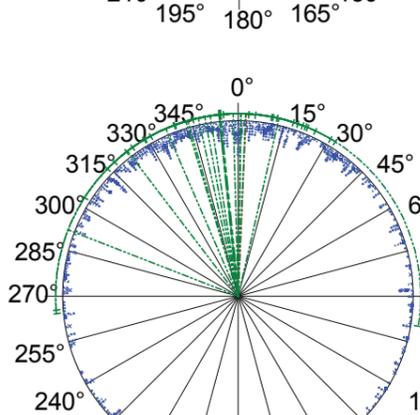
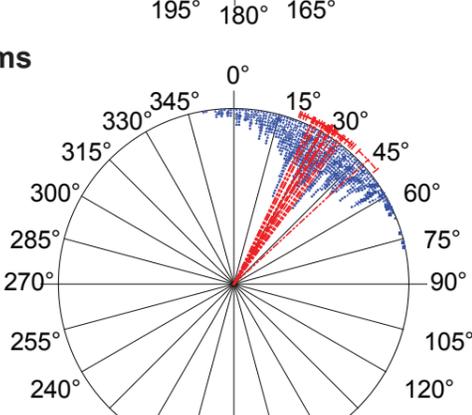
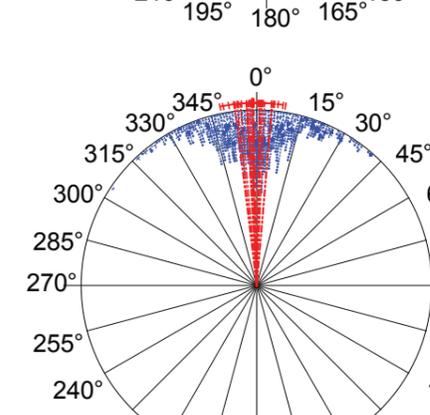
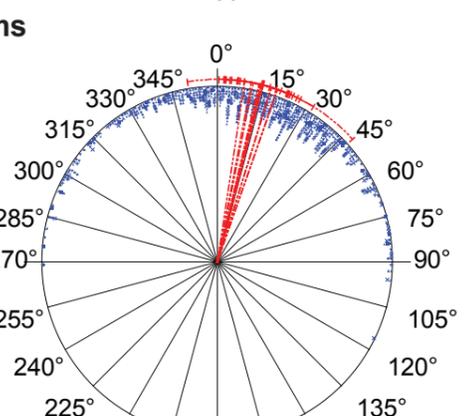
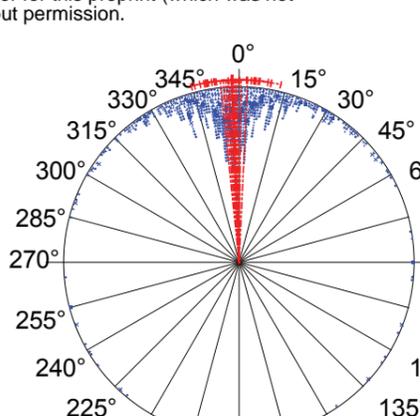
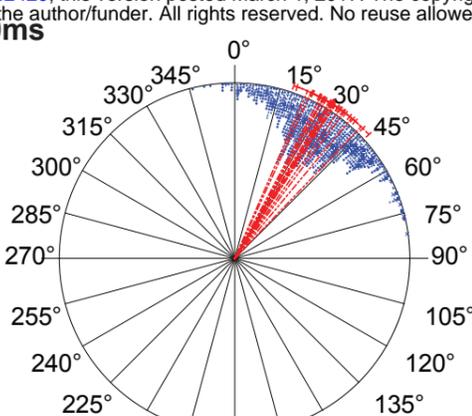
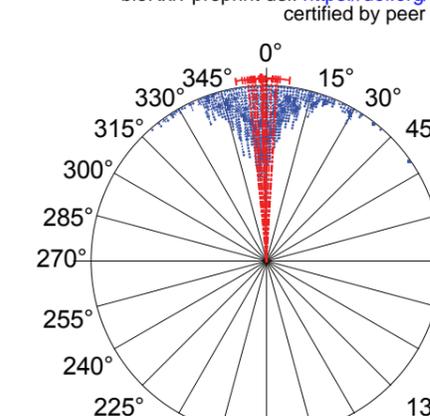
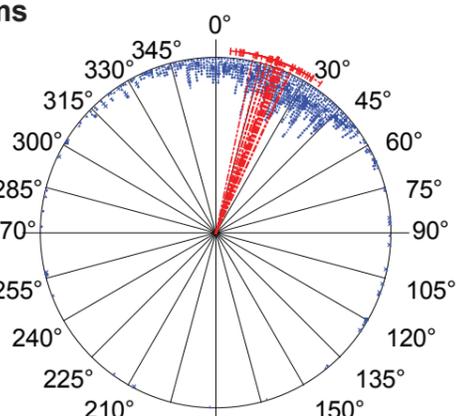
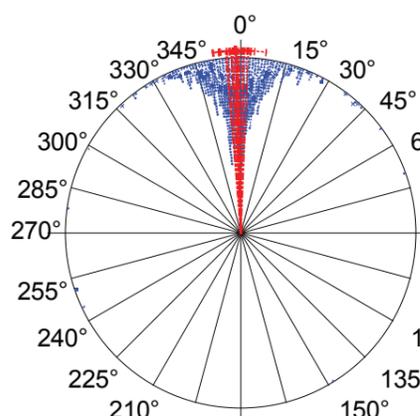
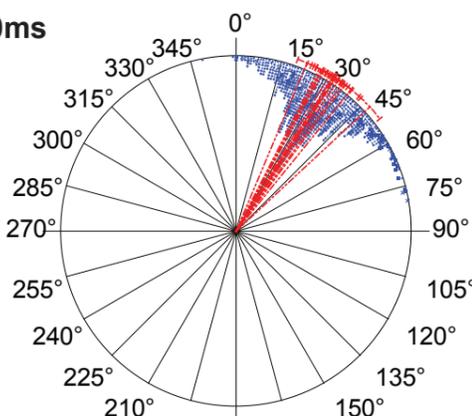
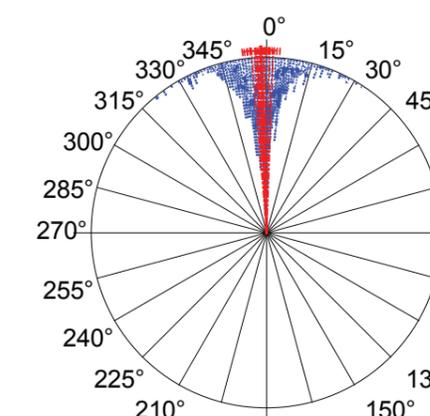
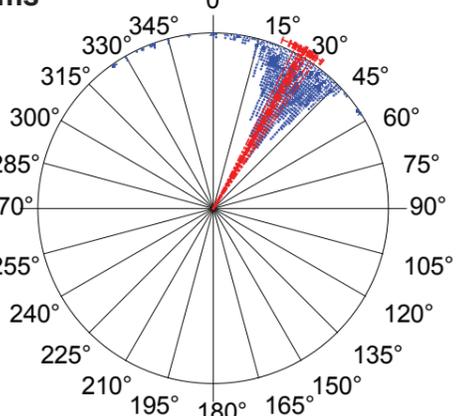
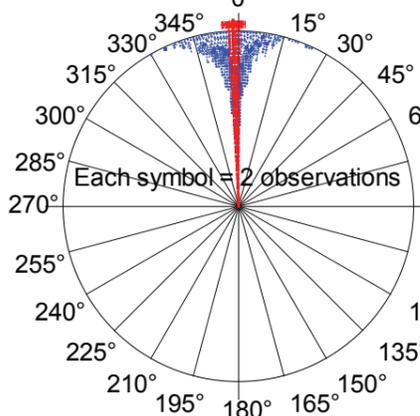
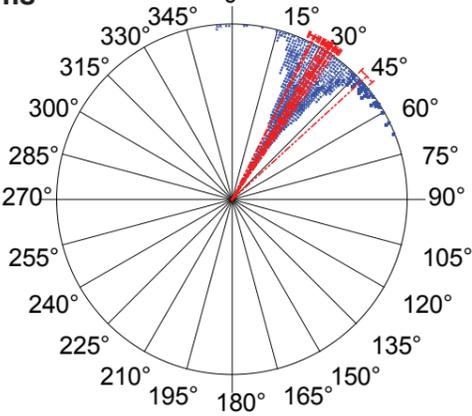
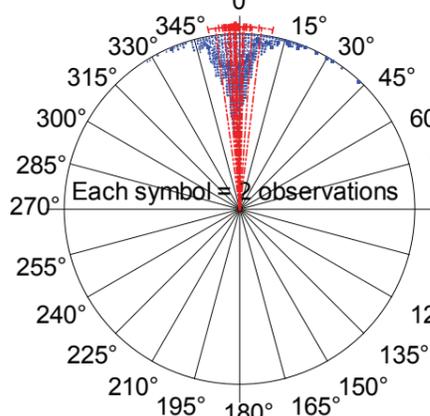
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**200ms**

**150ms**

**150ms**

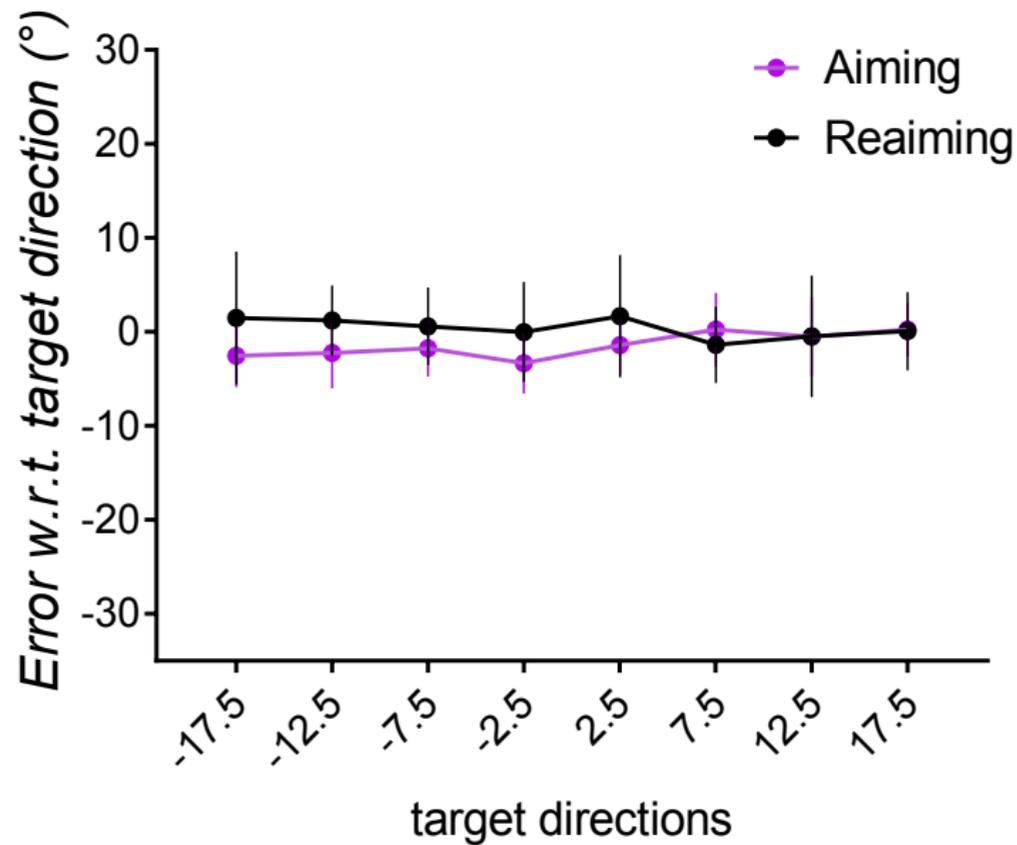
**100ms**



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Each symbol = 2 observations

150ms



100ms

