

Augmenting cognitive load during split-belt walking increases the generalization of motor memories across walking contexts

Dulce M. Mariscal¹, Pablo A. Iturralde¹, and Gelsy Torres-Oviedo¹

¹Department of Bioengineering, University of Pittsburgh, 15213,

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Corresponding author:

Gelsy Torres-Oviedo, PhD
Department of Bioengineering
University of Pittsburgh
3700 O'Hara St.,
Benedum Hall, Room 406
412-624-2660
gelsyto@pitt.edu

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1 **Abstract**

2 Cognitive load plays a role on the movement recalibration induced by sensorimotor
3 adaptation, but little is known about its impact on the generalization of movements from
4 trained to untrained situations. We hypothesized that altering cognitive load by distracting
5 subjects during sensorimotor adaptation would facilitate the generalization of recalibrated
6 movements beyond the training condition. We reasoned that awareness of the novel condition
7 inducing adaptation could be used to consciously contextualize movements to that particular
8 situation. To test this hypothesis, young adults adapted their gait on a split-belt treadmill
9 (moving their legs at different speeds) while they observed visual information that either
10 distracted them or made them aware of the speed difference between their feet. We assessed
11 the adaptation and aftereffects of spatial and temporal gait features known to adapt and
12 generalize differently when walking on the treadmill or overground. We found similar
13 adaptation and aftereffects on the treadmill across all groups. In contrast, both groups with
14 altered cognitive load (i.e., distraction and awareness groups) generalized their movements
15 from the treadmill to overground more than controls, who walked without altered cognitive
16 load. Of note, this effect was only observed in temporal gait features, which are less
17 susceptible to online motor adjustments, and were eliminated upon experiencing large errors
18 by briefly removing the split perturbation during adaptation (i.e., catch trial). Taken together,
19 increasing cognitive demands during sensorimotor adaptation facilitates the generalization of
20 movement recalibration, but this cognitive-mediated effect cannot eliminate the specificity of
21 actions due to context-specific errors.

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26 **New and Noteworthy:**

27 Little is known about how cognition affects the generalization of motor recalibration induced
28 by sensorimotor adaptation paradigms. We showed that augmenting cognitive load during
29 adaptation on a split-belt treadmill led to greater recalibration of movements without the
30 training device. However, this effect was eliminated when unusual motor errors were
31 experienced on the treadmill. Thus, cognition can influence the generalization of sensorimotor
32 adaptation, but it cannot suppress the context-specificity originated by the errors that one feels.

33 **Introduction**

34

35 Generalization of learning is defined as the ability to apply knowledge acquired in one
36 situation to new experiences. For instance, a tennis player will likely generalize the motor
37 learning acquired from playing tennis to other sports played with rackets. This motor ability is
38 studied in sensorimotor adaptation by assessing the carryover of movements recalibrated in a
39 novel environment to variations of the training task (Ingram et al. 2000; Krakauer et al. 2000;
40 Reynolds and Bronstein 2004; Cothros et al. 2006; Reisman et al. 2009; Torres-Oviedo and
41 Bastian 2010; Wang et al. 2011; Torres-Oviedo and Bastian 2012; Bédard and Song 2013;
42 Kitago et al. 2013; Howard and Franklin 2015; Wang and Song 2017). Notably, it has been
43 shown that arm movements recalibrated when reaching in one direction generalize to reaching in
44 other postures (Shadmehr and Mussa-Lvaldi 1994) or directions (Donchin et al. 2003; Malfait
45 and Ostry 2004; Howard and Franklin 2015; Wang and Song 2017). On the other hand, the
46 generalization of sensorimotor recalibration to movements without the training device is more
47 limited (Kluzik et al. 2008; Reisman et al. 2009; Torres-Oviedo and Bastian 2010, 2012). This is,
48 for example, evidenced by the reduced adaptation effects (i.e., aftereffects) following split-belt
49 walking when stepping overground (untrained situation) compared to when stepping on the
50 treadmill (trained situation) (Reisman et al. 2009; Torres-Oviedo and Bastian 2010, 2012). We
51 are particularly interested in identifying factors regulating the generalization of sensorimotor
52 adaptation because its translational value. Namely, the repetition of gait recalibration through
53 split-belt walking can lead to reductions of gait asymmetry post-stroke (Reisman et al. 2013;
54 Lewek et al. 2018), but it is critical that these improvements carryover to daily life situations.
55 Thus, we are interested in factors mediating the generalization of sensorimotor adaptation to

56 harness them such that motor improvements observed in clinical populations from these tasks
57 generalize to untrained circumstances.

58 Previous findings indicate that context-specific cues from sensory, motor, or cognitive
59 information regulate the generalization of sensorimotor adaptation. For example, sensory
60 information specific to the adaptation condition will determine its generalization to other
61 situations (Krouchev and Kalaska 2003; Wada et al. 2003; Osu et al. 2004; Ahmed et al. 2008;
62 Ingram et al. 2010; Torres-Oviedo and Bastian 2010; Addou et al. 2011; Wang et al. 2011;
63 Hirashima and Nozaki 2012; Howard et al. 2013). Similarly, actions before (Howard et al. 2012,
64 2013; Howard and Franklin 2015), during (Torres-Oviedo and Bastian 2012), or after (Howard et
65 al. 2015) experiencing the novel condition regulate the generalization of recalibrated movements.
66 Interestingly, cognitive load by altering subjects' attention to the adapted task can also modulate
67 the generalization of movements in reaching (Bédard and Song 2013). Thus, cognitive processes
68 can alter the generalization of sensorimotor adaptation in volitional actions, but it remains
69 unknown if this effect is also observed in more automated behaviors such as locomotion.

70 The idea that cognition can alter the generalization of locomotor adaptation is plausible
71 given growing evidence that cognitive processes have an effect on sensorimotor adaptation. For
72 example, changes in cognitive load during sensorimotor adaptation alter motor adjustments from
73 one trial to the next (Taylor and Thoroughman 2008), the magnitude of aftereffects (Redding et
74 al. 1992), or the rates at which individuals adapt (Bock 2010; Im et al. 2015) and de-adapt their
75 actions (Malone and Bastian 2010). Thus, cognitive processes can modulate the recalibration of
76 movements induced by sensorimotor adaptation, suggesting that it may also change the
77 generalization of adapted movements. We particularly tested the hypothesis that altering
78 cognitive load by distracting individuals would increase the generalization of motor patterns

79 across walking conditions (i.e., treadmill vs. overground), whereas explicit information about the
80 novel environment would reduce it. We further tested if the potential effects of altered cognitive
81 load would be maintained when subjects experienced unusual errors in the training environment,
82 which has been shown to limit the generalization of sensorimotor adaptation in reaching (Kluzik
83 et al. 2008) and walking (Torres-Oviedo and Bastian 2012).

84 **Methods**

85 *Subjects*

86 A group of young adults were tested to investigate the effect of cognitive load during
87 split-belt walking on the generalization of locomotor adaptation (experiment 1: n=30, 19
88 females; mean age 25.43 ± 1.53 yrs.). We also investigated the extent to which the effect of
89 cognition on generalization was sustained upon experiencing large errors induced by briefly
90 removing the split condition on a subsequent experiment (experiment 2: n=30, 19 females; mean
91 age 27.28 ± 1.37 yrs.). The study was approved by the University of Pittsburgh Institutional
92 Review Board and it is in accordance with the Declaration of Helsinki. All subjects gave
93 informed consent prior testing.

94 *Locomotor Paradigm*

95 General Protocol

96 All participants performed a gradual split-belt paradigm consisting of a baseline,
97 adaptation, and post-adaptation epochs (Fig. 1A). In the baseline epoch, two baseline blocks
98 were collected: one for overground and another for treadmill walking to measure subjects'
99 regular walking in these two contexts. During the overground baseline block, subjects walked
100 along an 8-meter walkway for 10 minutes at a self-selected speed. During the treadmill baseline

101 block, subjects walked on the treadmill when the belts moved at the same speed (i.e., tied
102 condition) at 1.125 m/s for 300 strides. A stride was defined as the time between two
103 consecutive heel strikes (i.e., foot landing) of the same leg. In the adaptation epoch, subjects'
104 walked on the split-belt treadmill while the speed difference between the feet was gradually
105 introduced (Fig. 1C). This was done to reduce the saliency of the split perturbation in the
106 distraction group and the same was done in all other groups for consistency purposes. The
107 general speed profile is illustrated in Figure 1C. In total subjects walked for 1200 strides. First,
108 both belts moved at 1.125m/s for 300 strides, then one belt started to gradually speed up and the
109 other to slow down during 600 strides until they reached a 2:1 belt speed ratio (i.e., fast belt
110 moving at 1.5m/s and the slow belt moving at 0.75 m/s). The dominant leg (i.e., self-reported leg
111 to kick a ball) walked on the fast belt. Lastly, the 2:1 split-belt ratio was maintained for 300
112 strides. In the post-adaptation epoch subjects walked overground and on the treadmill to assess
113 the generalization and washout of the split-belt pattern, respectively (Fig 1B). During the
114 overground post-adaptation block, subjects walked on a walkway for 10 minutes at a self-
115 selected speed. Importantly, subjects were transported to the beginning of the walkway in a
116 wheel chair to ensure we could record the initial overground steps following adaptation. Finally,
117 during the treadmill post-adaptation block, participants walked with the two belts moving at the
118 same speed of 1.125 m/s for 600 strides (figure1A). The initial steps during this epoch were used
119 to quantify the remaining aftereffects that were not washed out by overground walking, and
120 hence the remaining motor memory specific to the treadmill context (i.e., washout in Figure 1B).

121 For safety purposes, subjects held to a handrail during the very first few steps of the
122 baseline, adaptation, and post-adaptation blocks on the treadmill until they felt comfortable
123 walking with their arms unrestricted (as they walked during the overground blocks). Also, a

124 plastic divider was placed between the treadmill belts to ensure subjects could not step on the
125 wrong belt during treadmill blocks. Finally, all individuals wore a harness on the treadmill that
126 only provided support in the event of a fall.

127 Experiment 1:

128 To investigate the effect of cognitive load on the generalization of locomotor adaptation we
129 tested three groups: distraction group (n=10), awareness group (n=10), and control group (n=10).
130 The distraction and awareness groups were compared to the control group in which subjects
131 adapted their gait without any instruction (Fig. 1A, gray). Subjects in the distraction group (Fig.
132 1A, blue) had altered cognitive load by performing a secondary task unrelated to split-belt
133 walking. Specifically, they were required to count (with a handheld counter) the number of times
134 that a specific word was mentioned in a TV show. We used this distraction procedure because it
135 has been shown to have an impact on locomotor adaptation (Malone and Bastian 2010). On the
136 other hand, subjects in the awareness group (Fig 1A, red) observed the evolution of the speed
137 difference between their feet during the entire adaptation epoch. More specifically, these
138 participants watched two vertical progression bars displayed on the left and right side of a screen
139 placed in front of them (See snapshots of the screen on Fig 1D). This group was told that these
140 bars corresponded to the speed of the left and right leg, respectively. Each bar's height increased
141 in real-time as the duration of the foot in contact with the ground increased. Figure 1D illustrates
142 the time courses of the bars' heights. These show that they were of the same height when the
143 speed difference was zero and they were of distinct heights as the speed difference increased. We
144 chose to display a biometric parameter instead of each belt's speed because we wanted to use a
145 measure that encompassed the walking speed variability. Further, we chose to display stance
146 duration for each leg, rather than foot speed, because stance duration is a speed-related measure

147 (Reisman et al. 2005) that could be displayed reliably, whereas foot speed was susceptible to
148 marker occlusion. This visual feedback was created using a custom program coded with Vizard
149 (Worldviz, Santa Barbara CA). Individuals were familiarized to the visual feedback with two
150 short trials (~10 strides each) with the visual display while they walked at 1.5m/s and at 0.75m/s,
151 which were the speeds for each foot in the full split condition. In addition, subjects also
152 experienced a 300 pre-ramp phase with visual feedback and tied walking that served as a
153 familiarization period before the two legs moved at different speeds. Lastly, individuals in the
154 control and distraction groups wore a drape to prevent them from seeing their feet, whereas
155 subjects in the awareness group did not. This was done to allow individuals in the awareness
156 group to confirm the displayed speed difference by looking at their feet. All groups walked
157 without visual stimuli during baseline and post-adaptation epochs.

158 Experiment 2:

159 We ran a second experiment to investigate if the effect of cognitive load on the generalization of
160 recalibrated movements was altered by large errors upon removal of the split condition. To this
161 end, three additional groups were tested following the exact paradigm as in Experiment 1, but
162 these groups also experienced large errors by briefly removing the split condition (i.e., catch
163 trial) during the adaptation epoch. This catch trial was introduced 1050 strides into the
164 adaptation epoch, so that there were 150 strides of walking at the 2:1 split ratio before and after
165 this trial. It consisted of a 10-stride trial with the belts moving at the same speed (1.125 m/s, Fig
166 1C). The step length asymmetry (aftereffects) experienced during the catch trial were considered
167 errors specific to the treadmill environment. Importantly, individuals were instructed to walk
168 without holding the handrail on the treadmill during the catch trial, such that the steps on the
169 treadmill and overground context were more comparable.

170 ***Data collection***

171 Kinematic and force data were recorded to characterize subjects' gait. Kinematic data
172 were recorded at 100 Hz with a Vicon Motion System (Oxford UK) and force data were recorded
173 at 1000 Hz with an instrumented split-belt treadmill (Bertec, Columbus OH). Kinematic data was
174 collected by measuring the position of reflective markers located bilaterally on the ankle (lateral
175 malleolus) and hip (greater trochanter). Gaps in raw kinematic data due to marker occlusions
176 were filled with a spline interpolation (Woltring; Vicon Nexus Software, Oxford Uk). Force data
177 were used for detecting foot landing (i.e., heel-strike) and foot lifting (i.e., toe-off) in real-time to
178 count strides and to determine the stance duration used in the visual feedback of the awareness
179 groups. On the other hand, kinematic data were used to detect gait events on the treadmill and
180 overground as in previous work (Torres-Oviedo and Bastian 2010, 2012). This was done such
181 that the data analysis of these two walking contexts was more comparable given that we could
182 not collect force data overground.

183 ***Data Analysis***

184 **Gait Parameters**

185 Step length asymmetry, known to robustly adapt during split-belt walking (e.g., Reisman
186 et al. 2005), was used as a global measure to characterize gait adaptation and its generalization to
187 overground walking. Step length asymmetry is defined as the difference of step lengths (anterior-
188 posterior distance between ankle markers at heel strike) of two consecutive heel strikes and
189 normalized by the sum of the step lengths (Eq.1). As a result, zero values represent symmetric
190 step lengths, positive values indicate that the leg on the fast belt (i.e., fast leg) is taking longer
191 steps than the slow leg, and vice versa for negative values.

192 Eq. 1
$$S_a = \frac{SL_f - SL_s}{SL_f + SL_s}$$

193 We also characterized spatial and temporal components of step length asymmetry (Eq. 2;
194 Finley et al. 2015) because previous studies have shown distinct adaptation (Malone and Bastian
195 2010; Malone et al. 2012) and generalization (Torres-Oviedo and Bastian 2010; Sombric et al.
196 2017) of spatial and temporal gait features. Briefly explained, step length asymmetry can be
197 decomposed into spatial (StepPosition, S_p), temporal (StepTime, S_t) and velocity (StepVelocity,
198 S_v) components of two consecutive steps (Eq. 2). StepPosition quantifies how far the foot lands
199 away from the body when taking a step with one leg vs. the other (Eq. 3). StepTime compares
200 the time to take a step (i.e., duration between two subsequent heel-strikes) with one leg vs. the
201 other. This difference is scaled by the average velocity of the legs (Eq. 4). Lastly, StepVelocity
202 quantifies the difference in speeds at which the foot moves with respect to the body when taking
203 a step with one leg vs. the other. This difference is scaled by the averaged step time across the
204 legs (Eq. 5).

205 Eq. 2
$$S_a = S_p + S_t + S_v$$

206 Eq. 3
$$S_p = \frac{(\Delta\alpha_{fast} - \Delta\alpha_{slow})}{SL_f + SL_s}$$

207 Eq. 4
$$S_t = \frac{\frac{v_{slow} + v_{fast}}{2} * (t_{slow} - t_{fast})}{SL_f + SL_s}$$

208 Eq. 5
$$S_v = \frac{\frac{t_{slow} + t_{fast}}{2} * (v_{slow} - v_{fast})}{SL_f + SL_s}$$

209 Where $\Delta\alpha_{fast}$ indicates the difference in distances between the fast leg's landing position and the
210 body at fast heel-strike and the previous slow leg's landing position and the body at slow heel
211 strike. Similarly, $\Delta\alpha_{slow}$ compares the distances between the slow leg's landing position and the
212 previous fast leg's landing position (both with respect to the body location at slow and fast heel-
213 strike, respectively). t_{slow} quantified the duration between the fast leg's heel-strike and the

214 previous slow leg's heel strike and t_{fast} the duration between the slow leg's heel-strike and the
215 previous fast leg's heel strike. Lastly, v_{fast} and v_{slow} represent the step velocity quantified as the
216 relative velocity of the body with respect to the ankle in contact with the ground (i.e., fast ankle
217 for v_{fast} and slow ankle for v_{slow}). Note that step length asymmetry and all its components are
218 normalized by the sum of step lengths to account for differences in step sizes across individuals.

219 Outcome measures

220 Measures of subjects' adaptation and generalization were computed for each of the gait
221 parameters described above (i.e., Sa, Sp, St and Sv). Subjects' adaptation performance was
222 characterized with the steady state (SS) for each parameter and a global measure of extent of
223 adaptation (AdaptExt). The steady state (SS) characterized subjects' behavior at the end of the
224 split-belt condition before they walked overground. This was computed using the average of the
225 last 40 strides of adaptation ($Adapt_{late}$) without the baseline bias (mean of last 40 strides of the
226 treadmill baseline) as indicated in Eq. 6.

227 Eq. 6
$$SS = Adapt_{late} - TM_{base}$$

228 Extent of adaptation ($AdaptExt$) was used to measure the extent to which subjects
229 counteracted the split-belt perturbation. This parameter was computed as the difference between
230 the steady state for the step length asymmetry (SS_a) and the steady state for the velocity
231 component (SS_v), which is a good proxy for the perturbation experienced by each subject
232 (Finley et al. 2015). Formally expressed in eq 7.

233 Eq. 7
$$AdaptExt = SS_a - SS_v$$

234 AdaptExt is always a positive measure since SS_a monotonically increases from values
235 neighboring SS_v to zero values. Thus, large AdaptExt values indicated that subjects adapted their
236 gait substantially on the split-belt condition, whereas small values indicated that they did not.

259 (Experiment 2) on the adaptation and generalization of gait. Fisher's LSD post-hoc testing was
260 used to compare the behavior across groups when we identified group main effects. We set the
261 acceptable threshold for Type I errors to 5% in all statistical tests. Statistical analyses were
262 performed with Stata (StataCorp, TX).

263 **Results**

264 *Altered cognitive load did not affect the adaptation of gait*

265 We observed that all subjects reached the same adapted state, regardless of their cognitive
266 condition. This is qualitatively indicated by the time courses for all parameters during adaptation
267 (Fig. 2A). Specifically, we did not find an effect of cognition load during the steady state in
268 subjects who did not experience a catch trial (Steady State in Experiment 1 for Sa: $F(2,27)=2.13$,
269 $p=0.12$; Sp: $F(2,27)=1.15$ $p=0.33$; St: $F(2,27)=0.13$ $p=0.88$) nor in those who did (Steady State in
270 Experiment 2 for Sa: $F(2,27)=0.73$, $p=0.49$; Sp: $F(2,27)=0.24$, $p=0.79$; St: $F(2,27)=0.91$, $p=0.41$).
271 These findings were further supported by the similar counteraction of the perturbation across
272 groups with or without a catch trial (Experiment 1 without catch: AdaptExt $F(2,27)=2.13$,
273 $p=0.14$ and Experiment 2 with catch: AdaptExt: $F(2,27)=0.81$, $p=0.46$, Fig. 2B). In sum,
274 subjects' cognitive state did not affect their ability to counteract gradual split-belt perturbations.

275 *Altered cognitive load during split-belt walking increased the generalization of adapted step* 276 *timing to overground walking*

277 Cognitive load altered the aftereffects of step time overground. This is qualitatively
278 shown by the distinct time courses of overground aftereffects in experiment 1 (Figure 3A). Note
279 that the distraction and awareness curves (blue and red, respectively) have larger values than
280 those in the control group (gray curve) for step time. This difference is also observed to a lesser
281 extent in the time courses of step length asymmetry, but not of step position, for which curves

282 overlapped across groups. Consistently, we found a significant effect of cognitive condition on
283 overground aftereffects of step time ($F(2,27)=5.51$, $p=0.01$), but not for those of step length
284 asymmetry ($F(2,27)=1.55$, $p=0.23$) or step position ($F(2,27)=0.61$, $p=0.55$). Further, post-hoc
285 analysis indicated that the distraction and awareness groups had larger aftereffects overground in
286 step time than the control group (control vs. distraction $p=0.014$, control vs. awareness $p=0.005$).
287 Interestingly, there were no differences between the distraction and awareness groups ($p=0.65$).
288 This suggests that the increased cognitive load in the awareness condition facilitated the
289 generalization of motor adaptation, even if the secondary task provided contextual information
290 about the treadmill. Taken together, we found that visual distractors during adaptation increased
291 the transfer of updated step time on the treadmill to overground, but these differences in step
292 time were not large enough to significantly change step length asymmetry overground.

293 The increased generalization of the adapted step time was further supported by the
294 washout of treadmill aftereffects following overground walking. Figure 3B illustrates the time
295 courses for subjects walking under different cognitive conditions. Note that groups adapted with
296 altered cognitive loads during adaptation (i.e., distraction and awareness groups) showed smaller
297 step time aftereffects when they returned to the treadmill, while their step length asymmetry and
298 step position was similar across groups. Accordingly, we found a significant effect of cognitive
299 condition on subjects' remaining treadmill aftereffects following overground walking for step
300 time ($F(2,27)=5.47$, $p=0.01$), but not for step length asymmetry ($F(2,27)=0.22$, $p=0.81$) or step
301 position ($F(2,27)=0.79$, $p=0.46$). Moreover, post-hoc analysis on step time aftereffects indicated
302 that subjects with altered cognitive load during adaptation had significantly smaller remaining
303 aftereffects when they went back to the treadmill than those without it (control vs distraction
304 $p=0.003$, control vs awareness $p=0.034$). This indicated that the distraction and awareness groups

305 were more susceptible to washout from overground walking than controls. Once again, we did
306 not observe differences between the distraction and awareness groups ($p=0.33$), further
307 supporting that the increased cognitive load in the awareness group reduced, rather than
308 facilitated, the context-specificity of locomotor adaptation, even if the secondary task provided
309 explicit information about the unique split condition. Overall, our washout findings were
310 consistent with our transfer results, in the sense that, the groups transferring the most were also
311 those that had the least remaining aftereffects when returning to the treadmill. In sum, motor
312 memories were more general when cognition was altered during adaptation not only because
313 these memories carried over to an untrained situation, but because they were susceptible to
314 walking in the untrained context (i.e., overground).

315 *Large errors during adaptation eliminated the effect of cognitive condition on generalization*

316 The effect of cognition on the generalization of locomotor adaptation was not maintained
317 when subjects experienced large errors induced by a catch trial during adaptation. This is
318 indicated by the similar generalization and washout across cognitive conditions when
319 experiencing a catch. We first noted that the cognitive condition did not have an effect on the
320 treadmill aftereffects during the catch trial (Figure 4A. Sa: $F(2,27)=2.24$, $p=0.13$, Sp:
321 $F(2,27)=1.15$, $p=0.33$, St: $F(2,27)=0.87$, $p=0.43$). These are the aftereffects that are experienced
322 the very first time that the split condition is removed. Figure 4 also illustrates the time course of
323 aftereffects when walking overground (Fig 4B) and when returning to the treadmill following
324 overground walking (4C). Note that time courses for all groups overlap in all parameters and
325 walking contexts. Consistently, there was not a significant effect of cognitive condition on
326 overground aftereffects when subjects experienced a catch trial (Figure 4B. Sa: $F(2,27)=0.36$
327 $p=0.70$, Sp: $F(2,27)=0.82$, $p=0.45$, St: $F(2,27)=0.95$, $p=0.4$). Similarly, there was not a

328 significant difference between the groups experiencing the catch trial on treadmill aftereffects
329 following overground walking in all parameters (Figure 4C. Sa: $F(2,27)=0.39$, $p=0.68$), Sp:
330 $F(2,27)=1.32$ $p=0.28$; St: $F(2,27)=1.61$, $p=0.22$). Thus, all cognitive conditions had similar
331 transfer and washout of treadmill aftereffects when they experienced large errors during
332 adaptation.

333 **Discussion**

334

335 **Summary**

336 We investigated how altering cognitive load during split-belt walking affects subjects'
337 ability to adapt and generalize gait movements. We also studied the effect of large errors during
338 adaptation on the generalization of sensorimotor recalibration across different cognitive
339 conditions. We found that cognitive load does not modulate subjects' steady state in the split
340 condition and the subsequent treadmill aftereffects. In contrast, cognitive condition had an
341 impact on the generalization of temporal gait features adapted during split-belt walking. More
342 specifically, augmenting the cognitive load during adaptation increased the generalization of
343 aftereffects across walking contexts, even if the secondary task brought awareness to movements
344 specific to the training condition. Interestingly, the effect of cognition on generalization was
345 eliminated in the presence of large errors experienced during a catch trial (i.e., when the split
346 condition was removed). Therefore, we find that a more general recalibration of walking occurs
347 when cognitive resources during sensorimotor adaptation are occupied, but only in the absence
348 of unusual errors in the training environment.

349 *Cognitive load does not impact the sensorimotor adaptation to a gradual perturbation*

350 We found that subjects' performance during the adaptation epoch and subsequent
351 aftereffects on the treadmill were not altered by cognitive load. These observations contrast
352 previous findings indicating that increasing cognitive load limits subjects' steady state
353 performance (Ingram et al. 2000) or their ability to adjust movements from one trial to the next
354 (Taylor and Thoroughman 2007, 2008). Altered cognitive load during locomotor adaptation has
355 also been shown to slow down the adaptation rate (Malone and Bastian 2010). We believe that
356 these differences stem from the distinct adaptation schedules in our study compared to previous
357 work. More explicitly, our participants experienced a gradual perturbation, whereas the
358 referenced studies were done in response to abrupt perturbations. Recent work indicates that
359 cognitive-driven strategies, such as re-aiming contribute to motor performance upon large abrupt
360 perturbations (Bond and Taylor 2015; Morehead et al. 2015). Perhaps we find that subjects'
361 performance to gradual perturbations is not susceptible to cognitive load because motor
362 adaptation in this case requires less cognitive-based strategies.

363 Our results also showed that treadmill aftereffects, as measured in the catch trial, are not
364 affected by the altered cognitive load. This is consistent with other walking studies (Malone and
365 Bastian 2010; Long et al. 2016; Roemmich et al. 2016), but not with reaching literature showing
366 that aftereffects are reduced when subjects perform cognitive task (Keisler and Shadmehr 2010).
367 This discrepancy between reaching and walking could be explained by either 1) distinct
368 contributions of explicit strategies to the adaptation of reaching and walking, or 2) distinct
369 approaches for measuring aftereffects between these motor behaviors. First of all, consider that
370 cognitive load likely influences aftereffects linked to explicit (i.e., strategic) corrections during
371 adaptation, which may play a larger role in reaching than walking because reaching is a more

372 volitional action. Second, aftereffects in walking are measured by removing the split perturbation
373 (a.k.a., null condition), whereas aftereffects in reaching are measured by constraining the arm
374 (a.k.a., error-clamp condition) (Keisler and Shadmehr 2010). As a result, feedback-mediated
375 responses dominate aftereffects in walking (Iturralde and Torres-Oviedo 2018), but not in
376 reaching. These feedback-mediated responses to unexpected transitions between walking
377 conditions are more independent from cognitive processes than strategic actions (Malone and
378 Bastian 2010). Therefore, cognition may only alter the explicit component contributing to
379 aftereffects, but not the feedback-mediated one dominating aftereffects in walking.

380 *Cognitive load during adaptation facilitates the generalization of motor adaptation*

381 We found that increasing cognitive load during split-belt walking facilitates the
382 generalization of adapted step timing, even when the secondary task brings awareness to
383 movements specific to the training context. This was indicated by an increment on the
384 generalization of step timing adapted on the treadmill and larger washout of this adapted step
385 timing by overground walking; both of which observed in the distraction and awareness groups
386 with increased cognitive load during adaptation. Our findings are consistent with inter-limb
387 transfer literature showing that cognitive load during visuomotor rotations modulates the
388 generalization of adapted reaches from one arm to the other (Kasuga and Nozaki 2011) and that
389 explicit knowledge about the perturbation during adaptation does not disrupt generalization
390 (Wang et al. 2011). We believe distractors might result in more generalized motor memories for
391 two potential reasons. First, distractors might alter what is learned. We hypothesize that
392 cognitive load reduces the explicit component of motor adaptation, which is tied to the
393 environment, relative to the implicit one, which is tied to subjects' actions and can be applied to
394 other contexts. Second, large cognitive load might shift the credit assignment of errors during

395 adaptation from the environment to oneself because subjects are more variable when cognitive
396 resources are occupied. This potential change in credit assignment has been shown to alter the
397 generalization of sensorimotor recalibration (Berniker and Kording 2008; Fercho et al. 2014). In
398 sum, augmenting cognitive load during adaptation increases the generalization of learned
399 movement across contexts because large cognitive load might alter the encoding of adaptation
400 tied to subjects' actions, rather than explicit corrections associated with the training environment.

401 We also found that cognitive load did not modulate the generalization of adapted step
402 position. This observation is consistent with prior work showing that spatial and temporal aspects
403 of gait generalize differently, and that the generalization of temporal gait features are easier to
404 manipulate (Torres-Oviedo and Bastian 2010). This could be explained by the fact that during
405 overground walking subjects could see their feet and these overrides aftereffects of step position,
406 but not step timing. Notably, it has been shown that subjects use visual information to adjust
407 their foot placement when taking a step, but not step timing (Marigold et al. 2008; Matthis and
408 Fajen 2014; Maeda et al. 2016). Thus, we might not observe the influence of cognitive load on
409 the generalization of step position because of the reliance on online feedback control for foot
410 placement when walking overground.

411 *Large errors increase the context-specificity of locomotor patterns*

412 We observed that large errors upon removing the split condition override the impact of
413 cognition on aftereffects. This was shown by the similar aftereffects between groups
414 experiencing large errors during a catch trial, regardless of whether subjects walked overground
415 or on the treadmill. These results are consistent with previous work showing that large errors
416 during adaptation limit the generalization of aftereffects when walking overground (Torres-
417 Oviedo and Bastian 2012). It has also been shown that subjects can switch faster between

418 locomotor patterns when they experience transitions from split to tied walking (Malone et al.
419 2011; Sombric et al. 2017; Day et al. 2018). Therefore, aftereffects overground and on the
420 treadmill might be reduced because errors during the catch trial might facilitate the transitioning
421 between split and regular walking patterns.

422 *Clinical implications*

423
424 Our results might have an impact on the rehabilitation of hemiparetic gait because error-
425 augmentation protocols, like the one presented here, can induce gait improvements in stroke
426 survivors (Reisman et al. 2007; Savin et al. 2014) that persist with repeated exposure (Reisman
427 et al. 2013; Lewek et al. 2018). However, if treadmills and robots are to be used for correcting
428 patients' movements, it is critical that the learned movements carry over to "real-life" situations
429 beyond the training context. Here, we show that increasing cognitive load during sensorimotor
430 adaptation facilitates the generalization of adapted behavior to different environments. These
431 findings are promising for two reasons. First, individuals with motor disorders are often trained
432 by either bringing self-awareness to their motions and explicit instructions on how to move
433 (Lewek et al. 2018). Our results suggest that the generalization of motor improvements from
434 these motions with large cognitive load will not be limited. Second, our results suggest that
435 sensorimotor adaptation protocols, like split-belt walking, might lead to more general motor
436 improvements if patients adapt their movements with increased cognitive load. However, future
437 work is needed to test this hypothesis. In conclusion, our results suggest that increased cognitive
438 load during rehabilitation therapies might lead to encoding more general motor memories,
439 whereas errors specific to the training environment tied them to the training situation.

440 **Conflict of Interest**

441 The authors declare that the research was conducted in the absence of any commercial or
442 financial relationships that could be construed as a potential conflict of interest.

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- 566

567 **Figure Captions:**

568 Figure 1: A. Experimental protocols. These consisted of three epochs: Baseline, Adaptation, and
569 Post-adaptation, each of which had distinct blocks outlined with distinct colors. The adaptation
570 block was further divided into three colors to indicate the distinct cognitive load experienced by
571 each group: control (without altered cognitive load), awareness (with altered cognitive load by
572 receiving information about speed difference between the feet) and distraction (with altered
573 cognitive load by performing a secondary task unrelated to split-belt walking). Only the subjects
574 tested in Experiment 2 experienced a 10-stride catch trial (two legs moving at the same speed)
575 during the Adaptation epoch B. Outcome measures. Adaptation index, Steady State, Transfer
576 index, and Washout index were collected at time periods indicated on of interest C. Speed
577 profiles. We illustrate the time course of the speed at which the dominant (green) and non-
578 dominant leg (red) walked during the Adaptation epoch. Speed profiles for the legs in
579 Experiment 1 (black solid lines) and Experiment 2 (black dashed lines) are also presented to
580 illustrate that only Experiment 2 had a catch trial during which both belts moved at 1.125m/s. D.
581 Visual feedback that the Awareness groups received during Adaptation. Subjects observed
582 progression bars that informed them about each foot speed. The averaged time courses \pm
583 standard errors are displayed for each bar. We also show snap shots of image that subjects
584 observed during the pre-ramp, ramp, and hold phases during Adaptation.

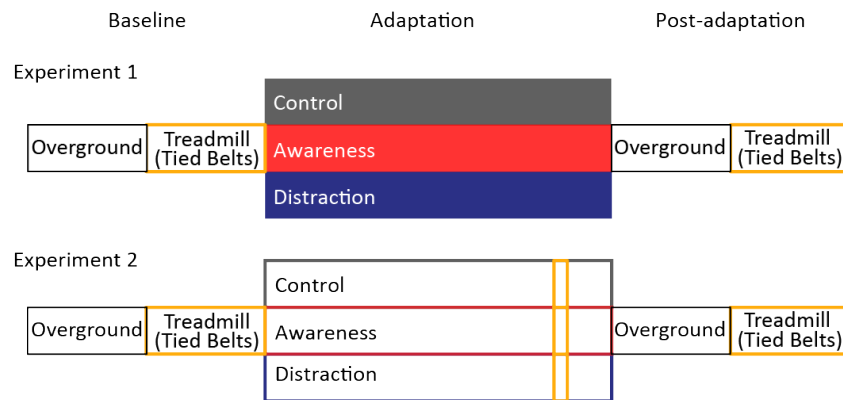
585 Figure 2: A. Time courses for each parameter during the Adaptation epochs of Experiment 1 (top
586 row) and Experiment 2 (bottom row). B. Steady State at the end of the Adaptation epochs of
587 Experiment 1 (top row) and Experiment 2 (bottom row). Bar plots indicate the mean adapted
588 steady state per group \pm standard errors. Note that we did not find a group effect for any gait
589 parameter, indicating that cognitive load did not have an impact on the Steady State behavior
590 prior to overground walking. C. Measure of adaptation extent for all groups. Bars' height
591 indicates the mean per group \pm standard errors. All groups adapted their gait similarly.

592 Figure 3: A. Stride-by-stride time courses and mean transfer values (i.e., overground aftereffects)
593 are shown for all parameters during the post-adaptation block overground. B. Stride-by-stride
594 time courses and mean washout values (i.e. remaining treadmill aftereffects) are shown for all
595 parameters during the post-adaptation block on the treadmill. In both panels, gray shaded areas
596 indicate the strides that are zoomed in the inserts. Each dot represents the average of 5

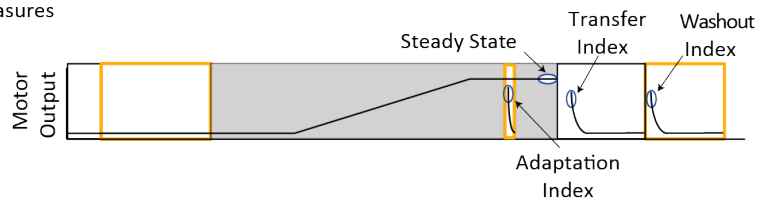
597 consecutive strides and colored shaded areas indicate the standard error for each group. Bar plots
598 indicate either the mean transfer value (in Panel A) or the mean washout value (in Panel B) for
599 each group \pm standard errors. The black horizontal lines indicate significant statistical differences
600 between groups. Recall that Experiment 1 was designed without a catch, thus aftereffects in the
601 training context are not recorded for this group. For display purposes we use the axes are scaled
602 as in Figure 4A presenting the aftereffects during catch for Experiment 2. This was done to
603 qualitatively show that aftereffects overground and remaining aftereffects on the treadmill in
604 Experiment 1 are much smaller than those observed during the catch.

605 Figure 4: A. Mean adaptation index per group indicating the mean value for aftereffects
606 experienced on the treadmill the first time that the split condition is removed. Error bars indicate
607 standard errors. B. Stride-by-stride time courses and mean transfer values (i.e., overground
608 aftereffects) are shown for all parameters during the post-adaptation block overground. C. Stride-
609 by-stride time courses and mean washout values (i.e. remaining treadmill aftereffects) are shown
610 for all parameters during the post-adaptation block on the treadmill. In both panels, gray shaded
611 areas indicate the strides that are zoomed in the inserts. Each dot represents the average of 5
612 consecutive strides and colored shaded areas indicate the standard error for each group. Bar plots
613 indicate either the mean transfer value (in Panel B) or the mean washout value (in Panel C) for
614 each group \pm standard errors. Cognitive condition did not have an effect on aftereffects on the
615 treadmill and overground when large errors were experienced.

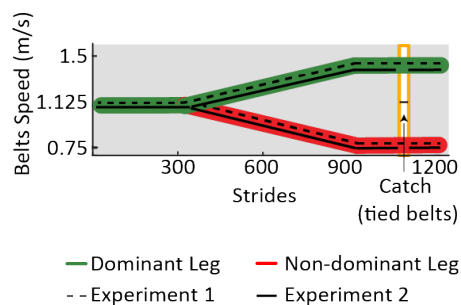
A. Experimental Protocols



B. Outcome Measures



C. Speed Profiles During Adaptation



D. Visual Feedback for the Awareness Group

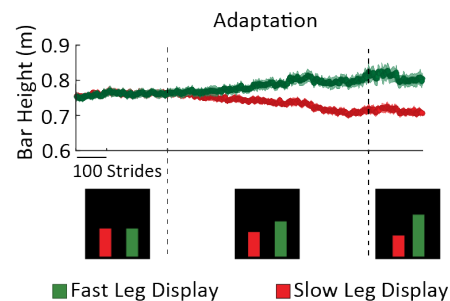
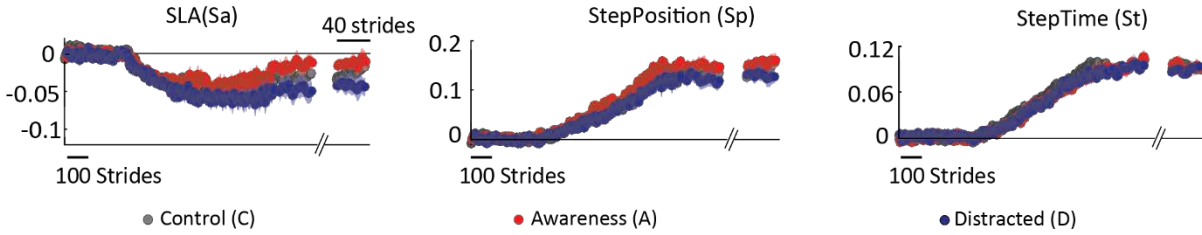


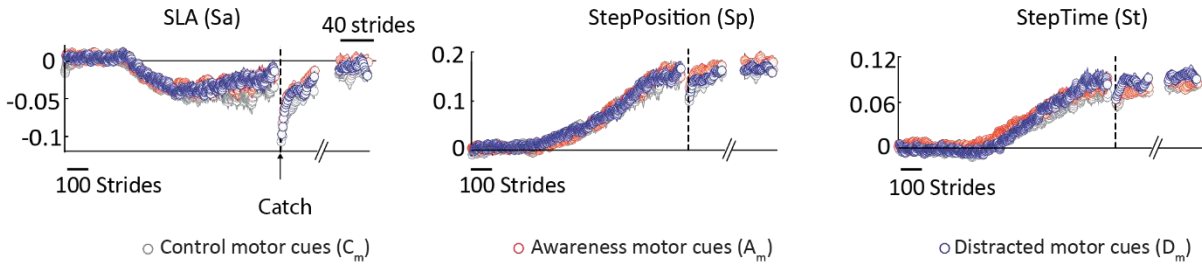
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A. Adaptation Time Courses

Experiment 1

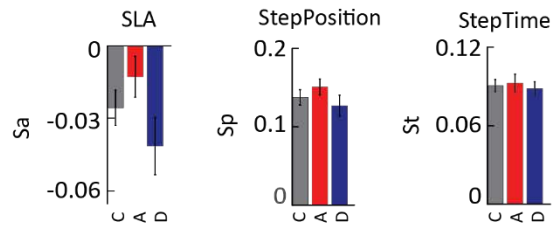


Experiment 2

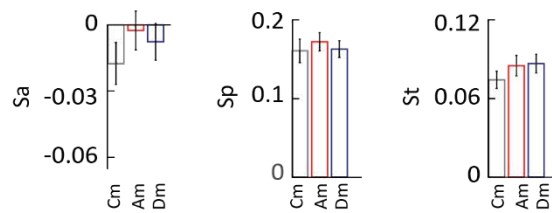


B. Steady State

Experiment 1

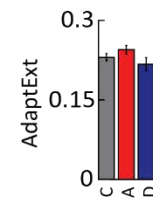


Experiment 2



C. Extent of Adaptation

Experiment 1



Experiment 2

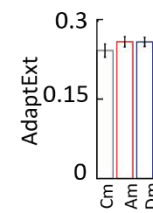


Figure 2: A. Time courses for each parameter during the Adaptation epochs of Experiment 1 (top row) and Experiment 2 (bottom row). B. Steady State at the end of the Adaptation epochs of Experiment 1 (top row) and Experiment 2 (bottom row). Bar plots indicate the mean adapted steady state per group \pm standard errors. Note that we did not find a group effect for any gait parameter, indicating that cognitive load did not have an impact on the Steady State behavior prior to overground walking. C. Measure of adaptation extent for all groups. Bars' height indicates the mean per group \pm standard errors. All groups adapted their gait similarly.

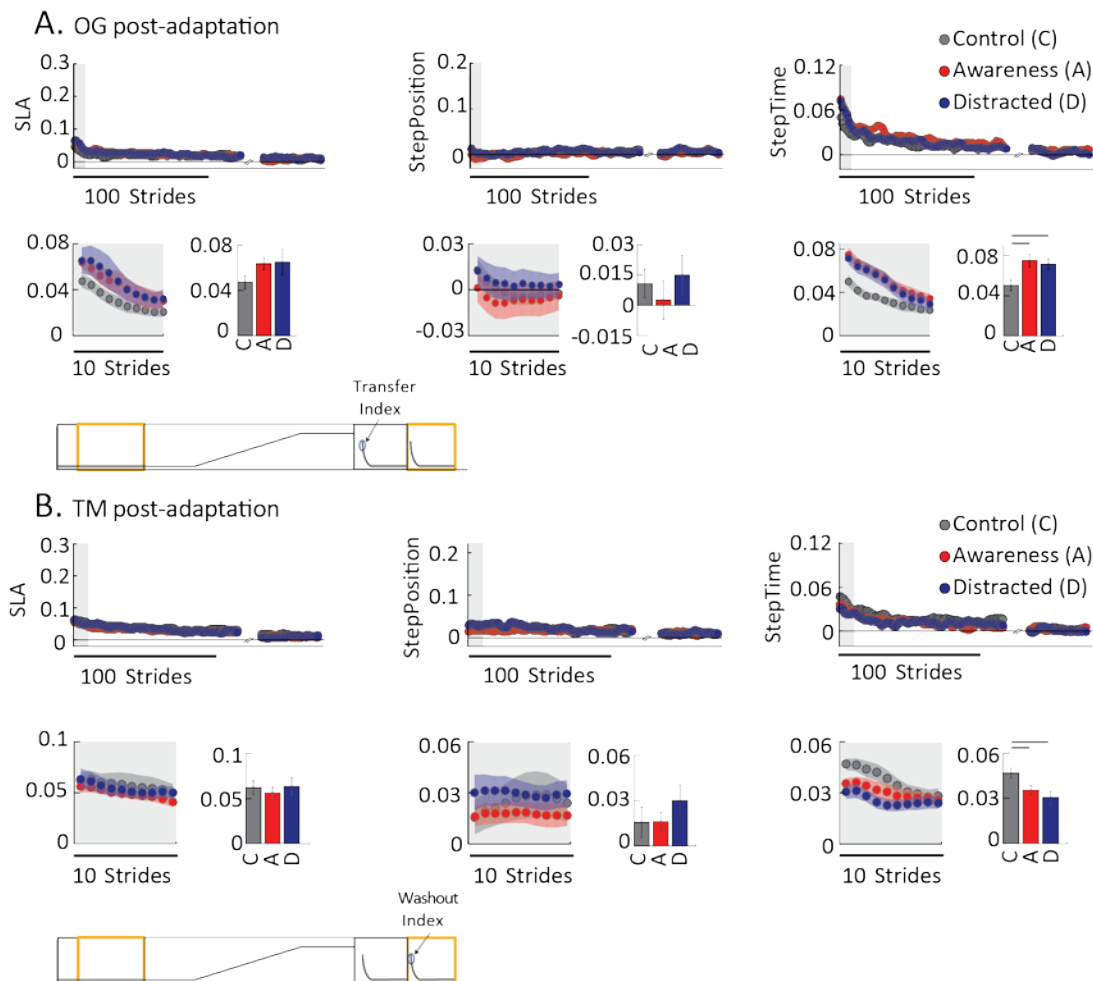
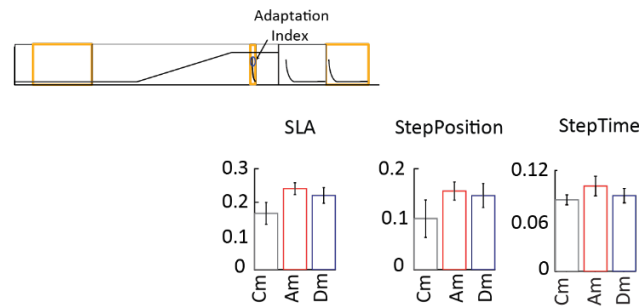
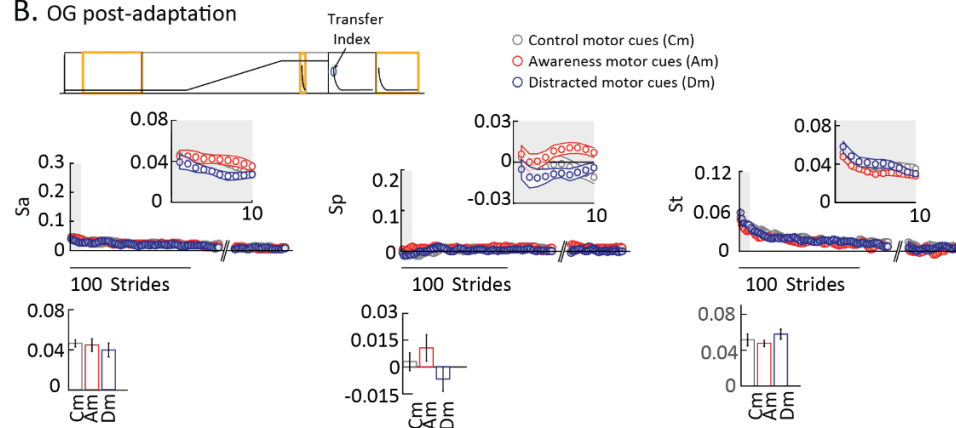


Figure 3: A. Stride-by-stride time courses and mean transfer values (i.e., overground aftereffects) are shown for all parameters during the post-adaptation block overground. B. Stride-by-stride time courses and mean washout values (i.e. remaining treadmill aftereffects) are shown for all parameters during the post-adaptation block on the treadmill. In both panels, gray shaded areas indicate the strides that are zoomed in the inserts. Each dot represents the average of 5 consecutive strides and colored shaded areas indicate the standard error for each group. Bar plots indicate either the mean transfer value (in Panel A) or the mean washout value (in Panel B) for each group \pm standard errors. The black horizontal lines indicate significant statistical differences between groups. Recall that Experiment 1 was designed without a catch, thus aftereffects in the training context are not recorded for this group. For display purposes we use the axes are scaled as in Figure 4A presenting the aftereffects during catch for Experiment 2. This was done to qualitatively show that aftereffects overground and remaining aftereffects on the treadmill in Experiment 1 are much smaller than those observed during the catch.

A. Adaptation Index



B. OG post-adaptation



C. TM post-adaptation

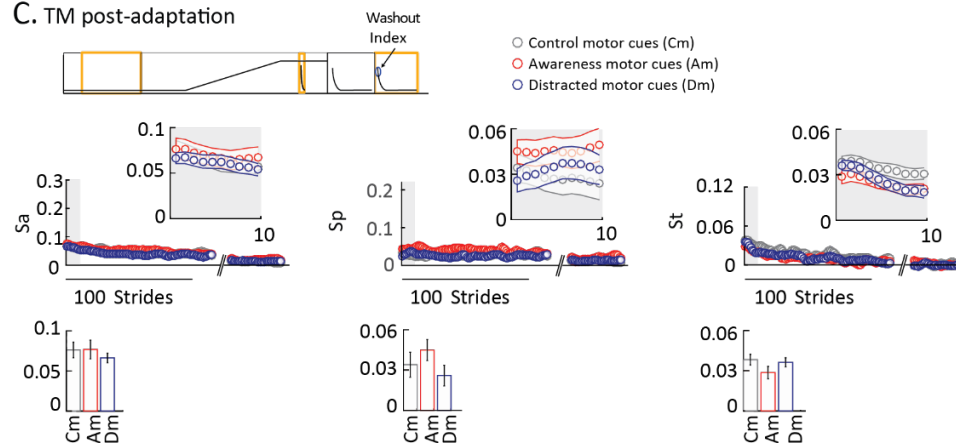


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