

1 **Signatures of contextual interference in implicit sensorimotor adaptation**

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15  
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17  
18 **Abstract**

19  
20 Contextual interference refers to the phenomenon whereby a blocked practice schedule results in faster  
21 acquisition but poorer retention of new motor skills compared to a random practice schedule. While  
22 contextual interference has been observed under a broad range of tasks, it remains unclear if this effect  
23 generalizes to the implicit and automatic recalibration of an overlearned motor skill. To address this  
24 question, we compared blocked and random practice schedules on a reaching task in which we used a  
25 feedback perturbation method that isolates implicit adaptation. The degree of implicit adaptation was  
26 quantified as the change in hand angle in the opposite direction of the perturbation, and retention was  
27 quantified as the percent of adaptation remaining after visual feedback was extinguished. In two  
28 experiments, participants tested under a random practice schedule exhibited slower implicit adaptation, but  
29 better retention compared to participants tested under a blocked practice schedule, the signature of  
30 contextual interference. These results indicate that contextual interference is not limited to the acquisition  
31 of new motor skills but also applies to the implicit adaptation of established motor skills.

32  
33 **Introduction**

34  
35 Contextual interference is a widely observed phenomena, in which motor skills are acquired faster but  
36 poorly retained following a blocked practice schedule compared to a randomized practice schedule (1,2).  
37 The ubiquitous nature of contextual interference has come to inform sports instructors and rehabilitation  
38 specialists. For example, baseball players who practice hitting curve balls, fast balls, and changeups one  
39 skill at a time learned faster but retained less than players who practiced hitting the three types of pitches  
40 in a randomized order (3–5). Similarly, patients post-stroke who practiced different compensatory feeding  
41 skills in a blocked manner learned faster but retained less than those who practiced the skills following a  
42 randomized schedule (6).

43  
44 Two related hypotheses have been proposed to account for the effect of contextual interference. According  
45 to the “elaborative-strategy hypothesis” (1), random practice encourages a learner to compare and evaluate  
46 strategies that may be relevant for different motor tasks (e.g., how does preparing for a fastball differ from  
47 preparing for a curve ball), and consequently, endows the learner with better contrastive knowledge than  
48 that afforded by blocked practice. While the cognitive demands of this exploratory process can produce  
49 interference during random practice and, thus, decelerate the rate of learning, randomized practice results  
50 in richer and more elaborate long-term motor memories (7,8). Alternatively, the “forgetting-reconstruction  
51 hypothesis” (9–11) centers on the idea that random practice results in forgetting between repetitions of the

52 distinct strategies required for different actions (e.g., hitting a fastball or curveball), forcing the learner to  
53 continuously reconstruct their explicit strategy with each repetition. While the forgetting process will slow  
54 learning, the act of reconstruction will result in stronger long-term memories. Both hypotheses highlight  
55 the relevance of strategy and effort during randomized practice that consequently establishes more robust  
56 motor memories.

57  
58 To date, it remains unknown if contextual interference generalizes to the implicit, effortless, and automatic  
59 recalibration of an already established motor skill. Consider implicit sensorimotor adaptation of a simple  
60 reaching movement, the process by which the sensorimotor system remains exquisitely calibrated in the  
61 face of subtle fluctuations in the environment (e.g., a heavier bat) and body (e.g., fatigue after a long  
62 baseball game). Given that implicit adaptation places little demands on resource-dependent processes such  
63 as decision making and working memory (12–14), one might expect that adaptation might be immune to  
64 contextual interference. We are aware of two studies that have tested this hypothesis, one involving force  
65 field adaption (15) and the other visuomotor rotation (16), where different perturbations were applied at  
66 different target locations. In both studies, subtle signatures of contextual interference effects were observed.  
67 However, given the design of each study, it is possible that these effects were related to the recall of explicit  
68 strategies (e.g., “aim clockwise from the target on the left”) (17–19), rather than the implicit component of  
69 sensorimotor adaptation.

70  
71 To fill this gap, we used a visuomotor rotation task in which learning is limited to implicit adaptation (Fig  
72 1a) (20,21). On each trial, the participant reached to one of three visual target with the only feedback  
73 provided by a visual cursor. The cursor position was time-locked to the radial distance of the hand.  
74 However, the angular position of the cursor followed an invariant path, always offset from the target by a  
75 fixed angle (“clamped”). Thus, unlike standard visuomotor adaptation tasks, the angular position of the  
76 cursor was not contingent on the position of the hand. Despite being fully informed of the manipulation and  
77 instructed to always reach directly to the target, participants exhibit a gradual, implicit shift in heading  
78 direction in the opposite direction of the cursor. To create conditions for contextual interference, we  
79 manipulated the schedule of the three reach locations. For a Blocked schedule, each target was tested in a  
80 block of trials, with the three locations tested across successive blocks. For a Random schedule, the three  
81 targets were interleaved across trials. We asked if the signatures of contextual interference, namely faster  
82 adaptation and worse retention in a Blocked practice schedule, would be observed for implicit sensorimotor  
83 adaptation.

84  
85 **Results**

86  
87 *Experiment 1*

88 During the perturbation phase, participants reached to one of three movement targets, separated by 120°,  
89 with a different “clamped” visual error size (30°, 45°, 60°) assigned to each target, counterbalanced across  
90 participants. Generalization of implicit adaptation is minimal among targets separated by more than 45°  
91 (20,22,23); as such, reaching movements to each target are independently recalibrated. Participants were  
92 divided into two groups (N = 120, 60/group): For the Random group, the three targets were interleaved  
93 throughout the training phase, and for the Blocked group, the three targets were presented in blocks of 90  
94 trials. For both groups, the three targets were randomly interleaved during the no feedback assessment phase  
95 to ensure that retention is assayed in the same way for both groups

96  
97 The adaptation functions for the Random (orange) and the Blocked (black) groups are shown in Fig 1b.  
98 During the baseline phases, participants moved directly to the target. When the clamped feedback was  
99 introduced, both groups exhibited a gradual shift in heading direction, approaching an asymptote around  
100 20°, a value convergent with that observed in previous studies that employed the clamped feedback method

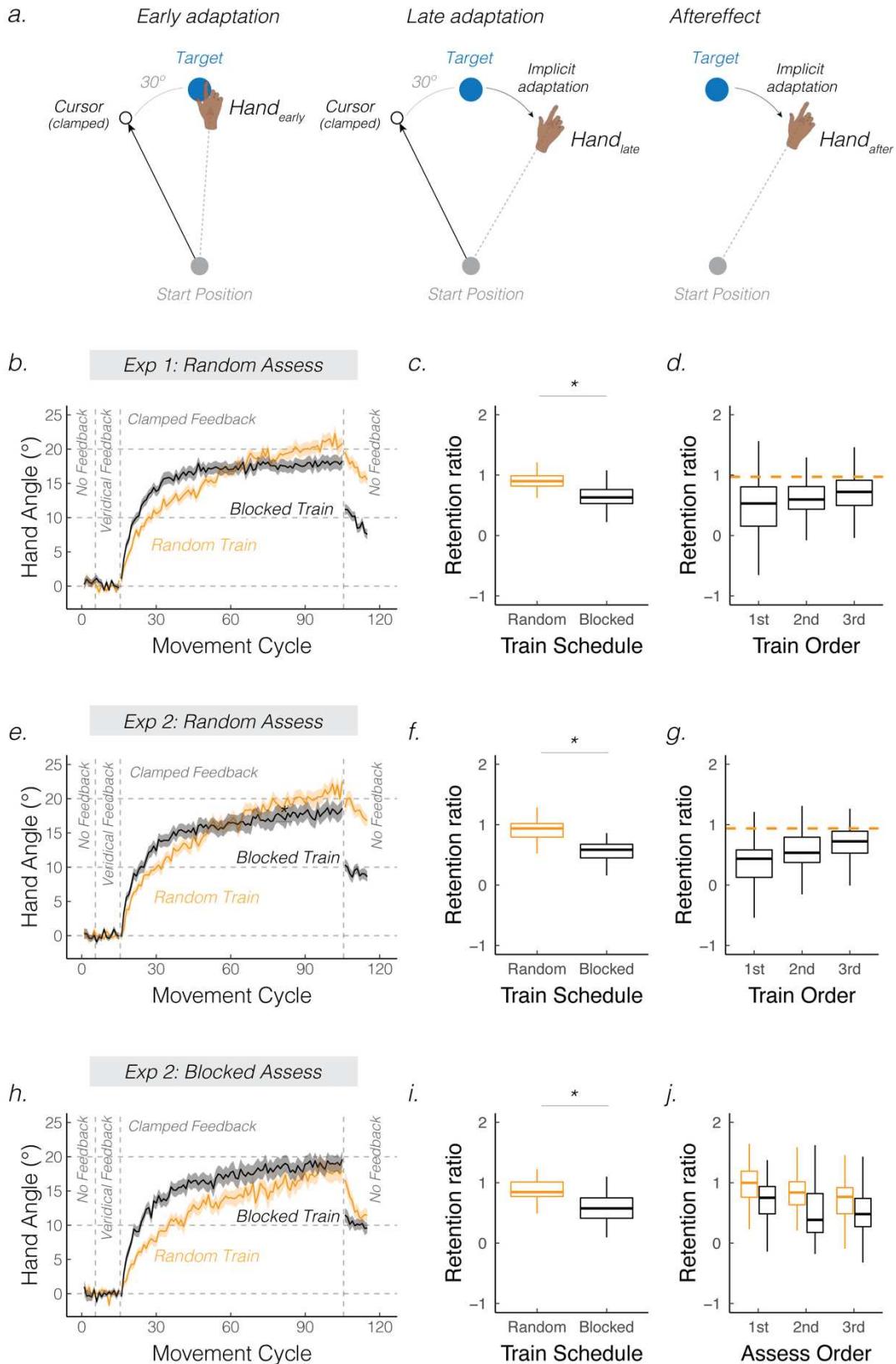
102 (20,24). After visual feedback was extinguished, participants exhibited a pronounced aftereffect, a key  
103 signature of implicit sensorimotor adaptation. Since this aftereffect was of similar magnitude for all clamp  
104 sizes (24), we collapsed over this factor in the following analyses, focusing on the effects of Training  
105 Schedule and Phase.

106 To examine contextual interference, our first analysis compared the two groups at an early timepoint during  
107 adaptation (early: first 10 cycles of the training phase) and late timepoint (late: last 10 cycles of the training  
108 phase). Participants adapted more in late adaptation compared to early adaptation (main effect of Phase:  
109  $F_{(1,118)} = 357.1, p < 0.001, \eta_p^2 = 0.8$ ), confirming that participants adapted in response to clamped  
110 feedback. There was a significant main effect of Training Schedule, with implicit adaptation being on  
111 average greater in the Blocked compared to the Random group ( $F_{(1,207)} = 5.2, p = 0.02, \eta_p^2 = 0.0$ ).  
112 Critically, there was a significant interaction between these factors ( $F_{(1,118)} = 21.0, p < 0.001, \eta_p^2 = 0.2$ ):  
113 Participants in the Random group adapted less during the early phase than those in the Blocked group  
114 ( $t_{207} = 2.3, p = 0.04, D = 0.7$ ). This difference diminished over the course of adaptation such that late  
115 adaptation was slightly larger in the Random group ( $t_{207} = 2.8, p = 0.01, D = 0.4$ ). Turning to retention,  
116 we quantified the magnitude of the aftereffect for each participant by taking the average of their first two  
117 cycles of the no-feedback assessment phase and dividing this number by the participant's late adaptation  
118 score (i.e., retention ratio). Using these normalized scores, the Random group showed greater retention than  
119 the Blocked group (Fig 1c; Wilcoxon-test:  $W = 2983, p < 0.001, D = 1.2$ ). Together, these results reveal  
120 contextual interference holds for implicit adaptation, namely that a random training schedule results in  
121 slower adaptation but greater retention.

122 However, the Random and Blocked groups have an inherent difference in terms of the delay between  
123 training and assessment. For the Random group, the delay between reaches to each target is similar (and  
124 small) for the training and assessment phases; that is, the retention test for each target occurs immediately  
125 after the end of a training phase that included reaches to all three targets. In contrast, for the Blocked group  
126 the delay between training and assessment is substantial for the 1<sup>st</sup> and 2<sup>nd</sup> training targets, and minimal for  
127 the 3<sup>rd</sup> training target. Thus, the weaker retention for the Blocked group compared to the Random group (as  
128 well as compared to previous studies using the clamped feedback task (21,24)) may reflect the effect of  
129 delay rather than the training schedule.

130 To examine the effect of delay, we honed in on the effect of training order in the Blocked group. As shown  
131 in Fig 1d, retention was strongly influenced by delay, being greatest for the 3<sup>rd</sup> training target (minimal  
132 delay between training and retention), and poorest for the 1<sup>st</sup> training target (largest delay). This result was  
133 verified statistically, with the slope of the function relating retention to training order exceeding 0 (robust  
134 lmer:  $t = 2.3, p = 0.02, \beta = 0.10 \pm 0.04$ ). These results are consistent with previous reports showing that  
135 implicit adaptation decays with time between training and assessment (16,25,26).

136 Given the effect of delay, we performed a stronger test of contextual interference by limiting the analysis  
137 to reaches to the third training target location for the Blocked group, comparing retention for this target to  
138 the average retention for all Random group. Strikingly, retention remained significantly larger in the  
139 Random group (Wilcoxon-test:  $W = 2536, p < 0.001$ ). Taken together, we observed marked signatures  
140 of contextual interference in implicit adaptation, even when the delay between training and assessment was  
141 equalized.



147 **Figure 1. Contextual interference is observed in implicit sensorimotor adaptation. (a)** Schematic of the clamped  
148 feedback task. The cursor feedback (black circle) follows a constant trajectory rotated relative to the target (Exp 1:  
149 30°, 45°, and 60°; Exp 2: 45°), independent of the position of the participant's hand. Participants were instructed to  
150 always move directly to the target (blue circle) and ignore the visual clamped feedback. Left, middle, and right panels  
151 display hand and cursor positions during the early, late, and aftereffect phases of adaptation, respectively. **First**  
152 **column (b, e, h):** Mean time courses of hand angle in each experiment. The Blocked Training group is shown in black,  
153 and the Random Training group is shown in orange. Shaded error bars denote SEM. **Second column (c, f, i):** Retention  
154 as a function of training schedule. **Third column (d, g, j):** Retention delineated by the order of targets during the  
155 training phase (**d, g**) or by the order of targets during the no-feedback assessment phase (**j**). Dashed orange line denotes  
156 the mean retention over all three targets for the Random Training group. These targets were interleaved, and therefore,  
157 do not have a specific order. Box plots show min, median, max, and 1<sup>st</sup>/3<sup>rd</sup> IQR. Dots denote individuals. \* p < 0.05.  
158

159 *Experiment 2*

160 In addition to delay, there is a second confound in Experiment 1: The contextual change that occurs in the  
161 test phase. For the Random Training group, this change was limited to the removal of the visual feedback.  
162 For the Blocked Training group, there was also the change from making repeated reaches towards a single  
163 target to reaches towards interleaved targets. The attenuated retention for the Blocked group may reflect, at  
164 least in part, an effect of this contextual change.  
165

166 To address this concern, we adopted a 2 x 2 between-subject design in Experiment 2 (N = 240, 60/group),  
167 crossing Training Schedule (Random, Blocked) with Assessment Schedule (Random, Blocked). For the  
168 Blocked assessment, there were 10 successive trials for each target. Specifically for the Blocked  
169 Training/Blocked Assessment group, the last training target was always assessed first in the aftereffect  
170 block to provide a measure of retention of the most recently trained target; for the Random  
171 Training/Blocked Assessment group, the target order during the aftereffect block was randomly determined.  
172 The clamp size was 45° for all three targets.  
173

174 We first focus on performance during the perturbation phase. All four groups exhibited robust implicit  
175 adaptation (random assessment groups in Fig 1e; blocked assessment groups in Fig 1h). There was a main  
176 effect of Phase, with implicit adaptation being greater late compared to the early ( $F_{1,247} = 261.3, p <$   
177 0.001,  $\eta_p^2 = 0.7$ ). The main effect of Assessment Schedule was not significant ( $F_{1,452} = 0.4, p =$   
178 0.55,  $\eta_p^2 = 0$ ), a result that provides a sanity check given that the assessment manipulation does not come  
179 into play until the no-feedback assessment phase (and this factor did not interact with the other variables  
180 during this phase).  
181

182 The main effect of Training Schedule was not significant, suggesting that Random and Blocked training  
183 groups exhibited a similar degree of implicit adaptation. Importantly, there was a significant interaction  
184 between Training Schedule and Phase ( $F_{1,247} = 12.4, p < 0.001, \eta_p^2 = 0.05$ ): Blocked Training led to  
185 faster early adaptation compared to the Random Training ( $t_{461} = 2.8, p = 0.02, D = 0.7$ ). Similar to  
186 Experiment 1, the difference in early adaptation between groups diminished in late adaptation ( $t_{461} =$   
187 1.3,  $p = 0.20, D = 0.1$ ). However, unlike Experiment 1, we did not observe a significant reversal in  
188 learning. (We return to this issue in the following section, “*Pooling together data from all conditions.*”)  
189

190 Turning to retention, we first pooled the data across the first two cycles of the aftereffect phase for each  
191 target, ignoring training order and assessment order (Fig 1f & 1i). There was a significant effect of Training  
192 Schedule (robust lmer:  $t = 8.6, p < 0.001$ ), with Random Training resulting in greater retention than  
193 Blocked Training. Critically, the benefit of a random training schedule did not depend on whether the  
194 assessment schedule was blocked or random (no effect of Assessment Schedule:  $t = 1.5, p = 0.16$ ; no  
195 significant interaction between Training x Assessment Schedule:  $t = 2.0, p = 0.05$ ).  
196

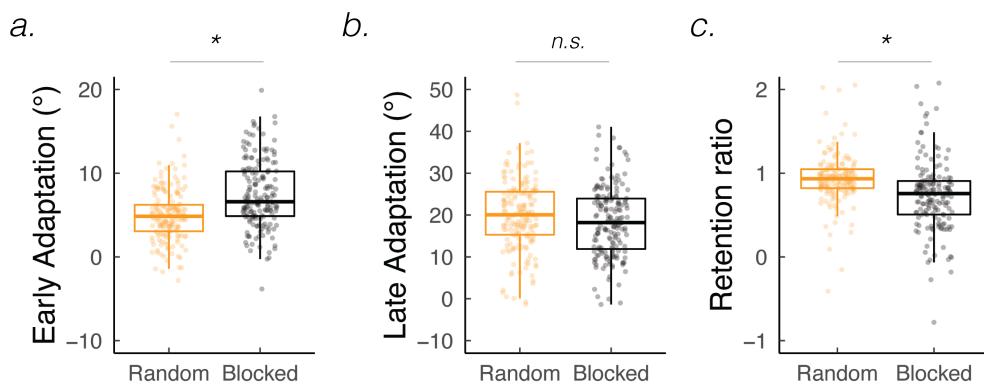
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198 We then evaluated the effect of delay. Replicating the effect observed in Experiment 1, the degree of  
199 retention decreased as the delay between training and assessment increased for the Blocked  
200 Training/Random Assessment group (Fig 1f, slope significantly different than zero:  $t = 3.8, p <$   
201  $0.001, \beta = 0.16 \pm 0.04$ ). The Blocked Assessment groups provide a second test of the effect of delay:  
202 Retention should decay across the no-feedback phase (i.e., greatest retention for the 1<sup>st</sup> assessed target, and  
203 least retention for the 3<sup>rd</sup> assessed target). Indeed, retention decreased incrementally with assessment order  
204 (Fig 1i,  $t = -3.7, p < 0.001, \beta = -0.11 \pm 0.03$ ).

205  
206 Given the effect of delay, the strongest test of contextual interference requires a comparison of conditions  
207 in which the timing of the assessment is roughly equalized following random or blocked training. In the  
208 Random Assessment groups, we compared retention for all three targets in the Random Training group to  
209 retention for reaches only to the last training target in the Blocked Training group. Correspondingly, in the  
210 Blocked Assessment groups, the retention comparison between the two training groups was limited to the  
211 first target assessed. Strikingly, retention was greater following random training in both scenarios  
212 (Wilcoxon test: Blocked assess,  $W = 2607, p < 0.001$ ; Random assess,  $W = 2510, p < 0.001$ ). These  
213 results highlight a robust contextual interference effect in implicit adaptation, one that holds across different  
214 assessment schedules.

215  
216 *Pooling together data from all conditions*

217  
218 Taking advantage of the large behavioral dataset obtained across these two on-line experiments ( $N = 360$ ),  
219 we pooled the data to examine the overall effect of contextual interference in implicit motor adaptation. As  
220 shown in Fig 2, compared to blocked training, random training resulted in attenuated early adaptation (Fig  
221 2a:  $t_{340} = 6.6, p < 0.001, D = 0.7$ ). By the end of the perturbation phase, adaptation is numerically greater  
222 from random training, although there is no statistical difference between the two types of training (Fig 2b:  
223  $t_{358} = 1.9, p = 0.06, D = 0.2$ ). Most striking is the greater retention associated with random training: Even  
224 when limiting the analysis to conditions in which adaptation was immediately assessed, random training  
225 resulted in a 17% increase in retention over blocked training (Fig 2c:  $W = 22864, p < 0.001$ ).



227  
228  
229 **Figure 2. Comparing random and blocked training across all experimental conditions:** (a) Early adaptation, (b)  
230 late adaptation, and (c) retention. Box plots show min, median, max, and 1<sup>st</sup>/3<sup>rd</sup> IQR. \*  $p < 0.05$ . Dots denote  
231 individuals ( $N = 360$ ). Outlier individuals greater than 1<sup>st</sup>/3<sup>rd</sup> IQR are not shown.

232  
233 **Discussion**

234  
235 Contextual interference is a widely discussed phenomena in the skill acquisition literature, with random  
236 practice schedules resulting in slower acquisition but better retention than blocked practice schedules. Here,  
237 we asked whether contextual interference will also manifest during the implicit and automatic adaptation

238 of an established motor skill, reaching. To test this, we employed a visuomotor adaptation task in which  
239 performance changes are solely due to the operation of implicit processes (20,21,27–29). In two  
240 experiments, we found that participants who performed interleaved reaches to three different target  
241 locations consistently adapted at a slower rate but exhibited better retention. These effects persisted even  
242 when the schedule of assessment and the timing of assessment were tightly controlled. Taken together,  
243 these results broaden the scope of contextual interference to encompass *both* the acquisition of new motor  
244 skills and the implicit recalibration of a highly learned skill.

245  
246 Our findings do not fit easily into the “forgetting-reconstruction” and “elaborative-strategy” accounts of  
247 contextual interference. These two hypotheses have focused on how random training enhances top-down  
248 control during motor skill acquisition (1,9). As a result, random training imposes greater interference during  
249 learning due to the presence of competing strategies, but at the same time, establishes more robust motor  
250 memories. However, it is highly unlikely that participants in the clamped feedback task use a re-aiming  
251 strategy to offset the visual error (18,30). Not only do the instructions emphasize that they should always  
252 aim directly to the target and ignore the visual cursor, but participants also report that their hand position  
253 remains near the target throughout the perturbation phase (21). As such, the contextual interference effects  
254 elicited in the current studies does not arise from interference occurring during random training between  
255 competing (explicit re-aiming) strategies.

256  
257 A more generic account of contextual interference effects centers on the difference in attentional demands  
258 for blocked and random training conditions (31,32). Specifically, while attention to the task is likely to be  
259 high near the start of the experiment, it is likely to dissipate as the task becomes familiar. By this hypothesis,  
260 the early benefit from blocked practice would come about because the high state of attention allows the  
261 system to rapidly come up with a solution. However, over time, blocked practice is likely to lose its  
262 attentional hold, leading to reduced retention relative to random practice. While this hypothesis can account  
263 for the current results, it is predicated on the assumption that the strength of implicit adaptation is modulated  
264 by attentional state. Although the effect of attention on adaptation has been the subject of many studies, this  
265 work has generally involved perturbations that engage both explicit and implicit learning processes  
266 (19,33,34). Future work using methods that restrict learning to implicit processes would be useful to assess  
267 an attentional account of contextual interference.

268  
269 Another hypothesis of contextual interference in implicit adaptation may be derived from work suggesting  
270 that implicit adaptation entails multiple processes that operate at different time scales (35,36). In a two-rate  
271 version of this model, one process adapts and decays quickly, operating in the seconds range (“labile”  
272 component), whereas a second process adapts and decays slowly, with the effects persistent across days  
273 (“stable” component) (25,37–39). We assume that these processes operate in parallel yet are constrained to  
274 reach a fixed asymptote due to limits in motor or sensory plasticity (38). As such, they trade-off: If implicit  
275 learning is dominated by the labile component, the stable contribution will be reduced. The relative  
276 contribution of labile and stable components will differ for blocked and random schedules. Blocked  
277 training, entailing repeated reaches to a single target, favors the accumulation of adaptation within the fast,  
278 labile process, resulting in fast adaptation but poor retention. In contrast, random training with relatively  
279 long temporal delays between reaches to a given target, favors the slow, stable process with the labile  
280 component decaying between successive reaches to that target. This would result in slower adaptation yet  
281 better retention. Future studies can provide direct tests of this hypothesis, asking how contextual  
282 interference in implicit adaptation is impacted by the inter-trial interval between successive reaches. We  
283 would predict that the retention cost associated with blocked practice would be eliminated by extending the  
284 inter-trial interval.

285  
286

287 **Methods**

288

289 *Ethics Statement*

290

291 All participants provided written informed consent in accordance with policies approved by the UC  
292 Berkeley's Institutional Review Board. Monetary compensation was provided to the participants for their  
293 time.

294

295 *Participants*

296

297 Participants were recruited via two online crowdsourcing platforms, Prolific and Amazon Mechanical Turk.  
298 We restricted our recruitment to participants who lived in the United States, had an approval rating greater  
299 than 95%, and had completed more than 50 web-based experiments. Participants were excluded if they  
300 completed previous web-based reaching experiments sponsored by our lab.

301

302 A total of 360 participants were recruited, each of whom completed one experimental session (~40  
303 minutes). 198 participants identified as male, 146 as female, and 16 as other. Age ranged between 18 – 70  
304 years old (mean  $\pm$  SD:  $32.6 \pm 10.7$ ). There were 195 participants who completed the experiment with a  
305 computer mouse and 65 participants with a trackpad. We did not enforce any restrictions on device usage  
306 since this factor had been shown to not affect reaching behavior and visuomotor adaptation (40).

307

308 *Apparatus*

309

310 Participants completed the experiment by accessing a dynamic webpage created using a customized  
311 platform, OnPoint (40). The task progression was controlled by JavaScript running locally in the  
312 participant's web browser. A typical computer monitor has a sampling rate around 60 Hz, with little  
313 variation across computers (41). The program automatically detected the parameters of the participant's  
314 monitor and used this information to adjust the size and position of the stimuli. For our sample, the average  
315 monitor size was 20-inch with a screen resolution of 1641 pixel width x 940 pixel height. For ease of  
316 exposition, the stimuli parameters reported below are based on this average screen resolution.

317

318 *Reaching Task*

319

320 The participant performed reach-like movements by moving the computer cursor with either the trackpad  
321 or mouse. On each trial, the participant made a center-out planar movement from the center of the  
322 workspace to a visual target. A white annulus (1% of screen height: 0.4 cm in diameter) indicated the center  
323 position and a blue circle (1% of screen height: 0.4 cm in diameter) indicated the target location. The radial  
324 distance of the target from the start location was 8 cm (40% of screen height). The target could appear at  
325 one of three locations on an invisible virtual circle (30°: upper right quadrant; 150°: upper left quadrant;  
326 270°: lower middle).

327

328 At the beginning of each trial, participants moved the cursor to the start location. The cursor was represented  
329 by a white dot on their screen (0.6% of screen height: 0.2 cm in diameter). When moving to the start  
330 location, feedback was only provided when the cursor was within 2 cm of the start location (20% of screen  
331 height). After maintaining the cursor in the start position for 500 ms, the target appeared. Participants were  
332 instructed that when ready to move, they should produce a fast movement, attempting to "slice" through  
333 the target. On feedback trials, the cursor remained visible throughout the duration of the movement and  
334 remained fixed for 50 ms at the radial distance of the target when the movement amplitude reached 8 cm.  
335 If the movement time exceeded 500 ms or if the reaction time exceeded 2000 ms, the message, "too slow"  
336 was displayed in red 20 pt. Times New Roman font at the center of the screen for 750 ms. After each

337 movement, the target (and feedback message when displayed) were blanked and the participant moved back  
338 to the start location to initiate the next trial.

339

#### 340 *Feedback conditions*

341  
342 There were three types of visual feedback during the experiments: No-feedback, veridical feedback, and  
343 clamped visual feedback. During no-feedback trials, the cursor was not visible once the movement was  
344 initiated (i.e., when the cursor exceeded 1 cm). During veridical feedback trials, the cursor accurately  
345 reflected the participant's hand position, given the standard horizontal-to-vertical translation associated  
346 with manipulating the mouse on a laptop computer. During clamped visual feedback trials, the radial  
347 position of the cursor was aligned with the hand, but the angular position was rotated by a constant angular  
348 offset from the target (Fig 1a).

349

#### 350 *Experiment 1*

351  
352 120 participants were recruited via Amazon Mechanical Turk for Experiment 1. The experiment consisted  
353 of 345 trials, divided into four phases (Table S1): A baseline no-feedback phase (15 trials, 5 reaches/target),  
354 a baseline veridical feedback phase (30 trials, 10/target), a clamped feedback training phase (270 trials,  
355 90/target), a no-feedback assessment phase (30 trials, 10/target).

356  
357 Prior to the baseline and assessment phases, an instruction screen was presented informing the participant  
358 to reach directly to the target. Prior to the clamped feedback training phase, an instruction screen informed  
359 the participant that the cursor would no longer be under their control. The instructions stated that the  
360 participant should ignore the visual feedback and reach directly to the target. Six demonstration trials were  
361 included to familiarize the participant with the visual clamped feedback. On these trials, the target appeared  
362 at 0° (right side of the screen), with clamped feedback provided at a 180° offset from the target. The  
363 instructions about the nature of the clamped feedback were repeated before each demonstration trial.

364  
365 There were two groups of participants (60/group), a Blocked Train/Random Assess group and a Random  
366 Train/Random Assess group. Baseline and no-feedback assessment phases were identical for both groups,  
367 with the target order pseudorandomized such that each target appeared once every three trials. The key  
368 manipulation centered on the structure of the training phase. For the Random Train/Random Assess group,  
369 the target location was randomized within cycles of three trials (one/target location). For the Blocked  
370 Train/Blocked Assess group, the targets were presented in a blocked fashion: 90 trials for one target, then  
371 90 for the second target, and then 90 for the third target. The order of the targets was counterbalanced across  
372 participants in the Blocked Train/Blocked Assess group.

373  
374 Each target was paired with a single clamp size (30°, 45°, 60°) and the clamp direction (clockwise or  
375 counterclockwise) was the same for all three targets. Clamp size, clamp direction, and target location  
376 pairings were fully counterbalanced across participants. Note that since contextual interference effects were  
377 largely similar across clamp sizes (Fig S1), we collapse across clamp size in the main analyses to focus on  
378 the effect of training schedule.

379

#### 380 *Experiment 2*

381  
382 240 participants were recruited via Prolific for Experiment 2. Experiment 2 had an identical schedule as in  
383 Experiment 1 (345 total trials): A baseline no-feedback phase (15 trials, 5/target), a baseline veridical  
384 feedback phase (30 trials, 10/target), a clamped feedback training phase (270 trials, 90/target), a no-  
385 feedback assessment phase (30 trials, 10/target). Given the results of Experiment 1, we opted to use a single  
386 clamp size (45°) for each target location. The direction of the clamp (clockwise or counterclockwise) was  
387 counterbalanced across participants.

388

389 We used a 2 x 2 between-participant design in Experiment 2, crossing training schedule (Blocked vs  
390 Random) with assessment schedule (Blocked vs Random), yielding four groups (60/group). Random  
391 assessment indicates that the three targets were interleaved during the no-feedback assessment phase (as in  
392 Experiment 1). Blocked assessment indicates that the three targets were provided in a serial manner. In the  
393 Blocked Train/Blocked Assess group, the last training target was always assessed first so that we could  
394 evaluate retention of the most recently trained target. In the Random Train/Blocked Assess group, there  
395 were no constraints on which target was assessed first since all three targets were learned simultaneously.  
396 The order of the three targets during the assessment phase for this group was counterbalanced.

397

### 398 *Data Analysis*

399

400 The primary dependent variable was hand angle, defined as the angle of the hand relative to the target when  
401 the amplitude of the movement reached the target radius (8 cm). Positive hand angle values correspond to  
402 the direction opposite the rotated feedback (i.e., we flipped all hand angle values at targets where a  
403 counterclockwise rotation was provided). The data were averaged across cycles (three successive reaches),  
404 and baseline subtracted to aid visualization. Baseline was defined as mean hand angle over the last 5  
405 movement cycles of the baseline phase with veridical feedback.

406

407 Outliers were defined as trials in which the hand angle deviated by more than three standard deviations  
408 from a moving 5-trial window, or if the hand angle on a single trial was greater than 90° from the target.  
409 These trials were discarded since behavior on these trials likely reflects attentional lapses (average percent  
410 of trials removed: Experiment 1: 1.1 ± 0.7%; Experiment 2: 1.4 ± 1.1%).

411

412 The degree of implicit adaptation was quantified as the change in hand angle in the opposite direction of  
413 the rotation. We calculated hand angle during early adaptation, late adaption, and the aftereffect phase.  
414 Early adaptation was defined as the mean hand angle over the first 10 movement cycles during the  
415 perturbation phase. Late adaptation was defined as the mean hand angle over the last 10 movement cycles  
416 during the perturbation phase. Aftereffect was operationalized as the mean hand angle over the first two  
417 movement cycles of the no-feedback assessment phase. Retention was quantified as the percent of  
418 adaptation remaining after visual feedback was extinguished, that is the ratio between the aftereffect and  
419 late adaptation scores (i.e., retention ratio = aftereffect divided by late adaptation).

420

421 The hand angle data were evaluated using a linear mixed effects model (R function: lmer). Post-hoc  
422 pairwise statistical tests were performed using t-tests (R function emmeans). P-values were adjusted for  
423 multiple comparisons using the Tukey method. Standard effect size measures are provided ( $D$  for between-  
424 participant comparisons;  $\eta_p^2$  for between-subjects ANOVA) (42). When assumptions of normality were  
425 violated, we used the robust linear mixed effects model (R function: rLmer) and the Wilcoxon rank test (R  
426 function: wilcox.test), statistical methods shown to be robust to distributional assumptions (43).

427

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432

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434

435 **Data availability statement:** Data and code will be available upon publication at  
436 <https://github.com/xiaotsay2015>.

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