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Rapid motor inhibition as a mechanism to prevent outdated movements.

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24 **Rapid motor inhibition as a mechanism to prevent outdated movements.**

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30

31 **Abstract**

32 Sudden environmental changes can render planned hand movements suboptimal or even
33 counterproductive. To prevent the execution of outdated motor plans, the motor system may
34 transiently inhibit actions following salient changes, allowing time to evaluate alternatives.
35 While such a mechanism is well-established for eye movements, its applicability to hand
36 movements remains unclear. Here, we present findings from three online behavioral
37 experiments and two lab-based replications designed to probe key features of this mechanism
38 in manual responses: reflexive inhibition, temporal precedence, complete movement updating,
39 and sensitivity to saliency. Participants of either sex performed rapid sequential tapping
40 movements toward onscreen targets. At an unpredictable time, either a relevant change (a
41 target displacement) or an irrelevant change (a brief luminance flash) occurred. We measured
42 movement initiation rates following these changes and compared them to a no-change
43 baseline. A significant transient inhibition of movement initiation followed both relevant and
44 irrelevant changes. This inhibition preceded observable updates to the movement plan. At the
45 time of inhibition release, the update to a movement plan was complete. Across experiments,
46 we observed stronger inhibitory effects for more salient changes. The lab-based replication
47 confirmed that the latency of this inhibitory response aligns with visuomotor reaction times.
48 These results support the existence of a general-purpose, rapid inhibitory mechanism in hand
49 movements analogous to inhibition in the oculomotor system. We propose that such inhibition
50 provides a reflexive, domain-general safeguard against obsolete actions following unexpected
51 changes.

52

53 **Significance Statement**

54 As we act within dynamic environments, sudden changes can invalidate our planned
55 movements. In such cases, rather than relying on continuous sensorimotor integration, the

56 brain may employ a different mechanism: the rapid inhibition of potentially outdated actions.
57 Our studies show that the human motor system exhibits abrupt, non-selective inhibition in
58 response to unexpected changes. This response occurs before the selection of a new action,
59 suggesting a central, preemptive control process. These findings highlight an automatic,
60 stimulus-driven mechanism that interrupts ongoing motor activity. This work advances our
61 understanding of how the brain prioritizes error prevention over movement execution in action
62 planning, with implications for models of sensorimotor control.

63

64 **Introduction**

65 Humans navigate dynamic environments, where actions depend on changing states of the
66 world. Consider an ice hockey goalkeeper: as players and puck shift positions, they must
67 continuously update predictions about where the puck might strike. Experts can anticipate
68 these changes effectively, but novices are often caught off guard (Goettker et al., 2021).
69 Reacting to a novel stimulus requires stimulus recognition (Donders, 1969; Franklin and
70 Wolpert, 2008), and a new motor plan must be formed. This process takes 150 to 200 ms
71 (Wolpert and Landy, 2012; Wong et al., 2015; Gallivan et al., 2018), during which outdated
72 motor plans that were formed before the unexpected change may be executed unless actively
73 interrupted. Executing obsolete actions wastes energy and can lead to unwanted outcomes -
74 like conceding a goal. Thus, swiftly interrupting outdated movements to allow updated
75 responses would be adaptive.

76

77 **Saccadic inhibition: interrupting outdated actions**

78 One candidate mechanism for rapid interruption exists in eye movement control. Humans
79 make about three large eye movements (saccades) per second and frequent smaller shifts
80 during fixation (microsaccades). When a sudden sensory change occurs – visual (Reingold
81 and Stampe, 1999, 2002, 2004), auditory (Rolfs et al., 2005, 2008), or tactile (Ossandón et
82 al., 2015, 2020; Badde et al., 2020) – these eye movements are briefly paused. This effect,
83 known as *saccadic inhibition*, begins ~60 ms after stimulus onset, peaks at ~90 ms, and
84 resolves by ~130 ms, followed by a rebound in movement rate. Saccadic inhibition has been
85 modeled as a pause in the evidence accumulation process that allows reevaluation of new
86 information (Salinas and Stanford, 2018). This delay improves behavioral accuracy. For
87 example, in double-step saccade tasks, participants make fewer errors when a distractor
88 triggers saccadic inhibition (Buonocore et al., 2017). Contrary to this early interpretation of the
89 pause as halting the evidence accumulation process, later modelling of neurophysiological

90 activity in the Frontal Eye Fields showed that pausing likely acts at the level of motor output
91 rather than perception or decision-making (Shinn et al., 2022). When a mismatch between
92 expected and actual sensory input is detected, the system suppresses the execution of an
93 imminent eye movement to prepare a more accurate one. This approach offers an elegant
94 solution: the integration of new information can continue while delaying the execution of
95 (potentially obsolete) responses.

96

97 Saccadic Inhibition exhibits four behavioral signatures:

- 98 • **Reflexive inhibition:** Any salient stimulus briefly suppresses saccade rates,
99 regardless of task relevance (Reingold and Stampe, 1999, 2002, 2004).
- 100 • **Temporal precedence:** The interruption occurs before the stimulus is fully processed
101 (Salinas et al., 2019).
- 102 • **Complete movement update:** The final response reflects the new target location, not
103 a blend of old and new (Buonocore et al., 2017).
- 104 • **Saliency dependence:** Only stimuli above a perceptual threshold trigger inhibition
105 (White and Rolfs, 2016); more salient stimuli elicit longer pauses (Bonneh et al., 2015;
106 Scholes et al., 2015).

107

108 **Does this mechanism extend to hand movements?**

109 While eye movements primarily gather information, are brief, and energetically inexpensive,
110 this is not true for other movements. We therefore asked: Does a similar rapid inhibition
111 mechanism exist for skeletal muscles?

112 Initial evidence supports this idea. Cortico-muscular resonance and action-stopping
113 responses can briefly interrupt movements following sudden stimuli (Badry et al., 2009;
114 Wessel and Aron, 2017; Novembre and Iannetti, 2021). The “pause-then-cancel” model
115 describes a rapid inhibitory phase followed by cancellation of action (Diesburg and Wessel,
116 2021), resembling saccadic inhibition. However, no behavioral study has systematically
117 examined parallels between saccadic inhibition and other motor systems.

118 We hypothesized that a mechanism akin to saccadic inhibition exists for hand movements
119 (**Figure 1**). To test this, we developed a task inspired by saccadic inhibition paradigms. We
120 predicted four signatures: reflexive inhibition, temporal precedence, complete movement
121 updating, and saliency dependence. Experiments were first conducted online, with

122 participants completing tasks remotely on smartphones (“remote”). After confirming behavioral
123 signatures, we replicated our findings in a lab-based, within-participant design to validate
124 timing and confirm results in a controlled setting (“lab-based”).

125

126 **Material and Methods**

127 **Experimental design**

128 We designed our task – a sequential manual tapping paradigm – to imitate reading paradigms
129 used to study saccadic inhibition (Reingold and Stampe, 1999, 2004). Participants tapped on
130 a series of six dots (*movement targets*) from left to right with their index finger. The maximum
131 time allowed to tap on all movement targets was 1500 ms, introducing tight temporal
132 constraints (average time per trial in Experiment I (remote): 1102.07 ± 36 ms; Mean \pm SEM).
133 Movement targets were filled circles with one degree of visual angle [dva] diameter that
134 disappeared as soon as they were touched. Each movement target was positioned around
135 one of six origin positions evenly spaced on a horizontal midline. For every trial, possible
136 locations of the movement targets were jittered around the origin position by a random value
137 between -1 and 1 dva along the x- and the y-axis.

138 At a random time point within 700 ms after the first tap, both behaviorally relevant (relevant),
139 or behaviorally irrelevant (irrelevant) changes could occur. Both types of changes were
140 present in 50% of all trials (independently chosen for relevant and irrelevant changes), and
141 absent otherwise. Relevant and irrelevant changes were *absent* or *present* in an
142 independently chosen 50% of all trials. We will refer to trials where both types of changes were
143 absent as *baseline* conditions. Trials in which any change was present will be called
144 *experimental* conditions. In the *relevant-only* condition the relevant change is present and the
145 irrelevant change is absent. In the *irrelevant-only* condition the relevant change is absent and
146 the irrelevant change is present. If both changes were present, the trials will be referred to as
147 *combined* conditions.

148

149 **Behaviorally relevant stimulus**

150 The relevant stimulus was a jump – a change in the position of the movement targets. Each
151 target jumped to a new location around the origin position (**Figure 2A**, lower panel). Targets
152 that had previously been tapped on and disappeared remained invisible. Participants were
153 instructed to tap on the target, even after it jumped, making this change relevant. We accepted
154 responses within a radius of 1.5 dva around the target location, allowing the trial to continue

155 even if participants accidentally tapped at the old location. The relevant change was the same
156 across all experiments.

157

158 **Behaviorally irrelevant stimuli**

159 The irrelevant stimulus was a flash – a 33 ms-long change in luminance in the background
160 (Experiment I remote and lab-based) or the movement target (Experiments II remote and lab-
161 based, and Experiment III, remote). Participants were instructed to ignore the flash and
162 continue tapping on the movement targets. The type of flash differed between experiments
163 and is described below. Because the studies were run in a browser, an exact value for the
164 maximum luminance could not be measured. Instead, we prompted participants to set their
165 screens to full brightness before starting the experiment and used the HEX color white
166 (#FFFFFF) to implement a flash with maximum luminance.

167

168 **Experiment I: flashes in the background – medium contrast**

169 Experiment I (remote and lab-based) showed movement targets with minimal luminance (HEX
170 #000000 - black) against an intermediately bright background (HEX #666666 - grey). The
171 background color changed from intermediate to maximum luminance during the irrelevant
172 flash. Movement targets remained at minimal luminance throughout the flash (**Figure 2B** -
173 Experiment I).

174 **Experiment II: flashes in the targets – high contrast**

175 Experiment II (remote and lab-based) showed the targets and the background at the same
176 luminance levels as Experiment I. The movement targets – rather than the background –
177 changed from minimal to maximal luminance during the flash (**Figure 2B** - Experiment II).
178 Targets that had already been touched and had disappeared remained invisible.

179 **Experiment III: Flashes in the targets – medium contrast**

180 Experiment III (remote) showed movement targets at the intermediate and the background at
181 minimal luminance, thus inverting the luminance scheme of Experiments I and II (**Figure 2B** -
182 Experiment III). The irrelevant stimulus was a flash inside the movement targets, which turned
183 from intermediate to maximal luminance. Note that this experiment combines the spatial
184 location of the irrelevant change used in Experiment II (the movement target) with the contrast
185 of the irrelevant change used in Experiment I (medium).

186

187 **Remote studies, recruitment, and instruction workflow**

188 Participants completed our experiment through the web browser on their smartphones and
189 tablets. We adjusted our typical data collection approach to ensure data quality. This
190 adjustment included splitting the experiment into four sessions, which weren't longer than 40
191 minutes, including instructions and calibration. This change was made to ensure that
192 participants would remain concentrated. All four sessions were identical in structure except for
193 the first session, which included video instructions, quiz-style comprehension tests of the task,
194 and giving informed consent. Participants completed 200 trials (50 per factor combination) per
195 session, for a total of 800 trials. Participants were given breaks during each session. Between
196 sessions, submissions from each participant were checked for compliance with the
197 instructions, and participants were excluded if their tapping behavior indicated that they did
198 not follow the instructions.

199

200 **Implementation**

201 All three experiments were implemented in JavaScript with jsPsych version 6.3.1
202 [<https://www.jspsych.org/6.3/>](Leeuw, 2015; Leeuw et al., 2023). Individual trials were
203 implemented with a custom-written jsPsych plugin, which was called with trial-specific
204 parameters. The plugin used an html canvas element to draw experimental stimuli, providing
205 better timing control than other html elements (Kuroki, 2021).

206 All experiments were hosted on an instance of a JATOS [<https://www.jatos.org/>] server (Lange
207 et al., 2015) owned by Humboldt Universität zu Berlin.

208

209 **Calibration**

210 In remote and lab-based studies alike, the size of the display and viewing distance were
211 calibrated before each session. We modified the virtual chinrest plugin from jsPsych and Li et
212 al. (2020) to touchscreen requirements. In the virtual chinrest procedure, participants first
213 adjust the image of a credit card on their screen to the size of a physical credit card or driver's
214 license. This method translates the screen size in pixels into millimeters or inches more
215 precisely than relying on CSS pixel size. In the original version of the virtual chinrest, the ratio
216 of height and width of the credit card is fixed. In our version, participants were allowed to adjust
217 them independently. We used this ratio to check the participant's scaling accuracy. Credit card
218 sizes were only accepted when the ratio between width and height was within 10% of the true
219 ratio ($1.588 \frac{\text{card width}}{\text{card height}}$).

220 In the next step of the virtual chinrest, we estimated the blind spot position, allowing us to
221 calculate the distance at which the participant was sitting from the screen. Participants were
222 asked to focus with their left eye on a black square located at the outer right border of the
223 screen while either closing or covering their right eye. A red circle moved from right to left,
224 away from the black square. Participants had to tap on the screen when the red circle visually
225 disappeared due to it entering the blind spot, prompting the procedure to start again. After five
226 repetitions, the average position of the circle at perceived disappearance was recorded. This
227 distance was assumed to be ~ 13.5 dva – the average distance from the fovea at which the
228 dot enters the blind spot (Li et al., 2020). Using the screen size in pixels and the translation
229 into dva, the virtual chinrest plugin computes the participant's distance from the screen. We
230 used this information to scale all movement targets to be uniform in dva across participants.

231 The calibrated distance to the screen was restrained to be between 20 and 60 cm, and
232 participants confirmed the calibrated distance. If the calibration failed, participants were shown
233 the instruction video (in remote studies) or were given additional help from the experimenter
234 (in lab-based studies) and could re-take the calibration. The mean viewing distance of
235 participants in the remote sessions was 336 ± 3.96 mm (Mean \pm SEM). This translates to an
236 average diameter of 6 ± 0.07 mm of the target. In lab-based sessions, the average viewing
237 distance was 395 ± 5.49 mm and the target size was 7 ± 0.10 mm.

238

239 **Participants in remote studies**

240 We recruited participants through Prolific [www.prolific.co], using the following filter: Self-
241 reported normal or corrected-to-normal vision, self-reported fluency in English, and an
242 approval rate between 90 – 100% on prolific. In the description of each study, we informed
243 participants that the complete experiment would consist of four sessions. For every session
244 after the first, we invited only participants who had completed the previous session.

245 To create an incentive to complete every session, we used an incremental compensation
246 structure, where participants received a higher compensation relative to the duration of each
247 session as they progressed in the experiment. In all sessions, payment complied with Prolifics
248 minimal pay regulations of 5£/hour in the first study and 6£/hour in the latter two experiments.
249 One person participated in Experiment II (remote) and III (remote).

250 Participants in Experiment I (remote) were on average 27.7 years old (range: 19 - 50). They
251 were based in 11 different OECD countries. 13 participants self-reported their sex as female,
252 7 as male. The average age in Experiment II (remote) was 28.0 years (range: 19 - 43).
253 Participants resided in 8 different OECD countries, and 9 indicated their sex as male, 11 as

254 female. In Experiment III (remote), the average age was 29.7 years (range: 20 - 64), and
255 participants resided in 9 different OECD countries. Self-reported sex was 8 females and 12
256 males.

257

258 **Pros and cons of our online methodology**

259 Conducting these studies online on mobile devices allowed rapid, diverse data collection on
260 complex motor behavior in naturalistic settings. However, it sacrifices precise control over
261 stimulus timing, response measurement, and environmental factors. Touchscreen delays
262 typically add 70–80 ms with up to 10 ms SD (Anwyl-Irvine et al., 2021), confounding absolute
263 latency estimates but preserving relative timing across same-modality measures.
264 Consequently, we cannot specify exact inhibition onsets. Still, our results demonstrate that
265 inhibitory patterns are robust enough to emerge under low experimental control – a promising
266 avenue for high-throughput motor-control research complementary to lab-based validation.

267

268 **Lab-based replication, setup and participants**

269 Experiments I (lab-based) and Experiment II (lab-based) were replicated in a within-participant
270 study. For this study, we invited participants to our lab at Humboldt-Universität zu Berlin. We
271 maintained the online character of previous studies and asked participants to bring their
272 phones. We presented the experiment in their browser, identical to the setup for online
273 participants. In the lab, the experimenter ensured the screen's brightness was set to its full
274 value, and notifications were turned off. Participants would sit in a chair in a room with constant
275 artificial lighting. The smartphone was mounted on a holder, which itself was mounted on the
276 table. This ensured a relatively constant viewing distance from the smartphone (**Figure 3**).

277 A photodiode (grove sensor, Seeed Technology, Shenzhen, China) (**Figure 3A**) was mounted
278 in the top-right corner of the smartphone. This light sensor recorded brightness changes in
279 that part of the screen – the “photodiode rectangle”. This rectangle was set up in the online
280 experiment to signal important time points, such as changes and block onsets. A microphone
281 (grove loudness sensor, Seeed Technology, Shenzhen, China) (**Figure 3B**) was mounted
282 below the smartphone stand. This sensor registered the sound participants made when
283 tapping on the screen. The photodiode and microphone readouts were recorded at 300 Hz
284 with a Raspberry Pi 3+ (Raspberry Pi, Cambridge, England) with a grove head mount (Seeed
285 Technology, Shenzhen, China) running a custom Python script (**Figure 3D**). At the beginning
286 of each session, the device's light and sound recordings were checked to ensure the diode
287 was placed correctly and the taps on the screen were audible. We recorded eye movements

288 with a wearable PupilCore eye tracker (PupilLabs, Berlin, Germany). This data served as a
289 control to show that the relevant and irrelevant changes triggered saccadic inhibition. The data
290 is included in the **Supplementary material (Text S1, Figure S1)**.

291 At the beginning of each session, participants scanned a QR code for the scheduled session,
292 which started the experiment on their phones. Each participant took part in four one-hour
293 sessions. In two sessions, participants performed the task of Experiment I (lab-based), and in
294 two separate sessions, they performed the task of Experiment II (lab-based). The order of the
295 sessions was counterbalanced, with half of the participants starting with Experiment I (lab-
296 based) and the other half starting with Experiment II (lab-based).

297

298 Participants were recruited through a local platform for Humboldt-Universität zu Berlin
299 (Psychologischer Experimental-Server Adlershof - PESA) and through word of mouth.
300 Twenty-one participants were recruited for the study, one of which was excluded due to
301 technical problems. The remaining participants were, on average, 26.3 years old (range: 19 –
302 35). Six participants self-identified as male, 13 as female, and one as agender. Four
303 participants were left-eye dominant, and 1 participant was left-handed. Participants were
304 debriefed by the experimenter about the setup and the data types recorded by the photodiode,
305 the microphone, and the eye tracker. They received the instructions about the task in a video
306 format, like the online participants. Participants were compensated for their participation,
307 either financially or with experimental participation credit.

308

309 **Statistical analysis**

310 Two types of data were collected in our studies. *Browser data* from the online study was
311 collected in remote and lab-based studies. *Sensor data* from the photodiode and microphone
312 was only collected in lab-based studies. Browser data from all three Experiments was
313 analyzed using the same pipeline. Sensor data was pre-processed to the same format as
314 browser data and then analyzed with the same pipeline described below, where applicable.

315

316 **Movement onset rate analysis**

317 We aligned all touch offsets – equivalent to the onset of a movement – to the onset of a change
318 (**Figure 2 C&D**). We computed each participant's movement onset rate per second (from here:
319 movement rate) from the movement onset times, following the procedure described in Rolfs

320 at al. (Rolf s et al., 2008), with a kernel width of $\alpha = 1/50$. This was done separately for
321 each participant and factor combination.

322 We corrected the movement rates for the upper bound of movements that could have occurred
323 by dividing by the number of trials that contributed to each time point (1 ms resolution). The
324 final value of movement rates reflects the number of movement onsets/second in one
325 standardized trial. These movement rates are shown in **Supplementary Figure S2**.

326 As fewer responses were recorded towards the end of each trial (participants tended to slow
327 down over the trial), we expressed movement rates as their difference from the mean baseline
328 rate. The mean baseline rate was computed for each participant as the average movement
329 rate in the null condition across all other participants. Normalized movement rates in
330 experimental conditions were compared against normalized movement rates in the null
331 condition with a cluster-based permutation test (see below).

332

333 **Movement endpoint analysis**

334 We analyzed whether movement endpoints discretely reflected the old (shown before) or the
335 new (shown after the relevant change) movement target or whether there was an average
336 between both. For this analysis, we collapsed across conditions with and without an irrelevant
337 change. In trials without a relevant change, we simulated a movement target after the change
338 by randomly permutating movement targets around the same origin, creating realistic
339 alternative movement targets.

340 We computed the angle between the old and the new movement target. We rotated the touch
341 positions by the inverse of this angle, aligning all touches in a 90-degree angle from the original
342 target. In this alignment, the x-component of the touch position reflects the distance from the
343 original target, and the y-component reflects orthogonal variation. We then normalized the
344 touch position by dividing the x and y components by the distance between the old and the
345 new target.

346 After these transformations, the touch position along the x-axis indicates the proportion of the
347 distance traveled between the old and the new target. Values around 0 are movement
348 endpoints on the old, while values around 1 are movement endpoints on the new target. We
349 created time-by-position frequency heatmaps, where the time axis indicated the time a
350 movement started (25 ms resolution), and the position axis indicated the normalized endpoint
351 (0.1 proportional resolution). We compared the heatmaps from trials with a task-relevant
352 change to heatmaps from trials without a relevant change with a cluster-based permutation
353 test (**Figure 4 D-F**).

354

355 **Cluster-based permutation tests**

356 We used cluster-based permutation tests to compare timelines or heatmaps. In those tests,
357 we computed the difference between each experimental condition and the baseline condition.
358 For each point on a timeline or entry on a heatmap, we computed the t-value of the difference
359 based on the mean and standard error between participants. Clusters above a critical t-value
360 of 2.093 (corresponding to a two-sided student t-test with $p=0.05$) were recorded. Next, we
361 randomly permuted the condition labels 1000 times and identified the largest clusters above
362 the critical t-value arising in these random permutations. We took the 95% percentile of the
363 largest clusters as the cutoff value for significance. The center of each cluster was defined as
364 the average weighted by the t-value along each investigated axis (time for all 2-dimensional
365 comparisons, time and movement endpoint for the 3-dimensional comparisons).

366

367 **Signal detection for photodiode and sound sensors**

368 **Detecting changes in the photodiode data**

369 An increase in the brightness of the photodiode rectangle accompanied all changes (relevant
370 and irrelevant). This increase lasted 33 ms. The photodiode rectangle flashed regardless of
371 whether changes were present or absent. Because the photodiode covered the flashing
372 rectangle, the participants did not see these flashes. We detected time points in the light data
373 stream when the brightness increased above a set threshold. Thresholds were set by hand to
374 account for differences in screen brightness and positioning of the photodiode that changed
375 the recorded signal. From the peaks detected above the threshold, we went backward to find
376 the first time the brightness started increasing. This time point was recorded as the change
377 onset.

378

379 **Detecting movement onsets in the sound data**

380 We applied a bandwidth filter to the recorded noise time series to extract the tap onsets from
381 the sound data. The bandwidth filter was adjusted manually for each recording, with lower
382 bounds between 30 and 100 Hz and upper bounds between 90 and 160 Hz. We detected
383 peaks in the bandwidth-filtered data with a threshold set individually per participant. Going
384 backward and forward in time, we detected the sound onset, indicating the contact between
385 the fingertip and the phone. Note that we are recording the sound of participants tapping on
386 the phone – which is the movement offset. In all analyses above, we used the movement onset

387 to compute tapping rates. To calculate the movement onset from the detected offsets, we
388 subtracted the relative timing between the movement offset and the movement onset recorded
389 in the browser data.

390

391 **Alignment of browser and sensor data**

392 To align the data streams, we relied on a signal that all data streams could record. This signal
393 was the photodiode rectangle changing between one second white, and one second black five
394 times. In the browser data these time points were registered when the command to change
395 the screen was sent. In the lab-based sensor data, the photodiode registered the light
396 changes.

397

398 **Code Accessibility**

399 Code and data are available through the Open Science Framework.

400 Experiment I (remote): <https://osf.io/fs985/>

401 Experiment II (remote): <https://osf.io/43dxc/>

402 Experiment III (remote): <https://osf.io/mkq84/>

403 Experiment I + II (lab-based): <https://osf.io/tzmb/>

404

405 **Results**

406 **Relevant and salient irrelevant changes are followed by movement inhibition.**

407 We first probed our data for the signature of inhibition: a drop in movement rates after salient
408 changes. According to our hypothesis, we expected to see reduced movement rates,
409 regardless of the behavioral relevance of the change. 100 ms before change onset movement
410 rates were on average $4.73 \pm 0.07 \text{ s}^{-1}$ (Mean \pm SEM) in the baseline condition of Experiment I
411 (remote). In the same time window, movement rates in the experimental conditions did not
412 differ from the baseline (combined: $4.68 \pm 0.07 \text{ s}^{-1}$, relevant-only: $4.67 \pm 0.07 \text{ s}^{-1}$, irrelevant-only:
413 $4.65 \pm 0.08 \text{ s}^{-1}$). Movement Rates in Experiment II (remote) (baseline: $4.78 \pm 0.12 \text{ s}^{-1}$, combined:
414 $4.70 \pm 0.11 \text{ s}^{-1}$, relevant-only: $4.76 \pm 0.10 \text{ s}^{-1}$, irrelevant-only: $4.76 \pm 0.10 \text{ s}^{-1}$) and Experiment III
415 (remote) (baseline: $4.86 \pm 0.11 \text{ s}^{-1}$, combined: $4.89 \pm 0.1 \text{ s}^{-1}$, relevant-only: $4.9 \pm 0.11 \text{ s}^{-1}$,
416 irrelevant-only: $4.84 \pm 0.10 \text{ s}^{-1}$) showed similar movement rates (**Supplementary Figure 2**).

417 As predicted, movement rates dropped in response to a stimulus change in all experimental
418 conditions. In the combined condition of Experiment I (remote) (**Figure 4A**), movement rates
419 were reduced to $62\pm 4\%$ (Mean \pm SEM) of the baseline rate in a cluster between 266-646 ms (t-
420 sum: -3239.64). Experiment II (remote) ($62\pm 4\%$, 278-643 ms, t-sum=-2486.07 – **Figure 4B**)
421 and Experiment III (remote) ($66\pm 4\%$, 279-651 ms, t-sum=-2923.45 – **Figure 4C**) showed
422 similar reductions. Those reductions in movement rates were followed by a rebound. In
423 Experiment I (remote), movement rates increased to $113\pm 5\%$ between 732-1066 ms (t-sum:
424 1585.95). Similar increases were observed in Experiment II (remote) ($117\pm 7\%$, 713-946 ms,
425 t-sum=890.54) and Experiment III (remote) ($117\pm 7\%$, 741-1053 ms, t-sum=1425.50).

426 Movement rates in trials with the relevant-only condition resembled movement rates in the
427 combined condition. We observed an initial decrease in movement rates (Experiment I
428 (remote): $65\pm 4\%$, 264-635 ms, t-sum: -3055.55; Experiment II (remote): $65\pm 4\%$, 273-626 ms,
429 t-sum=-2347.43; Experiment III (remote): $70\pm 4\%$, 297-659 ms, t-sum=-2625.41) that was
430 followed by a rebound (Experiment I (remote): $112\pm 4\%$, 759-1066 ms , t-sum: 1294.50;
431 Experiment II (remote): $117\pm 7\%$, 791-944 ms, t-sum=517.07; Experiment III (remote):
432 $121\pm 7\%$, 738-1054 ms, t-sum=1358.89).

433 We were particularly interested in movement rates in the irrelevant-only condition because we
434 predicted that movement rates should be inhibited regardless of the behavioral relevance of
435 the stimulus. We observed significant clusters of lower movement rates after irrelevant stimuli
436 in Experiment I (remote) ($93\pm 3\%$, 319-486 ms, t-sum: -535.27), where the stimulus was a
437 medium-contrast flash in the background. We also observed a reduction in movement rates
438 in Experiment II (remote) ($91\pm 4\%$, 304-479 ms, t-sum=-661.18), where the stimulus was a
439 high-contrast flash inside the movement targets. We did not find a significant reduction in
440 movement rates in Experiment III (remote), where the stimulus was a medium-contrast flash
441 inside the movement targets. A cluster around the time of an expected decrease in movement
442 rates did not cross the threshold for significance ($96\pm 3\%$, 422-446 ms, t-sum=-55.21). In
443 Experiment III (remote), but not in the other experiments, we found rebound-like pattern in the
444 irrelevant-only condition ($107\pm 5\%$, 809-1000 ms, t-sum=455.61).

445

446 ***Movement endpoints reflect two stages: a reduction of movements to the old target,***
447 ***followed by an increase of movements to the new target.***

448 In all three experiments, an analysis of movement endpoints shows an early reduction of
449 movements towards the old target, and a later increase in movements towards the new target.
450 The reduction of responses towards the old target centered at a latency of 600 ms, and a
451 relative position of -20% in Experiment I (remote) (t-sum= -769.84, **Figure 4D**). The other two

452 experiments showed highly comparable patterns (Experiment II (remote): center at 600 ms, -
453 20% relative position, $t\text{-sum}=-792.74$; Experiment III (remote): center at 600 ms latency, -10%
454 relative position, $t\text{-sum}=-563.50$, **Figure 4 E & F**). The increase in movement frequency
455 towards the new target was centered 150 ms after the earlier cluster. In Experiment I (remote),
456 this cluster center was at 750 ms, and 110% relative location ($t\text{-sum}=-1016.55$). Again, the
457 other two experiments replicated the results from Experiment I (remote) (Experiment II
458 (remote): center at 775 ms latency, 100% relative position, $t\text{-sum}=968.92$; Experiment II
459 (remote): center at 775 ms latency, 110% relative position, $t\text{-sum}=777.66$).

460

461 **Results from sensor data**

462 **The inhibition of hand movements starts 200 ms after any change.**

463 We replicated the movement rate analysis using the change onsets detected by a photodiode
464 and the movement offsets detected in the sound recording of a microphone. These two
465 measures are independent of processing times induced by the online device and provide an
466 accurate estimate of the inhibition delay. The inhibition after a combination of the relevant and
467 the irrelevant change lasted from 210-628 ms in Experiment I (lab-based) ($63\pm 6\%$, $t\text{-sum}=-$
468 2721.99) and from 195-543 ms in Experiment II (lab-based) ($54\pm 6\%$, $t\text{-sum}=-2481$). When
469 only the relevant change was displayed, hand movements were inhibited between 210-601
470 ms in Experiment I (lab-based) ($65\pm 6\%$, $t\text{-sum}=-2176.37$) and between 194-542ms in
471 Experiment II (lab-based) ($60\pm 6\%$, $t\text{-sum}=-2404.38$). After the irrelevant change, hand
472 movements were inhibited between 204-374 ms for changes inside the movement target
473 (Experiment II (lab-based), $88\pm 7\%$, $t\text{-sum}=-557.83$). A comparable cluster was not found after
474 irrelevant changes in the background.

475 The start point of corresponding inhibition clusters detected in the browser data of the lab-
476 based study was systematically delayed by up to 100 ms, and comparable in timing to the
477 clusters found in the remote study. In the combined condition, the browser data showed
478 inhibition between 291-592 ms (Experiment I (lab-based); $t\text{-sum} = -2073.19$; +81 ms) and 282-
479 604 ms (Experiment II (lab-based); $t\text{-sum} = -1902.33$, +87 ms). In the relevant-only condition,
480 the inhibition was found between 309-606 ms (Experiment I (lab-based); $t\text{-sum}=-1743.78$, +99
481 ms) and 289-592 (Experiment II (lab-based); $t\text{-sum}=-2004.01$, +94 ms). Finally, after irrelevant
482 changes, movement rates were inhibited between 312-466 ms (Experiment I (lab-based); $t\text{-}$
483 $\text{sum}=-563.68$, 102 ms) and 277-435 (Experiment II (lab-based); $t\text{-sum}=-666.11$, + 83 ms). The
484 movement rates are shown in **Figure 5**.

485

486 **Discussion**

487 Across three remote and two lab-based experiments, we showed that sudden, salient changes
488 elicit a rapid inhibition of hand movements, followed by fully updated movements to the new
489 target— evidence that the outdated motor plan was indeed discarded in favor of a motor plan
490 that was based on new information. In analogy to saccadic inhibition in the oculomotor system,
491 we hypothesized and confirmed three key behavioral signatures: (1) reflexive inhibition of
492 movement rates after both relevant and irrelevant changes, (2) temporal precedence of
493 inhibition before movement updates, (3) complete movement updates reflecting new targets
494 rather than blends. Weak evidence was present for the fourth signature, a saliency-dependent
495 modulation of inhibition magnitude. These findings support a model in which motor output is
496 briefly paused without disrupting perceptual decision stages, thereby facilitating accurate
497 responses after unexpected environmental changes.

498

499 **Reflexive inhibition: movement-rate drops**

500 The most pronounced signature of saccadic inhibition is a drop of movement rates after any
501 type of unexpected sensory signal. Experiments I (remote and lab-based) and II (remote and
502 lab-based) confirmed the same signature in hand movement rates: significantly fewer
503 movements were made even after task-irrelevant brightness changes. This is evidence that
504 the change triggers inhibition before its relevance is evaluated. An alternative explanation is
505 that inhibition following irrelevant stimuli reflects temporal conditioning due to their consistent
506 pairing with relevant changes. This explanation seems unlikely, however, as Experiment III's
507 (remote) medium-contrast flashes did not induce inhibition despite identical temporal
508 structure.

509 The inhibition onset after irrelevant changes coincided temporally with inhibition following
510 relevant changes, indicating that the early drop in movement rates in relevant conditions partly
511 stems from this pre-evaluation pause. Following a relevant change, movement rates fell to
512 about 60% of baseline within 400–550 ms across experiments. In the browser data, these
513 drops started ~300 ms after the change. This timing was surprisingly late. We suspected that
514 the inhibition timing was late due to technical limitations of the remote recording. In a lab-
515 based replication, we explicitly checked this suspicion by creating alternative ways to record
516 changes (through a photodiode) and response offsets (through a microphone). When
517 measuring the onset of the inhibition between these data points, we found that inhibition
518 started 100 ms earlier than previously observed — 200 ms after the change appeared on the
519 screen, fewer movements were detected through the microphone. This timing aligns with the

520 usual time of stop-signal responses (Wessel, 2023) and the planning of novel responses
521 (Biguer et al., 1982; Desmurget et al., 1998).

522 Delays in the movement responses following relevant changes could also be explained by a
523 smooth correction of the hand movement mid-air, resulting in a longer trajectory. To confirm
524 that the movement stops before the trajectory changes, high-resolution motion-tracking
525 studies are required. In our present dataset, the pause in the tapping rate is longer after
526 relevant changes. We argue that the timing of the short pause after irrelevant changes, which
527 coincides with the onset of the long pause after relevant changes, is evidence for a general
528 inhibitory mechanism that precedes any trajectory adjustments. The differences in pause
529 duration observed after relevant and irrelevant changes can be explained through additional
530 processes, such as trajectory adjustments.

531 Another alternative explanation for the drop in movement rates could be that saccadic
532 inhibition indirectly mediates hand movement rates. In a supplementary analysis
533 (**Supplementary Figure S3**), we split trials into those in which saccades followed a relevant
534 or an irrelevant event (suggesting a lack of saccadic inhibition), and those in which no
535 saccades occurred in the same time window. Movement rates in both subsets of trials were
536 strikingly similar, supporting the conclusion that hand movement inhibition is not exclusively a
537 by-product of saccadic inhibition.

538

539 **Inhibition temporally precedes a complete movement update.**

540 We examined the movement endpoints during relevant changes by normalizing the response
541 between old and new target locations. We observed that movement endpoints clustered
542 cleanly around the old, or the new target. There was no evidence of intermediate or “mixed”
543 endpoints. Despite allowing responses within a generous spatial window (1.5 dva),
544 participants fully updated their movements to the new target by the time they completed the
545 action. Comparing the timing of inhibition after irrelevant changes to movement endpoint
546 responses clearly shows that the automatic inhibition aligns with the reduction of responses
547 to the old movement target and temporally precedes the cluster of movements to the new
548 target by around 150 ms. This comparison demonstrates that the inhibitory pause – visible in
549 responses to irrelevant changes – is the signature of dropping outdated movements in favor
550 of those whose planning relied on new information.

551

552 **Saliency dependence**

553 While we did not include an explicit manipulation of saliency, we can post-hoc compare
554 inhibition magnitudes across three brightness-change conditions (**Figure 6**). The largest
555 inhibition followed a full-screen flash from black to white (Experiment I (remote and lab), the
556 next largest followed a maximum-contrast flash inside the target area (Experiment II (remote
557 and lab), and no inhibition occurred for a medium-contrast flash inside the target (Experiment
558 III (remote). These results parallel saccadic-inhibition findings: inhibition strength and duration
559 scale with stimulus saliency (Bonneh et al., 2015; Scholes et al., 2015; White and Rolfs, 2016),
560 not simply spatial coincidence with the movement target (Reingold and Stampe, 2004).

561 Because we did not systematically manipulate contrast and location within the same
562 participants, future work should vary these parameters in a fully crossed design to confirm the
563 threshold dynamics of manual inhibition.

564

565 **Relation to existing motor-inhibition models**

566 Our findings align with rapid inhibitory signatures in skeletal-muscle control, such as
567 cortico-muscular resonance (Novembre et al., 2018), global action-stopping responses (Badry
568 et al., 2009), post-novelty-slowing (Wessel and Aron, 2017), and with the “pause-then-cancel”
569 model of action stopping (Diesburg and Wessel, 2021). In the pause-then-cancel framework,
570 an initial fast pause halts motor output, then a slower pathway cancels or alters the command.
571 We propose that this initial pause is functionally equivalent to saccadic inhibition, serving a
572 generic role for cancelling outdated movements. Unlike traditional stop-signal tasks, where
573 inhibition is task-explicit, our paradigm shows that inhibition can unfold automatically under
574 time pressure to update actions in response to surprising stimuli.

575 A large and convincing body of research shows that movement updates can be fast, appearing
576 just 100 ms after a stimulus onset (Brenner and Smeets, 1997, 2023; Wijdenes et al., 2011),
577 and automatic – without signatures of overt stopping (Prablanc and Martin, 1992; Prablanc et
578 al., 2003). The timing of inhibition in our studies is too slow to interrupt such fast, automatic
579 online corrections, even after correcting for delays in the browser data. Studies of automatic
580 movement updates often work with a limited set of optional targets (Elliott et al., 2017;
581 Laquitaine and Gardner, 2018). In this case, multiple motor plans may be prepared in parallel,
582 enabling rapid switching between them (Haith et al., 2015; Xivry et al., 2017; Enachescu et
583 al., 2021; Meirhaeghe et al., 2023). In our study, we tried to prevent participants from being
584 able to rely on pre-planned, alternative movement plans by randomizing the locations where
585 the new targets could appear in each trial. Other studies that have shown remarkably fast
586 reaction times have used small changes to the visual stimulus (Brenner and Smeets, 2023). In

587 such cases, it is possible that these changes are indistinguishable from perceptual noise and
588 integrated into a perception of a single, moving target, rather than a surprising, non-integrable
589 change.

590 Another notable difference is that many online movement correction studies involve reaching
591 movements covering more distance than the hand movement in our paradigm. Our results
592 could thus be specific to the small-distance movements in our paradigm and not generalize to
593 larger movements.

594 To reconcile frameworks of smooth adjustments and automatic pauses, we suggest a
595 prediction-error-like mechanism. For visual changes, such a mechanism is likely located in the
596 visual cortex (V1). V1 is central in generating the phenomenon of saccadic inhibition (White
597 and Rolfs, 2016; White et al., 2022; Malevich et al., 2024). It also connects to subcortical areas
598 that control hand and other limb movements (Battaglia-Mayer et al., 2016; Cont and
599 Zimmermann, 2021). Hence, V1 could generate a disruption signal, travelling to subcortical
600 areas, blocking the execution of movements if the detected change is surprising enough to
601 generate a prediction error. Regardless of the presence of a prediction error, integration of
602 new visual information into a motor plan would continue. The difference would be that in the
603 absence of a disruption of execution, the integrated answer would be translated into an overt
604 response, whereas in the case of disruption, the integration would remain covert.

605

606 **Conclusion**

607 Our sequential-tapping paradigm reveals four behavioral signatures of rapid hand-movement
608 inhibition – reflexive inhibition, temporal precedence, full movement updating, and saliency
609 dependence – closely mirroring saccadic-inhibition phenomena. These results support a
610 framework in which motor output is briefly paused upon detecting salient changes, preventing
611 execution of outdated plans while leaving perceptual and decision processes uninterrupted.
612 This pause ends as soon as a fully updated motor action is executed. This general
613 motor-inhibition mechanism likely operates across effectors to optimize adaptive behavior in
614 dynamic environments, eliminating the need for upstream interruptions of sensory or cognitive
615 processing. Future work with precise motion tracking and systematic stimulus manipulations
616 will further elucidate the timing, neural pathways, and functional benefits of this ubiquitous
617 inhibitory pause.

618

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627

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629

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741

742

743 **Figure 1. Schematic depiction of the proposed mechanism.** A visual signal (IN) is processed by the perceptual
744 system through several steps, resulting in an action (OUT). Blue boxes indicate neurocognitive processing stages.
745 Grey boxes indicate functional processing steps. Arrows indicate the flow of information. Pink arrows show
746 information flow during the suggested inhibition process. Black arrows show information flow during information
747 evaluation. Note that the inhibition path skips and does not influence the evaluation process (including late
748 perceptual and motor control stages).

749

750

751 **Figure 2. Paradigm (A)** Illustration of the basic task and relevant changes used in all experiments, remote and
752 lab-based. Participants were instructed to tap on the targets (black circles) from left to right. A relevant change
753 appeared in 50% of all trials. In these trials, the movement targets changed their position to the illustrated dashed
754 positions. On each trial, positions were jittered relative to six origin positions (white crosses; not shown in the
755 experiment). **(B)** Illustrations of the irrelevant changes in Experiments 1-3. In Experiment 1, the background

756 changed to white for 33ms. In Experiment II, the targets changed to white. In Experiment III, the background was
757 black while the targets were grey, and the change was a white flash inside the targets. **(C)** Distribution of tap onsets
758 for each target (grey levels) relative to the first target being touched in Experiment I (remote, collapsed across all
759 observers and conditions). The black bar indicates the time frame during which changes occurred. **(D)** Touch onset
760 times in Experiment I (remote) relative to the time of a change.

761

762

763 **Figure 3. Setup of the lab-based replication of Experiments I (lab-based) and II (lab-based).** The smartphone
764 was held inside the smartphone stand. **(A)** Setup without the phone. **(B)** Setup with the phone, with labels for the
765 photodiode (1), the microphone (2), AprilTag markers (3) and the Raspberry Pi (4). **(C)** Close-up of the phone
766 screen, showing how the photodiode is mounted.

767

768

769 **Figure 4. Main results: Movement rates and endpoints.** **(A-C)** Movement rates over time as a function of
770 relevant (solid lines: present; dashed lines: absent) and irrelevant change (colored: present; black: absent). Error
771 bands (shaded areas in panel A-I) indicate the 95%-CI across participants. Horizontal lines at the bottom indicate
772 significant clusters in which movement rate (in a given condition) deviates from the baseline condition. **(D-F)**
773 **Relative movement endpoint frequencies in trials with, compared to trials without, relevant changes.**
774 Heatmaps show the contrast relevant change present – relevant change absent of proportion of answers made
775 towards a normalized location relative to the movement target shown before (blue line) and after (red line) the
776 change. Clusters in which the difference is significant are highlighted with a black outline. Black symbols (+) indicate
777 the center of the cluster. Dashed vertical lines illustrate the time window during which movements were inhibited
778 after irrelevant changes.

779

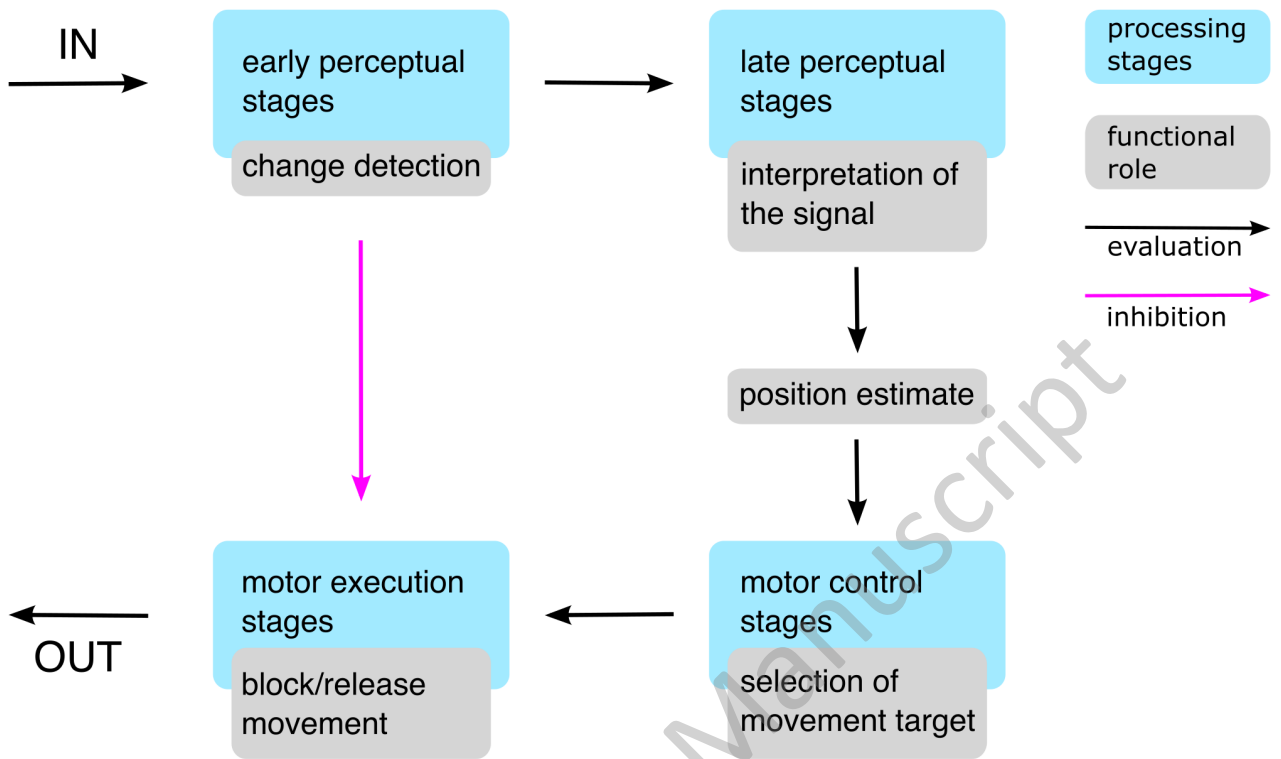
780

781 **Figure 5. Movement Rates calculated from tapping sound and photodiode onset.** Frequency of movement
782 onsets detected in the sound data (y-axis) as a function of the onset of a change detected through the photodiode
783 (y-axis). Panels **(A)** and **(B)** show normalized tapping rates relative to the baseline (dashed, black). Panels **(C)**
784 and **(D)** show the significant clusters detected in the browser data from lab-based experiments to compare the
785 delay visually. Conventions as in Figure 4.

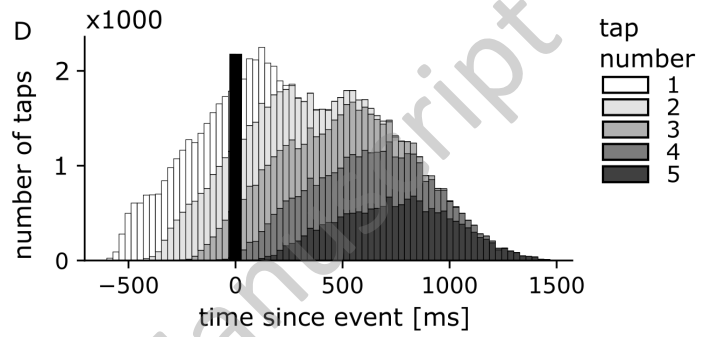
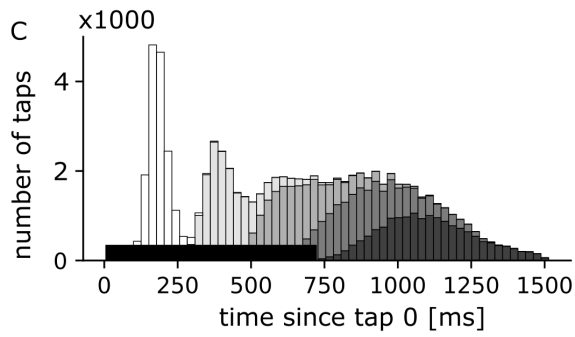
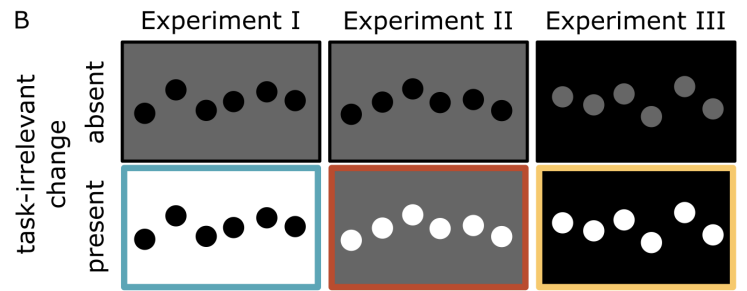
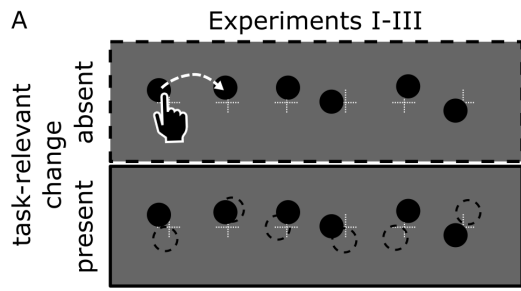
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787

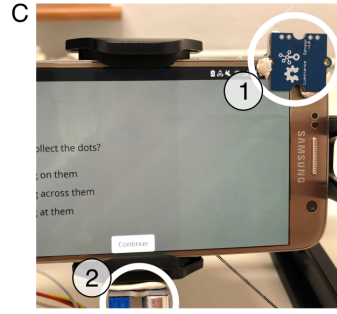
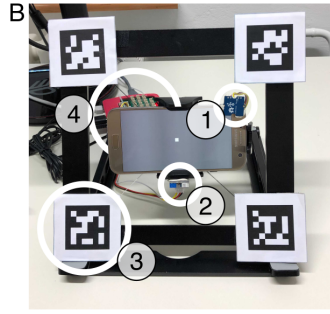
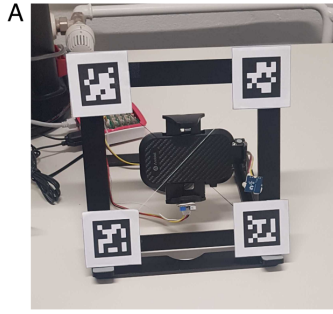
788 **Figure 6. Mean and individual participant's movement rate (normalized) at maximum inhibition after an**
789 **irrelevant change.** Maximum inhibition (the lowest recorded movement rate) occurred at 417 ms (Experiment I),
790 418 ms (Experiment II), and 434 ms (Experiment III).



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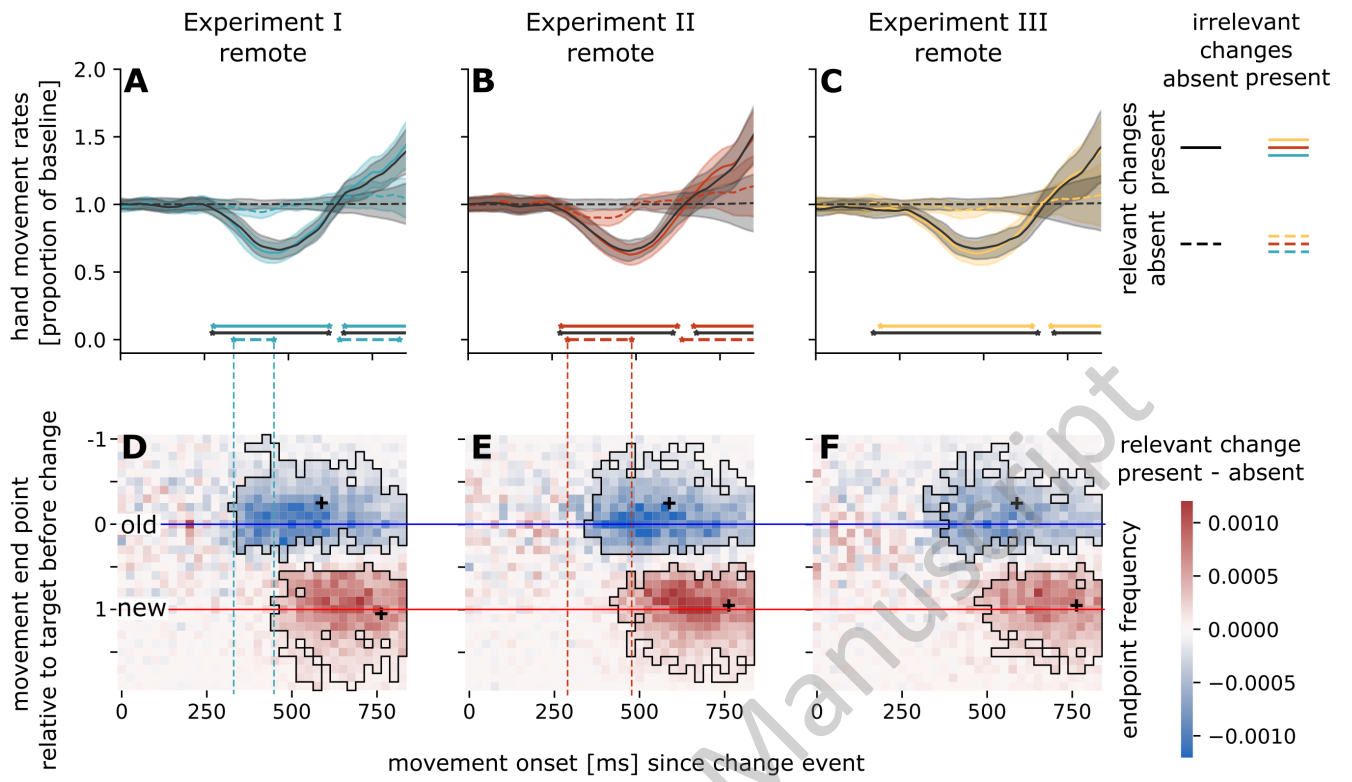


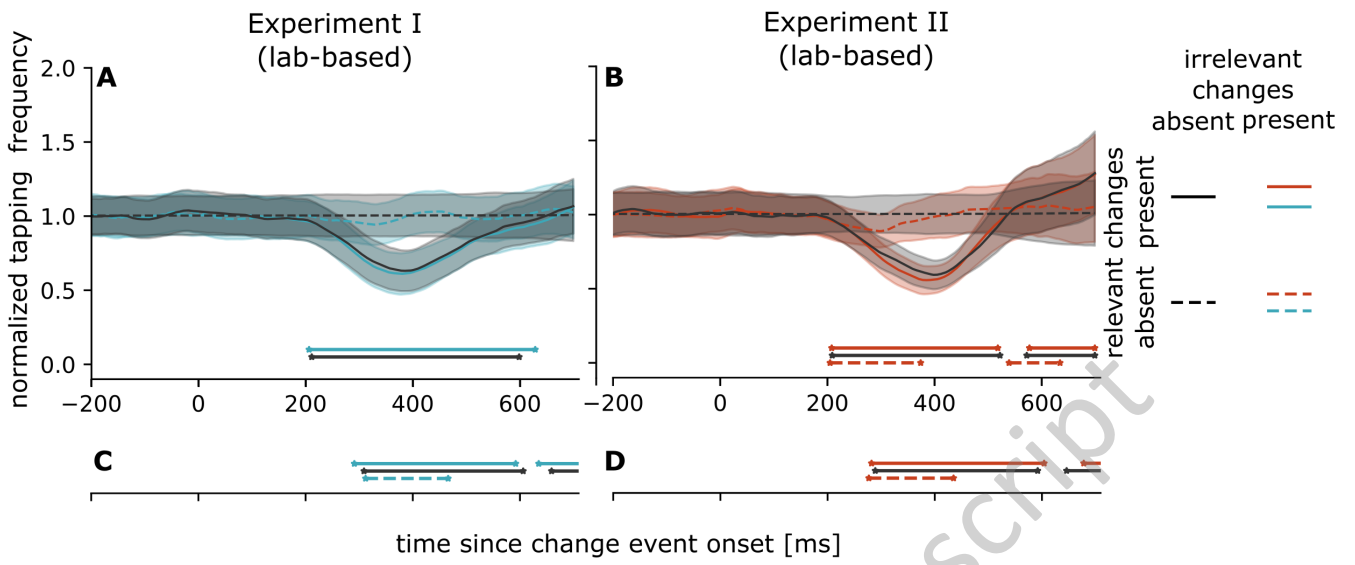
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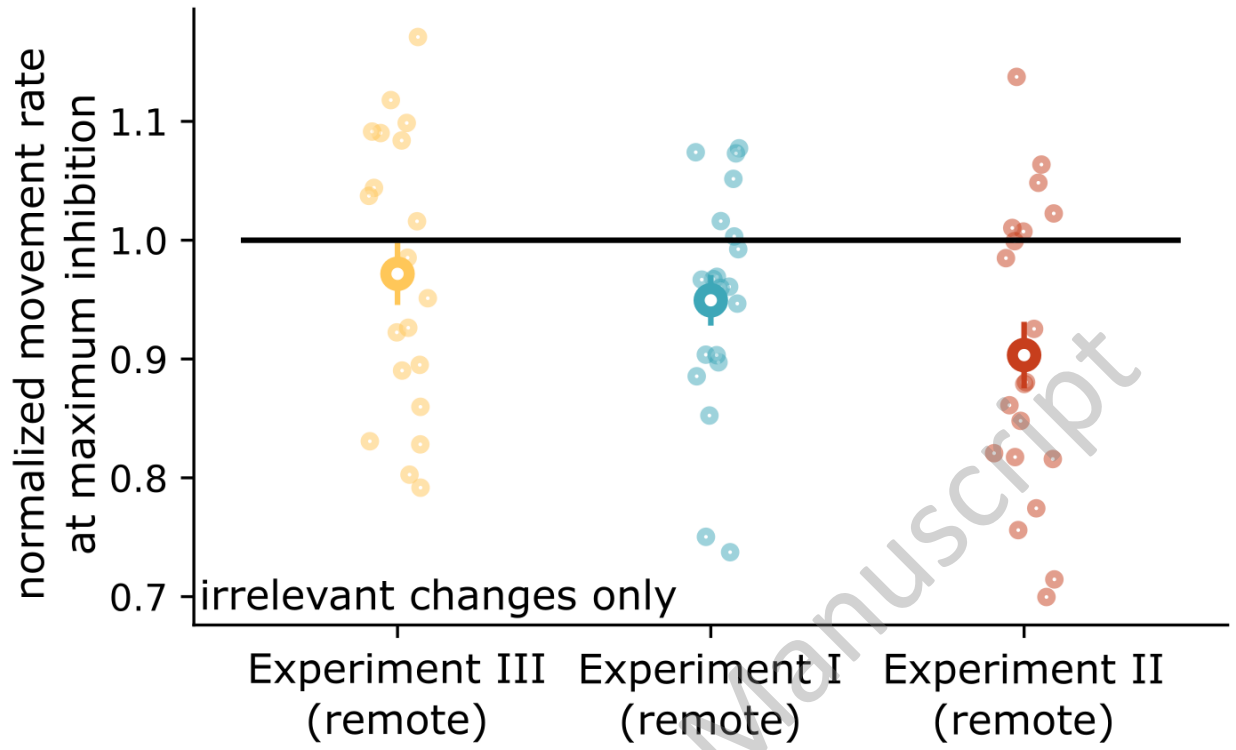
- ① Photodiode
- ② Microphone
- ③ AprilTag
- ④ RaspberryPi

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