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

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21 visuomotor rotation

22

23   **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.

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44

45   **Introduction**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

65   sensory outcomes develops with extended exposure to perturbation.

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

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

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

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

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

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

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

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

74   some contexts, and time-consuming. Secondly, the instruction to report aiming directions results

75   in faster error reduction than occurs in the absence of such instructions (Taylor et al. 2014),

76   presumably because the reporting requirement alerts participants to the benefits of re-aiming to

77   achieve task success. This raises the question of whether the reporting procedure might also

78   impact implicit processes, because the reduced task errors that accompany explicit strategy use

79   might affect the rate or extent of implicit adaptation via reward or reinforcement-related

80   processes (Reichenthal et al. 2016).

81   An alternative approach to probe implicit processes in sensorimotor adaptation is to

82   suppress the expression of explicit processes. This can be done either by employing dual-task

83   paradigms to limit attentional resources that can be devoted to explicit re-aiming (Galea 2010;

84   Keisler and Shadmehr 2010; Malone and Bastian ; Taylor and Thoroughman 2007; Taylor and

85   Thoroughman 2008), or by restricting the amount of time available to prepare a movement

86   (Fernandez-Ruiz et al. 2011; Haith et al. 2015). Restricting preparation time appears to be a

87   particularly promising approach, as there is a relationship between preparation time and

88   movement accuracy even without a sensorimotor perturbation (Georgopoulos and Massey 1987b;

89   Marinovic et al. 2017). Furthermore, there is a time cost of explicitly preparing movements

90   toward locations that are offset from the physical location of a target (Georgopoulos and Massey

91   1987b). In one such approach, Haith et al. (2015) carefully controlled movement preparation

92   time to dissociate learning resulting from explicit and implicit processes during adaptation to a

93   visuomotor rotation. They showed significantly slower error reduction when they restricted

94   movement preparation time by suddenly shifting target position in 20% of trials approximately

95   300ms before the imperative to move (Haith et al. 2015). The data suggest that explicit re-aiming

96   was supressed by the preparation time constraint. The approach also has the benefit that it

97   provides a within-subject contrast between presumed implicit remapping (from errors on the

98   short preparation trials) and combined implicit and explicit adaptation (from errors on the long

99   preparation trials). However, some aspects of this approach merit further consideration. First, it

100 is unclear whether 300 ms is sufficiently brief to prevent entirely strategy use during adaptation.

101 Second, the switch in target location might introduce an additional processing demand, and may

102 not be desirable in some experimental designs. More generally, it is unknown whether assays of

103 implicit sensorimotor adaptation obtained via preparation time manipulation differ from those

104 obtained via reporting procedures. Here, we compared implicit learning assayed by restricting

105 movement preparation time to implicit learning assayed via reporting procedures.

106 The first aim of the study was to determine the extent to which the capacity to explicitly

107 re-aim is suppressed by reducing the amount of time available to prepare movement. We asked

108 people to explicitly re-aim 30° clockwise or counter-clockwise to targets, under increasing time

109 pressure, but in the absence of a perturbation. We expected that there would be a minimum time

110 for movement preparation below which people would be unable to aim accurately to one side of

111 a target. However, we also wondered whether advance knowledge of the approximate location of

112 potential targets would influence the capacity to re-aim. To this end, voluntary re-aiming was

113 performed either to a narrow (0-35° range) (Experiment 1A) or uniform 360°distribution of

114 target directions (Experiment 1B). We predicted that people would be able to re-aim with shorter

115 preparation times when targets were distributed narrowly. We found that participants could re-

116 aim by 30° even at the shortest preparation times tested with a narrow target distribution, but at

117 the expense of increased movement variability. For a broad 360° target distribution, participants

118 could at least partially re-aim whenever movement time was sufficient to produce directionally

119 tuned movements (i.e., as opposed to randomly directed movements), but at more dramatic cost

120 to movement variability. Thus, the motor system is capable of systematic re-aiming to one side

121 of a target irrespective of time constraints. However, we noted that participants found re-aiming

122 at short preparation times extremely effortful. Given this, the purpose of Experiment 2 was to

123 determine whether people would choose to re-aim under time pressure in order to improve

124 performance on a visuomotor rotation task.

125 In Experiment 2, we compared adaptation to a 30° visuomotor rotation with a 360° target

126 distribution under three alternative conditions. Separate groups of participants were either

127 allowed: (1) a short time to prepare movement, (2) a longer time to prepare movement, but also

128 asked to report their aiming direction, or (3) a longer time to prepare movement, without

129 reporting aiming direction. If people chose not to re-aim reaches to counter the visuomotor

130 rotation when preparation time was constrained, then we expected the rate of error reduction in

131 this condition to resemble the rate of implicit adaptation estimated from the self-report procedure.

132 We were also interested in the effects of the three different conditions on an alternative measure

133 of implicit adaptation obtained from reaches made in the absence of visual feedback. We found

134   that the rate and extent of error compensation with short preparation time closely matched

135   implicit error compensation, as estimated from subtracting movement directions from self-

136   reported aiming directions. This suggests that restriction of preparation time can suppress

137   explicit re-aiming, and provide an estimate of implicit learning that does not require participants

138   to report their aiming directions. Surprisingly, in the post-perturbation no-feedback trials, less

139   implicit learning was shown in participants who reported aiming directions than participants who

140   did not report aiming directions. This raises the possibility that the reporting procedure itself

141   increased engagement of explicit learning, which inadvertently reduced engagement of implicit

142   learning.

143

Method

145   **Participants**

146   A total of 74 participants completed this study (Experiment 1A: n=14, mean age = 19.93,

147   range = 17-42 years, 12 females, 2 left-handed; Experiment 1B: n=14, mean age = 19.07, SD =

148   3.53, range = 17-31 years, 11 females, 2 left-handed; Experiment 2: n=36, 30 females, 2 left

149   handed, mean age =19.85, SD = 1.82). In Experiment 2, 36 people were initially assigned either

150   to a short preparation time condition or a long preparation time condition in which they had to

151   report aiming direction. Subsequently, in order to test whether differences in post-perturbation

152   estimates of implicit learning were due to the preparation time conditions or the reporting

153   procedure, a further 10 people were recruited to a long preparation time condition without

154   reporting (mean age 21, SD=4.7, range=18 to 34 years, all right-handed). For all experiments,

155   the participants were randomly assigned either to clockwise or counter-clockwise visuomotor

156   rotation conditions in equal proportions. All participants were naïve to visuomotor rotation and

157   force-field adaptation tasks.

158   **Apparatus and General Trial Structure**

159   Participants completed the task using the vBOT planar robotic manipulandum, which has

160   a low-mass, two-link carbon fibre arm and measures position with optical encoders sampled at

161   1,000 Hz (Howard et al. 2009). Participants were seated on a height-adjustable chair at their ideal

162   height for viewing the screen for the duration of the experiment. Visual feedback was presented

163   on a horizontal plane on a 27" LCD computer monitor (ASUS, VG278H, set at 60Hz refresh rate)

164   mounted above the vBOT and projected to the subject via a mirror in a darkened room,

165   preventing direct vision of their hand. The mirror allowed the visual feedback of the target (a 0.5

166   cm radius circle), the starting location (a 0.5 cm radius circle), and hand cursor (0.25 cm radius)

167   to be presented in the plane of movement, with a black background. The start circle was aligned

168   10cm to the right of the participant's mid-sagittal plane at approximately mid-sternum level.

169   **General Trial Structure**

170   Participants made centre-out reaching movements by moving the robot arm from the start

171   circle to the target. Targets appeared in random order at one of eight locations 9cm away from

172   the start circle—target locations were clustered either in a small range (Experiment 1A:

173   17.5°,12.5°,7.5°,2.5°,-2.5°,-7.5°,-12.5°,-17.5° from straight ahead), or distributed uniformly

174   throughout 360° (Experiment 1B & Experiment 2: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°).

175   At the start of each trial, the central start circle was displayed. If participants failed to move the

176   hand to within 1cm of the start circle after 1 second, the robotic manipulandum passively moved

177   the participant's hand to the start circle (using a simulated 2 dimensional spring with the spring

178   constant magnitude increasing linearly over time). A trial was initiated when the cursor remained

179   within the home location at a speed below 0.1 cm/s for 200 ms. We used a timed-response

180   paradigm (Ghez et al. 1989; Haith et al. 2015; Marinovic et al. 2014; Marinovic et al. 2008;

181   Schouten and Bekker 1967) to manipulate movement preparation time. Across all conditions, a

182   sequence of three tones spaced 500 ms apart was presented at a clearly audible volume via

183   external speakers. Participants were instructed to time the onset of their movements with the

184   onset of the third tone (see Figure 1). They were instructed not to stop on the target, but to slice

185   through it. Movement initiation was defined online as when hand speed exceeded 2cm/s. Targets

186   appeared at 1000ms, 250ms, 200ms, 150ms, or 100ms, minus a display latency (27.6 ± 1.8 ms),

187   prior to the third tone. Thus target direction information became available 972.4, 222.4, 172.4,

188   122.4, or 72.4 ms before the desired initiation time. When movements were initiated 50 ms later

189   than the third tone, the trial was aborted: the screen was blanked and a "Too Late" on-screen

190   error signal appeared. Similarly, when movements were initiated more than 100 ms before the

191   desired initiation time, the trial was aborted: the screen was blanked and a "Too Soon" on-screen

192   error signal appeared. No visual feedback about movements was available when trials were
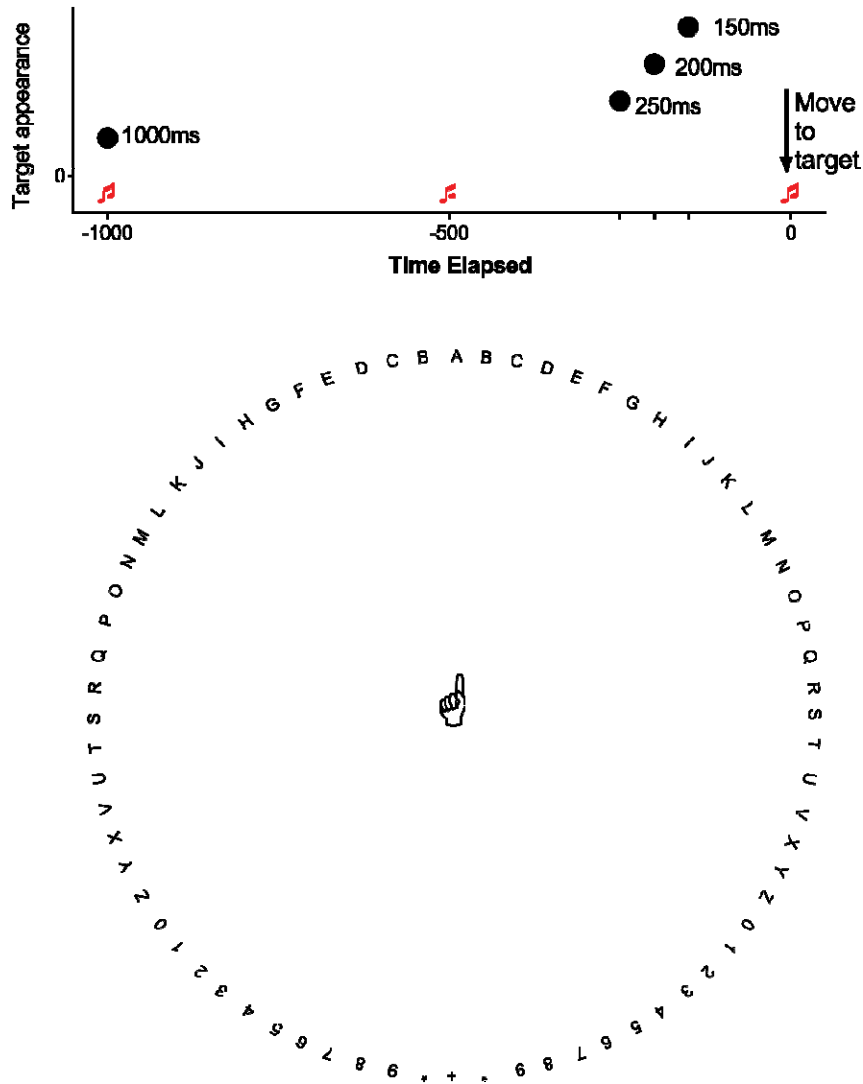
193   aborted. Thus, all movements recorded and analysed were made according to the following "hard

194   cut-off" times: within 1022.4, 272.4, 222.4, 172.4, 122.4 ms after target presentation.

195

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

203   **Experiment 1**. The aim was to test re-aiming performance under progressively shorter
204   preparation times, to determine whether restricting movement preparation can prevent strategic
205   re-aiming. This paradigm of asking participants to re-aim by a specified angle relative to a visual
206   target is similar to that used by Georgopoulos and Massey (1987a). In each trial, participants
207   encountered one of eight targets which either spanned a small range of 35° (-17.5°, -
208   12.5°…17.5°) in Experiment 1A, or a distribution of 360° (0°, 45° … 360°) in Experiment 1B.
209   Targets were presented in random order. In all trials, thirty-six "landmarks" were presented on-
210   screen as white circles spaced 10° apart throughout the 360° range, 10 cm from the start circle. In
211   the re-aiming condition, half of the participants were instructed to re-aim to the third landmark
212   located clockwise from the target, and half were instructed to re-aim to the third landmark
213   counter-clockwise to the target (i.e., 30° either side of the target). All participants completed the
214   aiming condition before the re-aiming condition in blocks of 48 trials for each preparation time
215   condition. The preparation times were progressively shortened, such that the trial schedule was:
216   1000ms aiming, 1000ms re-aiming, 250ms aiming, 250ms re-aiming, 200ms aiming, 200ms re-
217   aiming, 150ms aiming, 150ms re-aiming, 100ms aiming, 100ms re-aiming. The 100ms condition
218   was not included in Experiment 1B because most participants could not initiate target-directed
219   movements prior to the deadline.

220   **Experiment 2.** To examine whether shortening preparation time can provide a sufficient
221   assay of implicit learning, we compared adaptation behaviour with short preparation time to an
222   estimate of implicit learning obtained by subtracting self-reported aiming direction from the
223   actual direction of hand movement (Bond and Taylor 2015; Brudner et al. 2016; McDougle et al.
224   2015; Taylor et al. 2014). Participants were assigned either to a 250ms preparation time
225   condition (Short), or one of two 1000ms preparation time conditions. In the LongReport
226   condition, they had to verbally report aiming directions by stating which of 72 landmarks spaced
227   5° apart most closely corresponded to the direction that they were aiming towards (Bond and
228   Taylor 2015; Taylor et al. 2014). Previous studies exclusively used numerical landmarks (Bond
229   and Taylor 2015; Brudner et al. 2016; Morehead et al. 2015; Taylor et al. 2014), which allowed
230   the use of mental addition or subtraction strategies in some participants (Bond and Taylor 2015).
231   We thus avoided using only number landmarks. Landmarks consisted of the letters A to Z, the
232   numbers 1-9, and the symbol "*" (reported as "star"). For ease of reporting, multiple-syllable

233   characters (i.e., W) were not used. Landmarks rotated with the target, such that the same

234   landmarks would always appear in the same location relative to the target, because rotating

235   landmarks are more sensitive to explicit processes than fixed-location landmarks (Bond and

236   Taylor 2015). Because of this, only a subset of the possible landmark values (A, B…G, *, 1,

237   2, …9) were actually used by participants when reporting their aiming directions. Participants

238   were allowed to report their aiming direction at any time between target appearance and

239   movement completion. Verbal reports of aiming directions were recorded online by the

240   experimenter. To estimate implicit learning, these self-reported aiming directions were

241   subtracted from actual movement directions. A third control group (LongNoReport) had a

242   1000ms preparation time, but did not have to report aiming directions. We did not apply the

243   reporting manipulation to the Short condition, as piloting showed that it was extremely difficult

244   to report the aiming direction when the target appeared 250 ms prior to the imperative signal to

245   move.

246   Prior to the start of the experiment, participants were given no information about the

247   nature of the rotation; they were only told that a disturbance of the cursor would be present in

248   some trials, which may increase task difficulty. Participants in all conditions first completed a

249   **pre-rotation** block of 6 cycles (48 trials) with veridical feedback of their movement trajectories

250   to familiarize them with the task. LongReport participants began to verbally report their aiming

251   direction in last 24 trials in the pre-rotation block to familiarize them with the reporting

252   procedure. The pre-rotation block was followed by a **rotation** block (60 cycles, i.e., 480 trials)

253   with either a 30° clockwise or counterclockwise rotation of visual feedback relative to the centre

254   of the start circle. Halfway through this block, participants were given a 30 second break. The

255   rotation block was followed by a **no-feedback** block of 6 cycles (i.e., 48 trials), where visual

256   feedback of the cursor position was hidden immediately after the cursor left the start circle.

257   Crucially, before commencing this block, participants were explicitly instructed that there was no

258   longer any disturbance of visual feedback, and that they should aim straight towards the target

259   (Heuer and Hegele 2008; Taylor et al. 2014). The no-feedback block therefore provides an

260   alternative assay of implicit remapping. Finally, participants completed a **washout** block of 6

261   cycles (48 trials) where unrotated visual feedback was available to enable participants to return

262   movements back to the unadapted state. Landmarks were removed from the no-feedback block

263 and the washout block, and participants were no longer required to report aiming direction in

264 these blocks. The same preparation time constraints were maintained throughout the entire

265 experiment for each group.

266 **Data analysis**

267 Movement onset time was taken as the time at which hand speed first exceeded 2 cm/s.

268 Movement direction was quantified 100ms after movement onset, prior to the potential influence

269 of online corrections. For Experiment 2, data from the counterclockwise rotation group were

270 sign-transformed to allow us to collapse the dataset with data from the clockwise rotation group.

271 Negatively signed angles indicate that the deviation in hand direction relative to the target was

272 opposite to the direction of the rotation (i.e., to reduce visual error).

273 **Experiment 1:** To determine which of the preparation times was sufficiently short to

274 suppress strategic re-aiming, we first quantified movement directions relative to the target as

275 mean vectors and variability of movement directions as mean vector lengths, denoted as *r* for all

276 preparation times tested using circular statistics. In the aiming condition, mean vectors values

277 close to zero suggest that movement directions were close to the target. In the re-aiming

278 condition, values close to 30° indicate that movement directions were close to the instructed re-

279 aiming direction. Longer mean vectors indicate less variable movement directions, with a value

280 of 1 indicating all directions aligned, and a value of 0 indicating an absence of directional tuning

281 (i.e. a uniform distribution throughout all possible directions). We then compared movement

282 directions and variability for the aiming conditions to the re-aiming conditions. When directional

283 data is normally distributed, one can use the Hotelling's Paired Test, which is the equivalent of

284 the paired t-test for circular statistics (Zar 2010). However, as aiming directions were not

285 normally distributed, we used a non-parametric alternative (Moore's paired sample second order

286 tests) to determine whether mean vectors differed reliably between aiming and re-aiming

287 conditions (Zar 2010). Similarly, mean vector lengths typically show skewed distributions close

288 to 1, and thus Wilcoxon-Rank analyses were used to compare variability between the aiming and

289 re-aiming conditions. Circular statistics analyses were conducted with the software Oriana. For

290 Experiment 1a (narrow target distribution), we also tested whether participants re-aimed by

291 moving towards the middle of a (hypothetical) re-aiming target distribution by measuring the

292 errors made to each target, for the two shortest preparation time conditions (100 ms & 150 ms).

293   If re-aiming errors were smallest at the central 0° target and largest at the surrounding targets,

294   then this would suggest that participants adopted a strategy to re-aim to the middle of the

295   hypothetical re-aiming target distribution by initiating movements prior to full integration of

296   target direction information.

297   **Experiment 2**. Prior to statistical analyses, movements further than 90° clockwise or

298   counterclockwise away from the target (i.e., outside of a 180° range) were deemed as outliers,

299   and were discarded from the analysis. This procedure excluded a small proportion of trials

300   (Short: 4.00%, LongReport: 0.58%, LongNoReport: 0.39%). We evaluated whether the direction

301   of hand movement relative to the target, under reduced movement preparation time conditions,

302   was similar to the estimate of implicit learning obtained by subtracting self-reported aiming

303   directions from actual movement directions (Taylor et al. 2014). To this end, we recoded verbal

304   reports of landmarks into angular aiming directions, and then estimated implicit learning by

305   subtracting reported aiming directions from actual movement directions. Trials were averaged in

306   cycles of eight (one trial for each target angle) for statistical analysis. To compare adaptation

307   behaviour between conditions, ANOVAs with the within-subjects factor Cycle and two between-

308   subjects factors of Condition and Rotation Direction (clockwise, counterclockwise) were run on

309   relevant cycles. For the early adaptation phase, the relevant cycles were cycles 1-30 of the

310   adaptation block. For the late adaptation phase, the relevant cycles were cycles 31-60 of the

311   adaptation block. For the no-feedback block, the relevant cycles were all 6 cycles of the no-

312   feedback block. For the washout block, the relevant cycles were all 6 cycles of the washout

313   block. For all ANOVAs, when Mauchly's test of sphericity was statistically significant, the

314   Greenhouse-Geisser correction was used to adjust degrees of freedom.

315

316   **Results**

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

318   Movement directions for all trials pooled across all subjects are shown in Figure 2 for

319   Experiment 1A (small target range) and for Experiment 1B (large target range). With the small

320   target range, movement directions were close to the target directions when aiming, and

321   approximated the required 30º offset when re-aiming, even with the shortest preparation time

322   condition of 100ms (i.e., hard initiation cut-off of 122.4ms). Rao's tests run for each participant's

323   dataset within each preparation time condition indicated that movement directions were

324   directionally tuned for all conditions, even for the shortest 100ms preparation time condition (all

325   p<.0001).With the large target range, re-aiming movements were directed progressively closer to

326   the original target (i.e., further from the instructed 30º offset) as preparation times were

327   shortened. Rao's tests run for each participant's dataset within each preparation time condition

328   indicated that movement directions were not directionally tuned for 5 of the 13 participants who

329   completed the 150ms aiming condition and 10 of the 13 participants who completed the150ms

330   re-aiming conditions.

331

332
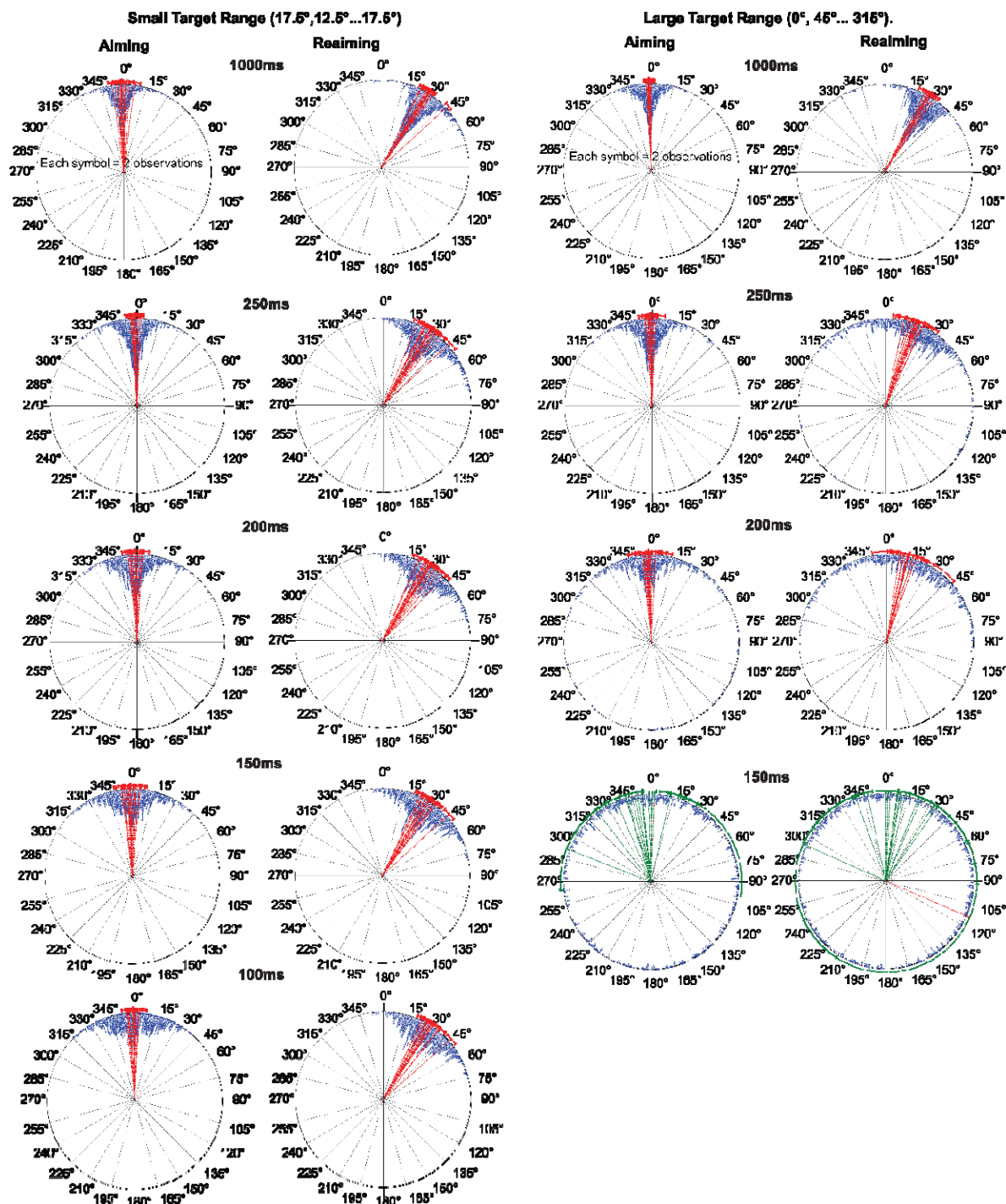
Figure 2. Movement directions for the narrow target range (-17.5° to 17.5°) and large target range (0° to 360°) plotted relative to target direction at 0°, in the aiming and re-aiming conditions. Data from participants in the counterclockwise re-aiming condition were normalized to the clockwise direction and collapsed with data from participants in the clockwise re-aiming condition. Symbols represent movement directions in individual trials for all participants across the preparation time conditions (1000ms, 250ms, 200ms, 150ms to 100 ms). Note that the hard cut-off times for movement initiation in these conditions were:

338 *1022.4, 272.4, 222.4, 172.4, 122.4 ms after target appearance. Red vectors represent individual mean vectors for each*
339 *participant, and error bars represent the mean and 95% confidence intervals of mean movement direction for each participant.*
340 *Green vectors represent individual mean vectors that were not significantly directionally tuned according to a Rayleigh's test.*

341

342

343 Table 1.

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

| **Movement Preparation Time**	Direction Variability (vector length)	Mean Vector Angle	Movement Time (mean+/-SEM)	Direction Variability (vector length)	Mean Vector Angle	Movement Time (mean+/-SEM)
Exp. 1A: Small target range: -17.5 ° to 17.5 °				**Exp. 1B**: 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-aiming235+/-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

347

348   Table 1 summarizes statistical comparisons between aiming and re-aiming across

349   preparation times for both the narrow target distribution (Experiment 1A) and the full 360° target

350   distribution (Experiment 1b). For both target distributions, movement directions were more

351   variable (shorter vector lengths) when re-aiming away from the target than when aiming to the

352   target across all preparation times. When errors were averaged across all targets in the narrow

353   range (Experiment 1a), it appears that participants could re-aim away from the target in all

354   preparation times tested (even when movements were initiated within 122.4 ms of target

355   preparation). That is, mean vector angles were on average approximately 30° away from the

356   target across all preparation times tested. We were surprised at this apparent success in re-

357   aiming, since Haith et al (2016) showed that directionally tuned movements to a unique target

358   require approximately 130 ms, and the process of re-aiming (and preparing movements to a

359   direction offset by 30° to the target) should require at least some additional processing (Haith et

360   al. 2016). We therefore examined errors for each target in the distribution individually, to search

361   for evidence that participants might have been able to achieve task success by aiming toward the

362   middle of the re-aiming target distribution (i.e. 30° away from the central visual target

363   distribution). In this case, movement could be initiated prior to integration of target direction

364   information, but average errors collapsed across targets would be close to zero.

365   Figure 3 shows clear evidence that subjects adopted such a strategy for the shortest

366   preparation time condition, under both aiming and re-aiming conditions. Errors were similar for

367   all targets in the 150ms preparation time condition, indicating that there were no large inherent

368   biases in reaching performance. There were no statistically significant differences in error size

369   across targets ($F(7,91) = 1.10$, $p = 0.39$, partial η-squared = 0.08) or conditions ($F(1,13) = 1.1$, p

370   = 0.3, partial η-squared = 0.08), nor an interaction between target and condition ($F(7,91) = 1.2$, p

371   = 0.3, partial η-squared = 0.09). By contrast, with 100ms preparation time (122.4 ms hard cut-

372   off), errors were systematically larger in absolute terms as the angle from the centre of the

373   distribution increased for the aiming condition (main effect of target $F(7,91) = 199$, $p < 0.001$,

374   partial η-squared = 0.94). The signs of errors indicate that participants made reaching movements

375   that were biased towards the central target. The pattern of errors for aiming and re-aiming

376   conditions were similar for the aiming and re-aiming conditions, with no statistically significant

377   main effect of condition ($F(1,13) = 0.6$, $p = 0.45$, partial η-squared = 0.04) or interaction between

378   condition and target ($F_{(7,91)}$ = 1.6, p = 0.15, partial η-squared = 0.11). Note that errors from the

379   required (re-aiming) target are plotted and analysed, rather than errors relative to the presented

380   target. Critically, the similarity in error directions and magnitudes for the aiming and re-aiming

381   conditions, across all preparation time conditions, suggests that if participants had sufficient time

382   to aim towards the target, then they also had time to re-aim to one side of the target by a

383   specified angle. Although this process of re-aiming must require some additional processing, our

384   data suggest that such processing is extremely rapid, to the point that we were not able to detect a

385   time-cost for re-aiming under the conditions of our experiment. The data also suggest that people

386   are able to apply a re-aiming strategy to an anticipated target location when there is insufficient

387   time to adequately process visual information related to the actual target. This indicates that the

388   approach of restricting strategic re-aiming through preparation time constraints might be

389   especially problematic for single or dual target paradigms.
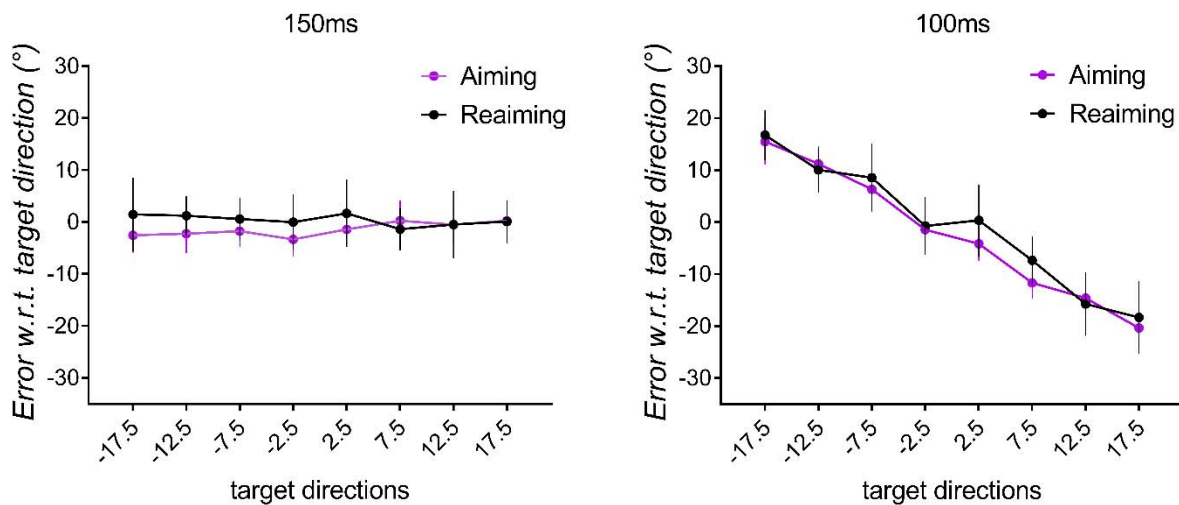
390

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

397   In Experiment 1b, which involved the broad target distribution, participants were less

398   accurate at re-aiming away from the target (20.1°) with 250ms preparation, although re-aiming

399   away from the target was still possible with 200 ms (14.6°) and 150ms (7.7°) preparation. This

400   confirms that voluntary re-aiming is not absolutely prevented by shortening movement

401   preparation time, irrespective of whether potential targets lie within a narrow or large angular

402   range. Self-reports from our participants indicated, however, that re-aiming was extremely

403   effortful at short preparation times, especially when targets were distributed around the circle.

404   Moreover, the accuracy cost of re-aiming was dramatically greater when targets were distributed

405   around the circle. Given this, in Experiment 2, we considered whether participants would choose

406   to re-aim under time pressure in order to improve performance in a visuomotor rotation task. For

407   this experiment, targets were radially arranged throughout the circle (0°, 45°…315°) and

408   movement preparation time was restricted to 250ms. We decided to use 250ms as an arbitrary

409   trade-off between a sufficient time to allow accurate aiming to the presented target, and

410   sufficient time-pressure to make re-aiming effortful.

411

412   **Experiment 2: Suppressing strategic re-aiming with short preparation time constraints**

413   **reduces the rate and extent of error compensation.**

414   Figure 4 shows the group mean, cycle-averaged, movement directions across different

415   phases of the experiment. To evaluate whether the discrepancy between the measures of implicit

416   learning (i.e., implicit learning estimated from subtracting aiming directions from movement

417   directions and implicit learning estimated from the no-feedback trials) is related to the process of

418   reporting explicit aiming angles or the preparation time constraints, we compared this data to 10

419   additional task-naïve participants (5 counterclockwise, 5 clockwise) who completed the

420   visuomotor rotation task with the same 1000ms preparation time constraints via the same timed-

421   response paradigm, but who did not report aiming directions and had no visual landmarks

422   throughout the task (LongNoReport). In the baseline block (i.e., before encountering the

423   perturbation) a counterclockwise bias was evident in the Long preparation time group, as Cycle

424   (Cycle 1…6) x Condition (Long, Short, LongNoReport) x Rotation Direction (clockwise,

425   counterclockwise) ANOVA revealed a significant main effect of Condition, $F(2,30) = 4.267$, p =

426   0.023, partial η-squared = 0.221. To estimate the bias, we averaged mean movement directions

427   from baseline cycles 2-6 (baseline cycle 1 was not included as participants were still

428   familiarising themselves with the vBOT at this stage). To eliminate the influence of this bias on

429   the subsequent test phases, we subtracted the bias from mean movement directions from each

430   subsequent cycle (i.e., the first cycle of the adaptation block to the last washout cycle). The

431   adaptation phase was arbitrarily separated into Early (Cycle 1-30) and Late blocks (Cycle 31-60).

432   ANOVAs were run on each block for all three conditions (LongReport, Short, LongNoReport),

433   according to a mixed within-between effects model (Cycle x Rotation Direction x Condition

434   [LongReport, Short, LongNoReport]). In the Early phase, there was a significant main effect of

435   Condition, $F(2,30) = 6.25$, p = 0.005, partial η-squared = 0.294, as well as a significant Cycles x

436   Condition interaction, $F(24.6,370.2) = 1.59$, p = 0.037, partial η-squared = 0.09, as less error

437   compensation was evident with Short (-17.3+/-1.3°) compared to LongReport, (-22.4+/-1.3°,

438   p=.033) and compared to LongNoReport (-24.4+/-1.8°, p=.009). Error compensation in this early

439   phase did not differ reliably between LongReport and LongNoReport (p=.75). Similarly, for the

440   Late phase, there was a significant main effect of Condition, $F(2,30) = 4.77$, p = 0.016, partial η-

441   squared = 0.241; as less error compensation was evident with short preparation time (-23.1+/-

442 1.1°) compared to LongNoReport (-28.7+/-1°, p = .007) and compared to LongReport (-26.7+/-

443 1.1°, p =.036). Error compensation was also more complete for clockwise than counterclockwise

444 rotations, as evident in significant main effect of Rotation across all phases: Early: F(1,30) =

445 21.643, p < 0.001, partial η-squared = 0.419, Late: F(1,30) = 10.96, p = 0.002, partial η-squared

446 = 0.268]. There were no other significant interactions.

447 **Preparation time constraint as an assay of implicit learning**

448 　　　　The implicit component of error compensation observed for the Long preparation group

449 was estimated by subtracting the participants' reported aiming direction from their actual

450 movement direction, similar to previous work (Bond and Taylor 2015; Brudner et al. 2016;

451 McDougle et al. 2015; Taylor et al. 2014). This measure of error is hereafter termed

452 "LongImplicit", and was compared to angular errors observed between the target and movement

453 for the short preparation time condition. There were no significant differences between

454 LongImplicit and Short, as shown by Condition (LongImplicit, Short) x Cycle (Cycle 1…30) x

455 Rotation Direction (CW, CCW) ANOVAs run for the early adaptation phase [main effect of

456 Condition, F(1,24) = 1.33, p = 0.26, partial η-squared = 0.05, Cycle x Condition F(12.6,303.9) =

457 1.05, p = 0.4, partial η-squared = 0.04 interaction], as well as the late adaptation phase

458 [Condition, F(1,24) = 1.44, p = 0.2, partial η-squared = 0.06, Cycles x Condition, F(11.9,287.1)

459 = 1.4, p = 0.16, partial η-squared = 0.05]. The main effect of rotation direction was statistically

460 significant for the early adaptation phase, F(1,24) = 26.29, p < 0.001, partial η-squared = 0.52 as

461 well as for the late adaptation phase: F(1,24) = 11.473, p = 0.002, partial η-squared = 0.32. There

462 were no significant interactions. Thus, the extent and rate of implicit learning did not differ

463 reliably between estimates based on subtracting self-reported aiming directions and restriction of

464 preparation time.

465
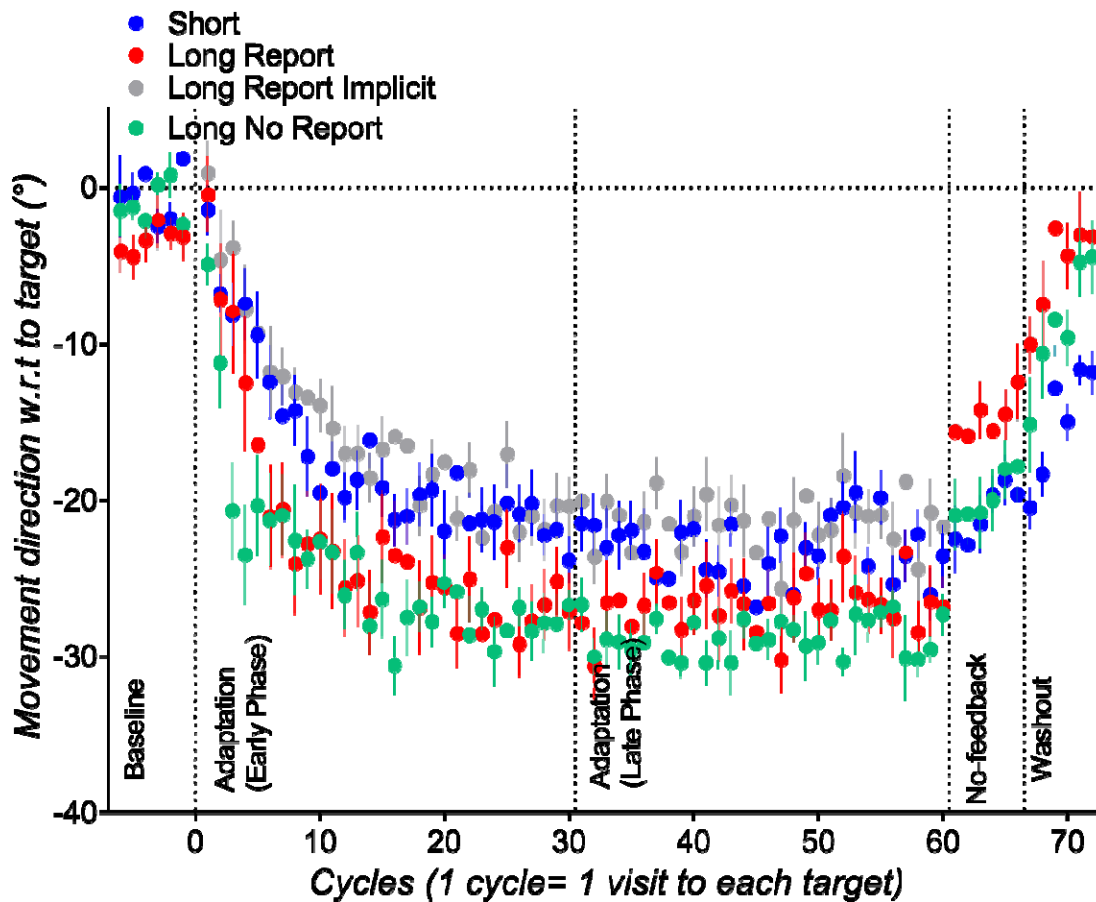
Figure 4. Experiment 2 mean movement direction in every cycle, averaged across each condition. Data from participants who encountered counterclockwise rotations were sign-transformed to allow collapsing with data from participants who encountered clockwise rotations. Error bars are standard errors of the mean. Negative values indicate movements that were opposite from the direction of rotation, positive values indicate movements that were in the same direction as the rotation. Note that Long Report Implicit is not an additional experimental condition, but is derived from subtracting self-reported aiming directions from movement directions in the Long Report condition.

Difference in estimate of implicit learning from subtracting aiming directions and estimate of implicit learning from no-feedback trials

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

481   from this no-feedback block appears substantially lower (i.e., movements were less adapted) than

482   the measure of implicit learning obtained by subtraction of reported aiming direction in the last

483   adaptation cycle. In contrast, for the Short group, errors in the last adaptation cycle were similar

484   to those in the first no-feedback cycle. To compare implicit learning (estimated by subtracting

485   aiming direction or by shortening preparation times) to implicit learning estimated by no-

486   feedback trials, we compared the last adaptation cycle (after subtracting aiming directions for the

487   LongReport group) to the first no-feedback cycle for the LongReport group and the Short group,

488   via a Condition (LongReport, Short) x Rotation Direction (CW, CCW) x Phase (last adaptation

489   cycle, first no-feedback phase cycle) ANOVA. There was a significant Phase x Condition

490   interaction, $F(1, 24) = 4.36$, $p = .047$, partial eta-squared= .15. Follow-up Rotation Direction x

491   Phase (last adaptation cycle, first no-feedback phase cycle) ANOVAs were run separately for the

492   LongReport and the Short condition. For LongReport, implicit learning estimated by subtracting

493   aiming direction in the last adaptation cycle (21.7+/-1.8°) was more than implicit learning

494   estimated in the first no-feedback cycle (15.8+/-1.6°), as shown by a significant main effect of

495   phase $F(1,12) = 6.94$, $p = 0.022$, partial η-squared = 0.37. In contrast, for the short preparation

496   time, the last adaptation cycle (-23.5+/-1.8°) did not differ reliably from the first no-feedback

497   cycle (-22.5+/-1.9°): the main effect of Phase was not significant ($F(1,12) = 0.33$, $p = 0.57$,

498   partial η-squared = 0.02), and did not interact significantly with any other factor. Thus, for the

499   LongReport group, there was a discrepancy between the estimates of implicit learning provided

500   by the reporting method, obtained in the presence of the rotation, and the no-feedback condition,

501   obtained after the final movement performed under the visuomotor rotation. There was no

502   discrepancy between implicit learning estimates for the short preparation time group, even

503   though the final estimate of implicit learning at the end of adaptation was similar to that obtained

504   after subtracting aiming directions for LongReport group, and despite the fact that both groups

505   had explicit knowledge that the rotation was removed.

506   This discrepancy between the estimates of implicit learning from reporting, in the last

507   adaptation cycle, and from no-feedback trials in which participants were instructed that the

508   rotation was absent, was also evident in previous work using the reporting procedure (c.f. Fig 2C,

509   Fig 5C Bond and Taylor 2015). Taylor et al. (2014) attributed the effect to trial-by-trial decay of

510   adaptation within the first no-feedback cycle, because there was no statistically significant

511 difference between the last adaptation trial and the first no-feedback trial (Taylor et al. 2014).

512 Our LongReport group similarly showed no reliable difference in estimated implicit learning

513 from the last adaptation trial to the first no-feedback trial (Trial x Rotation Direction ANOVA on

514 the LongReport group showed a non-significant main effect of Trial $F(1,12)=.30$, $p =.59$, partial

515 eta-squared =.03). However, we hesitate to make inferences from this non-significant effect,

516 because comparing trial-by-trial data in multi-target designs can be problematic: target directions

517 were likely to differ between the last adaptation trial and the first no-feedback trial between-

518 subjects, and directional accuracy differs between targets (Gordon et al. 1994). Moreover,

519 movements were also less adapted on average over all six no-feedback cycles for the LongReport

520 than the Short group, as shown by a significant main effect of Condition, $F(1,24) = 6.91$, $p =$

521 0.01, partial η-squared = 0.22 in a Condition x Rotation Direction x Cycle ANOVA. This

522 suggests that the extent or persistence of implicit learning was less for the long preparation with

523 reporting condition than the short preparation condition.

524   To evaluate whether the discrepancy between measures of implicit learning is related to

525 the reporting procedure (i.e., the process of reporting explicit aiming angles and/or the presence

526 of visual landmarks), we compared error compensation data from the Long Report group to the

527 LongNoReport group. Error compensation during exposure to the rotation did not differ reliably

528 between this LongNoReport group and the LongReport group, as Cycle x Reporting

529 (LongNoReport, LongReport) x Rotation Direction (CW, CCW) ANOVAs run separately for the

530 early adaptation phase (Cycles 1…31) and the late adaptation phase (Cycles 31…60) showed a

531 non-significant main effect of reporting for the early adaptation phase [$F(1,18) = 0.67$, $p = 0.424$,

532 partial η-squared = 0.036], and no significant interactions, as well as for the late adaptation phase,

533 $F(1,18) = 0.843$, $p = 0.371$, partial η-squared = 0.045, no significant interactions]. However, the

534 estimate of implicit learning obtained from no-feedback trials was greater for the LongNoReport

535 group than the LongReport condition: Cycle (Cycle 1-6) x Reporting (LongNoReport,

536 LongReport) x Rotation Direction (CW, CCW) ANOVA on the no-feedback block showed a

537 significant main effect of reporting, $F(1,18) = 7.32$, $p = 0.015$, partial η-squared = 0.289. There

538 were no other significant interactions. The main effect of Rotation Direction was significant

539 $F(1,18) = 16.64$, $p = 0.001$, partial η-squared = 0.48—similar to the adaptation phase,

540 movements were more adapted with the clockwise direction (-21.0+/-1.0°) than the

541   counterclockwise direction (13.4+/-1.0°). Performance in the no-feedback trials did not differ

542   significantly between the LongNoReport and the Short group—a Cycle (Cycle 1-6) x Condition

543   (LongNoReport, Short) x Rotation Direction ANOVA showed a non-significant main effect of

544   condition [$F(1,18) = 0.449$, $p = 0.511$, partial η-squared $= 0.024$], and no significant interactions

545   with condition, all $p>0.5$. The main effect of rotation direction was significant $F(1,18) = 15.98$,

546    $p = 0.001$, partial η-squared $= 0.47$.

Discussion

548   This study aimed to evaluate a previously established method of assaying implicit

549   learning by restricting the time available to prepare movement (Fernandez-Ruiz et al. 2011;

550   Haith et al. 2015). Experiment 1 showed that restricting time available to prepare movements

551   does not prevent people from applying a deliberate strategy to re-aim to one side of a target,

552   particularly when targets are distributed within a narrow angular range. However, Experiment 2

553   showed that restricting movement preparation time effectively reduces strategic re-aiming during

554   adaptation to visuomotor rotation when targets are distributed throughout 360°, as shown by

555   slower and less complete error compensation compared to when movement preparation times

556   were not shortened. Moreover, the errors made by participants when preparation time was

557   shortened were indistinguishable from an assay of implicit learning obtained by subtracting self-

558   reported aiming directions from movement directions (Bond and Taylor 2015; Brudner et al.

559   2016; McDougle et al. 2015; Taylor et al. 2014). Surprisingly, despite this similarity in estimates

560   of implicit learning obtained for the two methods during exposure to the visuomotor rotation,

561   participants who reported aiming directions showed less implicit remapping in the post-

562   perturbation no-feedback trials than those who did not report aiming directions. This suggests

563   that the process of reporting aiming direction reduces the extent or persistence of implicit

564   learning.

Suppressing the expression of explicit learning by restricting preparation time

566   Despite a long history of studies on implicit and explicit processes in sensorimotor

567   adaptation (Jakobson and Goodale 1989; Uhlarik 1973), our understanding of how these

568   processes interact to determine behaviour remains incomplete. Here, we further evaluated the

569   method of assaying implicit learning by restricting movement preparation time (Fernandez-Ruiz

570 et al. 2011; Haith et al. 2015). We showed that when there is intention to re-aim (i.e., when

571 participants were explicitly instructed to re-aim) and potential targets were distributed within a

572 small (35°) range, accurate re-aiming is possible irrespective of the time between target

573 presentation and movement initiation. The accuracy cost of re-aiming in such conditions was

574 modest. Moreover, for the shortest preparation time condition (movement initiation constrained

575 to occur within 123 ms of target presentation), it appears that participants initiated movement

576 prior to complete integration of visual information about the actual target, and were able to

577 achieve task success by aiming or re-aiming to the centre of the (required) target distribution.

578 When target direction (and thus re-aiming direction) was less predictable (targets distributed

579 throughout 0-360°), however, re-aiming accuracy declined with progressively shorter preparation

580 times. Participants were still able to partially re-aim away from the target whenever they had

581 sufficient time to produce directionally tuned movements, but at the expense of dramatically

582 increased movement variability. Hence, compressing preparation time does not introduce an

583 absolute limit upon the capacity for re-aiming, particularly for narrow target distributions.

584   However, during sensorimotor adaptation to a perturbation, restricting preparation time

585 appeared to suppress re-aiming when targets were distributed about 360°, such that error

586 compensation was indistinguishable from the assay of implicit learning obtained from

587 subtracting reported aiming direction from actual movement direction. This suggests that people

588 choose not to apply re-aiming strategies to correct for visuomotor perturbations under time

589 pressure, presumably to avoid the increases in effort and variability associated with re-aiming

590 under such conditions.

591   This interpretation prompts a formal definition of the distinction between implicit and

592 explicit processes. Here, consistent with others (Huberdeau et al. 2015), we define explicit

593 processes as those which can be deliberately engaged and disengaged. By contrast, implicit

594 processes are automatic and difficult to deliberately disengage. We do not distinguish between

595 explicit processes from implicit processes based on awareness of the perturbation or a re-aiming

596 strategy, as classically defined (Reber 1967). Indeed, many of our participants in the short

597 preparation time condition were able to accurately describe the nature of the rotation and could

598 articulate a compensatory strategy, but found it simply too difficult to implement the strategy

599 when preparation times were restrained.

600   Our findings that asymptotic error levels were greater for short than long preparation time

601   conditions differ from those of Haith et al. (2015). In their task, which involved two potential

602   targets, participants were eventually able to reduce errors to a similar degree for the short and

603   long preparation time targets. This discrepancy in findings probably relates to the predictability

604   of the target locations. Targets only appeared in two locations in Haith et al. (2015), with

605   preparation time of ~300 ms. However, our Experiment 1A shows that explicit re-aiming is

606   possible even at 123 ms when the target direction was predictable within a small 35° range.

607   Hence, although the target-switch protocol in Haith et al. (2015) appears to have restricted

608   explicit processes initially, the method may not have been sufficient to suppress re-aiming by the

609   end of the adaptation block.

610   **Discrepancy between different estimates of implicit learning.**

611   In Experiment 2, the extent of implicit learning inferred from aiming reports in the long

612   preparation time condition was similar to the extent of error compensation observed for the short

613   preparation time condition. However, for the long preparation condition, there was a difference

614   between estimates of implicit learning obtained from reporting during exposure to the rotation,

615   and estimates of implicit learning obtained from subsequent movements made without feedback.

616   A discrepancy has been reported previously between measures of implicit learning measured via

617   movement directions after subtracting aiming directions, and via movement directions in

618   subsequent no-feedback trials (c.f. Fig 2C, Fig 5C Bond and Taylor 2015). However, we found

619   that there was no such decay between errors in the last perturbation trials and first no-feedback

620   trials for the short preparation time condition. Furthermore, the overall amount of implicit

621   remapping (indicated by adapted movements in the no-feedback block despite explicit

622   knowledge that the rotation had been removed),was less in the reporting group than in either of

623   two groups that did not report aiming directions (i.e., the LongNoReport group and the Short

624   group), irrespective of movement preparation time. We note that this difference might result

625   from either the act of reporting aiming directions, and/or the presence of visual landmarks,

626   however, as the original reporting procedure often requires the use of landmarks, we did not

627   attempt to dissociate between the two possibilities.

628   We propose two possibilities to account for these observations. One possibility is that

629   implicit learning is more labile (i.e., more sensitive to decay due to a change in task context or

630   the passage of time) when it is acquired in a context in which people report their re-aiming

631   strategies to compensate for errors. The proposal that explicit processes reduce the persistence of

632   implicit remapping is consistent with findings in prism adaptation, where explicit knowledge of

633   the nature of the perturbation reduces the extent of implicit remapping measured in post-

634   perturbation no-feedback trials (Jakobson and Goodale 1989; Uhlarik 1973). One caveat to this

635   interpretation is that, although all three groups experienced the same change in context (i.e., from

636   having feedback of cursor position with visuomotor rotation to having no cursor feedback and

637   explicit knowledge that the rotation had been removed), the LongReport group experienced an

638   additional context change (i.e., from having to report aiming directions to no longer having to

639   report aiming directions). Thus, we cannot rule out the possibility that the extent of context

640   change, rather than sensitivity to change, was the key factor underlying a reduced estimate of

641   implicit learning in the LongReport condition.

642   An alternative possibility that could explain our data is that people may have

643   systematically under-reported their aiming angle (i.e., people re-aimed to a greater extent than

644   they reported). This would result in an underestimation of explicit learning and an

645   overestimation of implicit learning in the error compensation phase. In this case, the no-feedback

646   trials would provide a more accurate measure of implicit learning than the reporting trials, which

647   in turn would imply that the reporting procedure enhanced explicit learning and impaired

648   implicit learning relative to non-reporting conditions. The possibility that the reporting procedure

649   enhanced explicit re-aiming is supported by previous findings of faster error compensation with

650   the reporting procedure than without (Taylor et al. 2014). Such a situation would suggest a

651   competitive push-pull relationship between implicit and explicit processes in sensorimotor

652   adaptation. A push-pull relationship between implicit and explicit processes has been shown for

653   other motor learning tasks. For example, in sequence learning, disrupting explicit awareness of a

654   sequence to be learned, by performing a concurrent verbal declarative task, improved post-task

655   recall of implicitly acquired sequences (Brown and Robertson 2007). Similarly, in force-field

656   adaptation, engaging a declarative verbal memory task resulted in poorer recall of a fragile,

657   possibly explicit memory created by a fast process, and improved recall of a robust, possibly

658   implicit memory created by a slow process (Keisler and Shadmehr 2010).

659   By contrast, implicit adaptation to visuomotor rotation has been argued to be inflexible,

660   such that it develops in parallel with, but independently from, explicit learning (Bond and Taylor

661   2015). Although it is difficult to test whether self-reports of aiming direction are accurate,

662   discrepancies between self-reported aiming directions and actual aiming directions seem possible.

663   Georgopoulos and Massey (1987a) showed that when participants were explicitly instructed to

664   re-aim by a specified angle, their re-aiming was in excess of the instructed angle, particularly

665   with smaller instructed re-aiming angles of less than 35°. Thus, the question of whether implicit

666   and explicit processes operate independently or competitively in visuomotor rotation learning

667   warrants further attention.

668   **Summary**

669   This study evaluated the method of dissociating implicit and explicit learning by

670   manipulating the amount of time available to prepare movements. The method has previously

671   been shown to unmask implicit visuomotor rotation learning on a trial-by-trial basis (Haith et al.

672   2015). We found that although shortening preparation time does not prevent people from

673   voluntarily aiming to one side of a target, it appears sufficient to suppress strategic re-aiming

674   during visuomotor adaptation when targets are distributed about a broad angular range.

675   Estimating implicit learning by subtracting aiming directions from movement directions yielded

676   a discrepancy between the estimate of implicit error compensation obtained during exposure to

677   the perturbation, and the estimate of implicit learning obtained from post-perturbation trials

678   without feedback. It is possible that the reporting procedure inadvertently increased explicit re-

679   aiming and decreased implicit learning, which would suggest a push-pull relationship between

680   explicit and implicit learning. In contrast, shortening movement preparation time did not result in

681   a discrepancy between the estimate of implicit learning obtained from self-report during

682   exposure to the perturbation, and the estimate of implicit learning obtained from trials performed

683   subsequently without visual feedback.

684

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759
760

761 Figure Legends
762 Figure 3. Top panel: A schematic representing the timed-response paradigm. Three tones spaced
763 500 ms apart were presented, and participants were instructed to time the onset of their
764 movements with the onset of the third tone. Targets appeared at different latencies prior to the
765 third tone (Experiment 1a: 1000ms, 250ms, 200ms, 150ms, or 100ms; Experiment 1b: 1000ms,
766 250ms, 200ms, 150ms; Experiment 2: Long preparation time condition: 1000ms, short
767 preparation time condition: 250ms). Note that these latencies were minus a display latency of
768 27.6 ± 1.8 ms. Bottom panel: Experiment 2 landmark layout for the LongReport conditions.
769
770 Figure 4. Movement directions for the narrow target range (-17.5° to 17.5°) and large target
771 range (0° to 360°) plotted relative to target direction at 0°, in the aiming and re-aiming conditions.
772 Data from participants in the counterclockwise re-aiming condition were normalized to the
773 clockwise direction and collapsed with data from participants in the clockwise re-aiming
774 condition. Symbols represent movement directions in individual trials for all participants across
775 the preparation time conditions (1000ms, 250ms, 200ms, 150ms to 100 ms). Note that the hard
776 cut-off times for movement initiation in these conditions were: 1022.4, 272.4, 222.4, 172.4,
777 122.4 ms after target appearance. Red vectors represent individual mean vectors for each
778 participant, and error bars represent the mean and 95% confidence intervals of mean movement
779 direction for each participant. Green vectors represent individual mean vectors that were not
780 significantly directionally tuned according to a Rayleigh's test.
781
782 Figure 3. Movement errors for each target direction from -17.5° to 17.5° with respect to (w.r.t)
783 the required reaching direction (i.e., presented target or re-aiming target depending on condition).
784 Data from participants in the counterclockwise re-aiming condition were normalized to the
785 clockwise direction and collapsed with data from participants in the clockwise re-aiming
786 condition. Separate plots are shown for the 150ms to 100 ms preparation time conditions. Note
787 that the hard cut-off times for movement initiation in these conditions were 172.4 and 122.4 ms
788 after target appearance. Values are group mean errors and error bars represent 95% confidence
789 intervals.
790
791 Figure 4. Experiment 2 mean movement direction in every cycle, averaged across each condition.
792 Data from participants who encountered counterclockwise rotations were sign-transformed to
793 allow collapsing with data from participants who encountered clockwise rotations. Error bars are
794 standard errors of the mean. Negative values indicate movements that were opposite from the
795 direction of rotation, positive values indicate movements that were in the same direction as the
796 rotation. Note that Long Report Implicit is not an additional experimental condition, but is
797 derived from subtracting self-reported aiming directions from movement directions in the Long
798 Report condition.
799
800
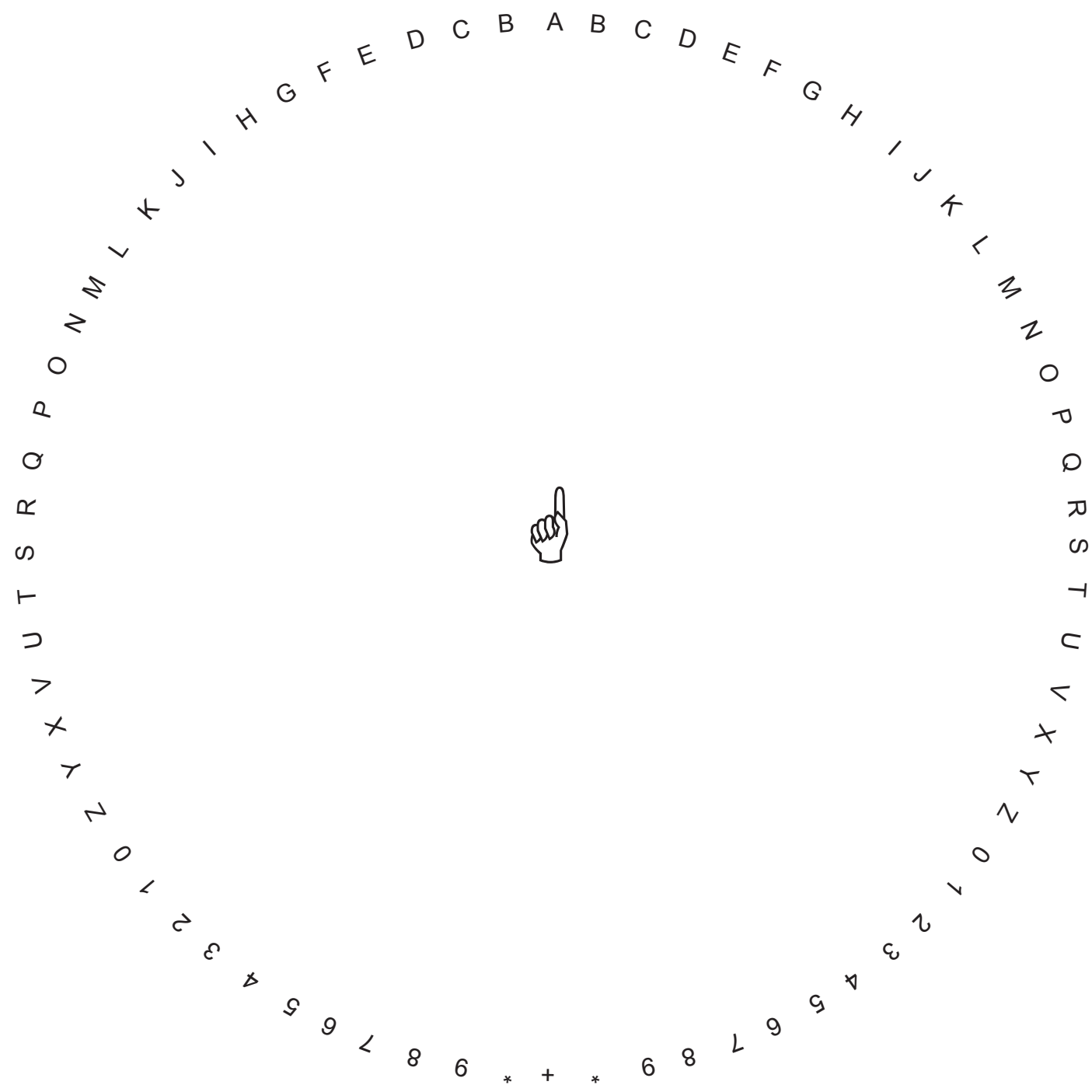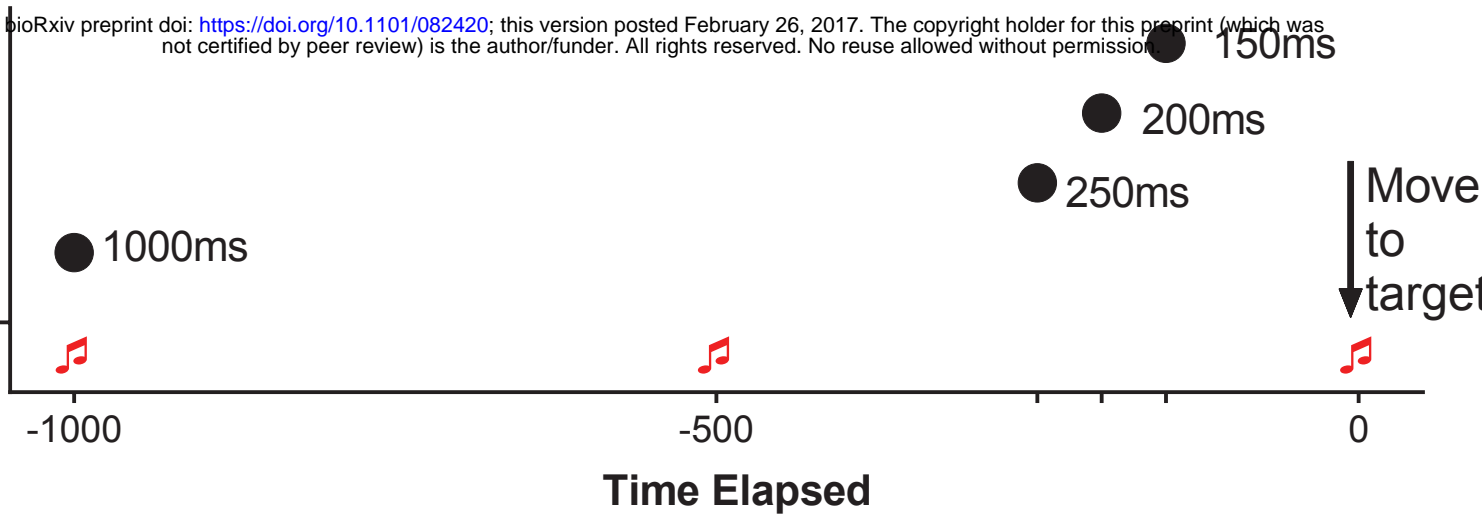
Small Target Range (17.5°,12.5°...17.5°)

Large Target Range (0°, 45°... 315°).

Aiming | Reaiming | Aiming | Reaiming

1000ms
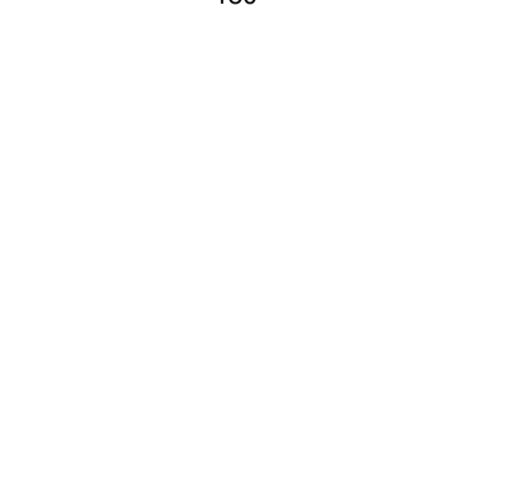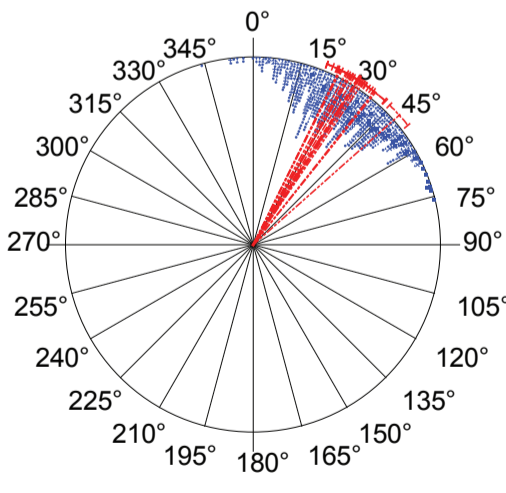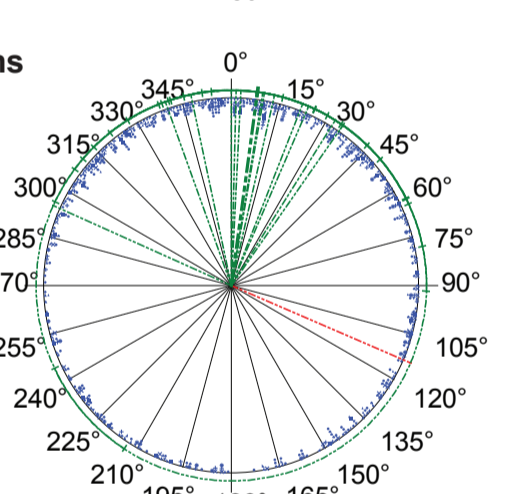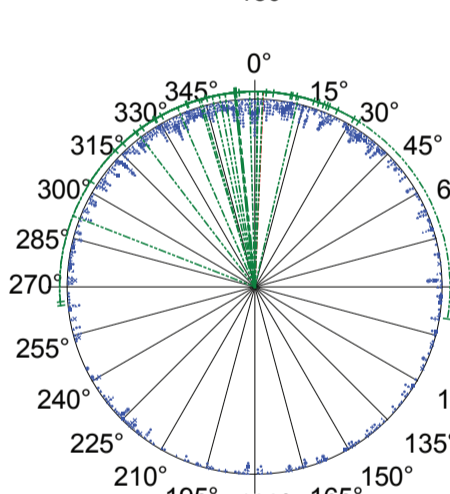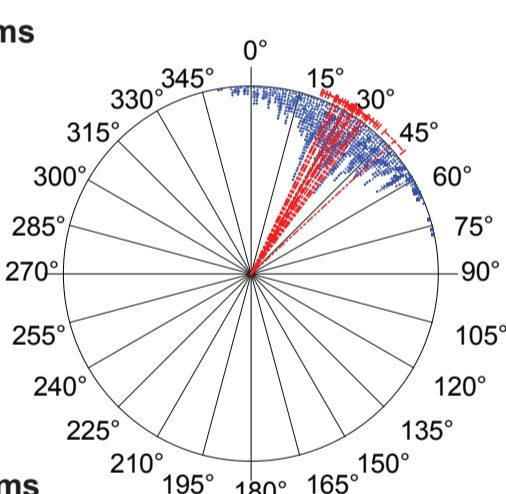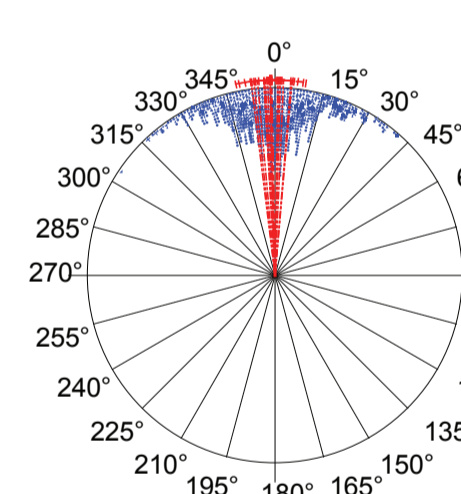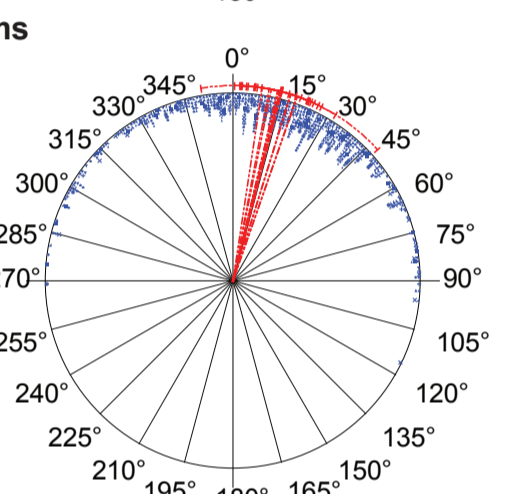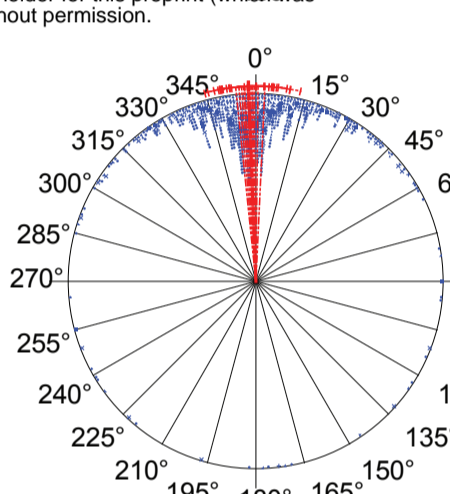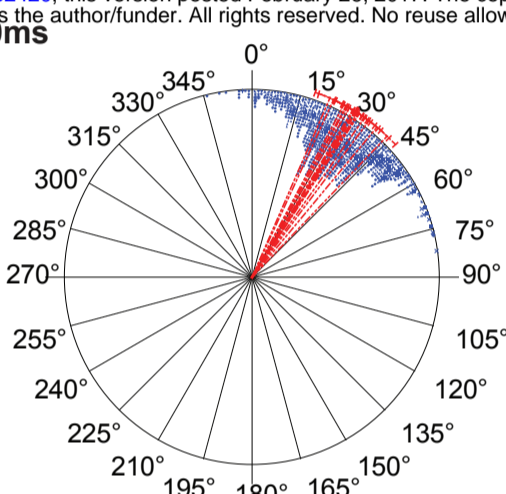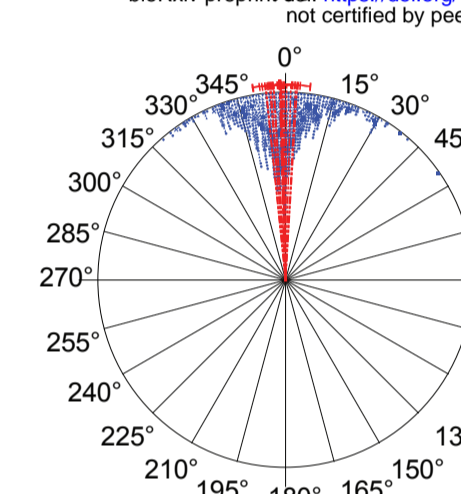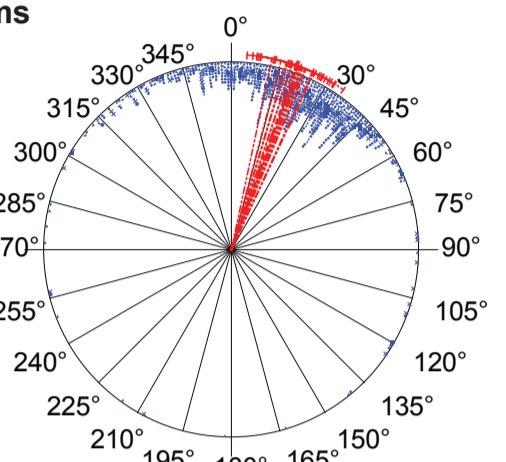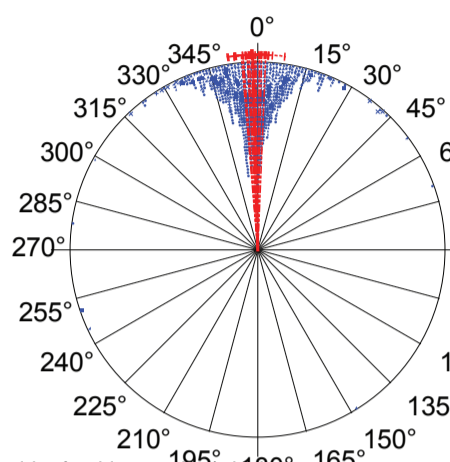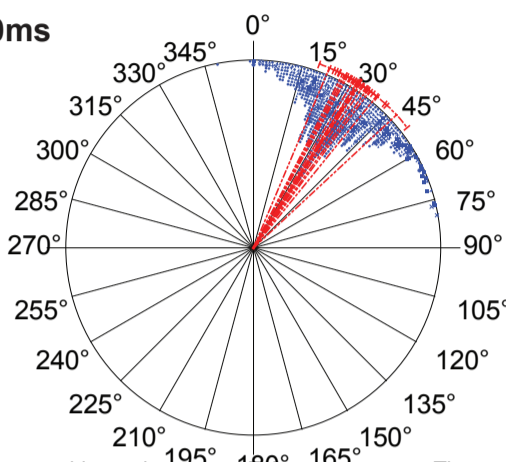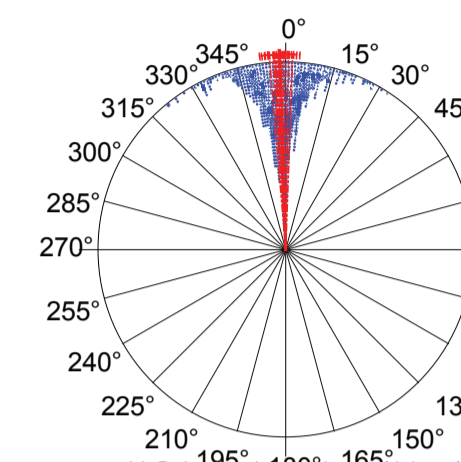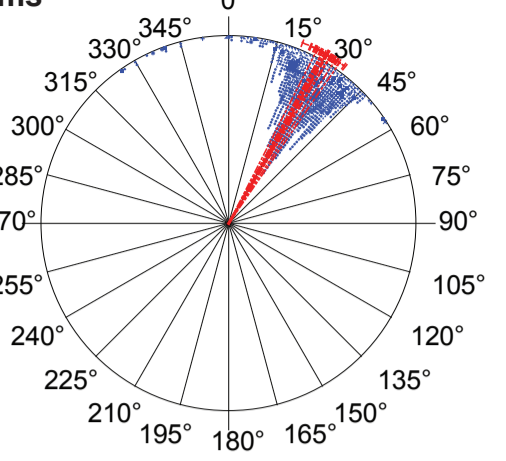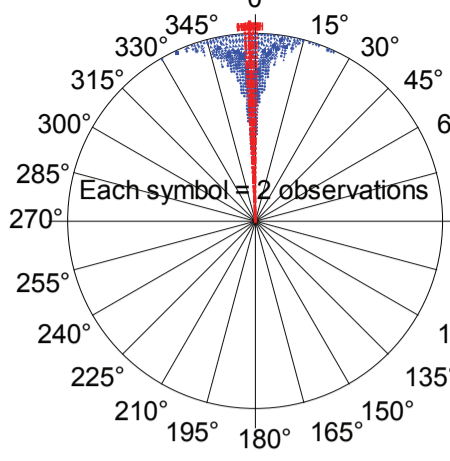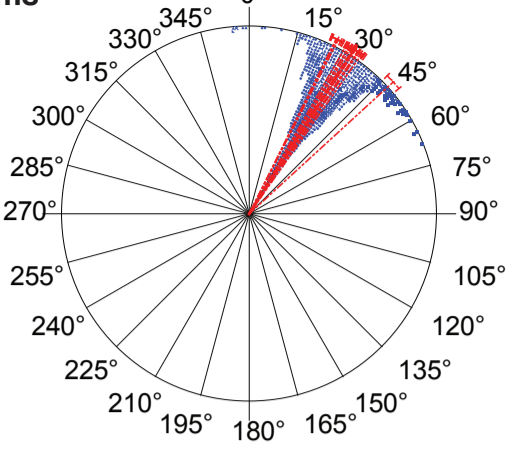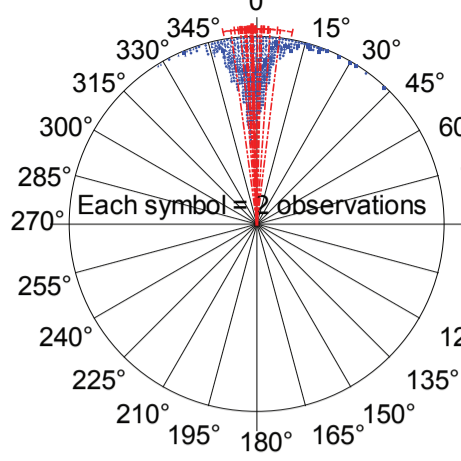
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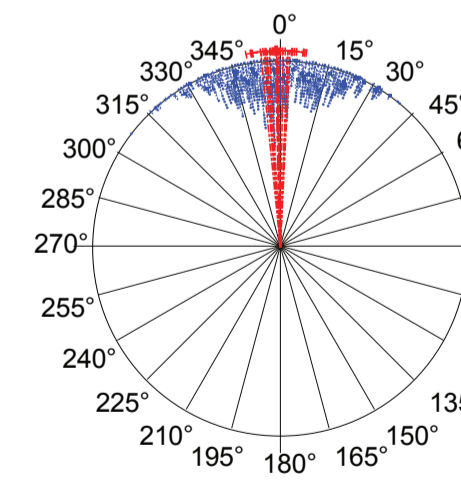
250ms

200ms

150ms

100ms