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RESEARCH ARTICLE *Control of Movement*

Altering attention to split-belt walking increases the generalization of motor memories across walking contexts

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Mariscal DM, Iturralde PA, Torres-Oviedo G. Altering attention to split-belt walking increases the generalization of motor memories across walking contexts. *J Neurophysiol* 123: 1838 ï 1848, 2020. First published April 1, 2020; doi:10.1152/jn.00509.2019.ð Little is known about the impact of attention during motor adaptation tasks on how movements adapted in one context generalize to another. We investigated this by manipulating subjectsô attention to their movements while exposing them to split-belt walking (i.e., legs moving at different speeds), which is known to induce locomotor adaptation. We hypothesized that reducing subjectsô attention to their movements by distracting them as they adapted their walking pattern would facilitate the generalization of recalibrated movements beyond the training environment. We reasoned that awareness of the novel split-belt condition could be used to consciously contextualize movements to that particular situation. To test this hypothesis, young adults adapted their gait on a split-belt treadmill while they observed visual information that either distracted them or made them aware of the beltôs speed difference. We assessed adaptation and aftereffects of spatial and temporal gait features known to adapt and generalize differently in different environments. We found that all groups adapted similarly by reaching the same steady-state values for all gait parameters at the end of the adaptation period. In contrast, both groups with altered attention to the split-belts environment (distraction and awareness groups) generalized their movements from the treadmill to overground more than controls, who walked without altered attention. This was specifically observed in the generalization of step time (temporal gait feature), which might be less susceptible to online corrections during walking overground. These results suggest that altering attention to oneôs movements during sensorimotor adaptation facilitates the generalization of movement recalibration.

NEW & NOTEWORTHY Little is known about how attention affects the generalization of motor recalibration induced by sensorimotor adaptation paradigms. We showed that altering attention to movements on a split-belt treadmill led to greater adaptation effects in subjects walking overground. Thus our results suggest that altering patientsô attention to their actions during sensorimotor adaptation protocols could lead to greater generalization of corrected movements when moving without the training device.

cognition; dual task; human; kinematics; motor adaptation

INTRODUCTION

Generalization of learned movements can be defined as the ability to apply movements acquired in one situation to another situation. For instance, a tennis player will likely generalize the motor learning acquired from playing tennis to other sports played with rackets. This motor ability is studied in sensorimotor adaptation by assessing the carryover of movements recalibrated in a novel environment to variations of the training task. Notably, it has been shown that arm movements recalibrated during reaching in one posture and direction generalize to reaching in other postures (Shadmehr and Mussa-Ivaldi 1994) or directions (Donchin et al. 2003; Howard and Franklin 2015; Malfait and Ostry 2004; Wang and Song 2017). Conversely, the generalization of sensorimotor recalibration to movements without the training device is more limited (Kluzik et al. 2008; Reisman et al. 2009; Torres-Oviedo and Bastian 2010, 2012). This type of generalization is of interest because of its translational value. Namely, the repetition of gait recalibration through split-belt walking can lead to reductions of gait asymmetry poststroke (Lewek et al. 2018; Reisman et al. 2013), but it is critical that these improvements carryover to daily life situations. Thus we are interested in factors mediating the generalization of sensorimotor adaptation to harness them such that motor improvements observed in clinical populations from these tasks generalize to untrained circumstances.

Previous findings indicate that context-specific cues from sensory, motor, or cognitive information regulate the generalization of sensorimotor adaptation. For example, sensory information specific to the adaptation condition, such as the orientation of a virtual object (Ahmed et al. 2008), the color of a target (Hirashima and Nozaki 2012; Ingram et al. 2010), or the context-specific visual flow (Torres-Oviedo and Bastian 2010), will determine its generalization to other situations. Similarly, actions before (Howard et al. 2013, 2012; Howard and Franklin 2015), during (Torres-Oviedo and Bastian 2012), or after (Howard et al. 2015) the novel condition is experienced regulate the generalization of recalibrated movements. Interestingly, altering subjectsô attention to the adapted task can also modulate the generalization of movements in reaching (B®dard and Song 2013). Thus cognitive processes can alter the generalization of sensorimotor adaptation in volitional

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actions, but it remains unknown if this effect is also observed in more automated behaviors such as locomotion.

The idea that cognition can alter the generalization of locomotor adaptation is plausible given growing evidence that cognitive processes have an effect on sensorimotor adaptation. For example, changes in cognitive load during sensorimotor adaptation alter motor adjustments from one trial to the next (Taylor and Thoroughman 2008), the magnitude of aftereffects (Redding et al. 1992), or the rates at which individuals adapt (Bock 2010; Im et al. 2015) and deadapt their actions (Malone and Bastian 2010). Thus cognitive processes can modulate the recalibration of movements induced by sensorimotor adaptation, suggesting that it may also change the generalization of adapted movements. Consistently, recent work has shown that cognitive constructs of visuomotor perturbations regulate the generalization of reaches from one direction to another (Day et al. 2016; McDougle et al. 2017; Taylor and Ivry 2013) or from one arm to the other (Kasuga and Nozaki 2011). In this study we particularly investigated if attention, a cognitive-mediated process, to the altered movements in the split-belt walking environment regulates the generalization of adaptation effects. We hypothesized that altering attention by distracting individuals would increase the generalization of motor patterns across walking contexts (i.e., treadmill vs. overground), whereas explicit information about the novel environment would reduce it.

METHODS

Subjects

A group of neurologically intact, young adults were tested to investigate the effect of attention during split-belt walking on the generalization of locomotor adaptation (n ^ 30, based on power analysis, 17 women; mean age 26.37 ^ 5.26 yr.). All participants were naive to the experimental protocol and have never experienced split-belt walking. Eligible subjects needed to meet the following criteria: *1*) be able to walk with or without a handheld device at a self-paced speed for at least 5 min, *2*) have no orthopedic or pain conditions interfering with the assessment, *3*) have no neurological conditions, *4*) have no contraindications for performing moderate intensity exercise, and *5*) have no diagnosed mental health conditions (e.g., anxiety, depression, etc.). The study was approved by the University of Pittsburgh Institutional Review Board and is in accordance with the Declaration of Helsinki. All subjects gave written informed consent prior testing.

Locomotor Paradigm

General protocol. All participants performed a gradual split-belt paradigm consisting of baseline, adaptation, and postadaptation epochs (Fig. 1*A*). This was done to reduce the saliency of the split perturbation in the distraction group, and the same was done in all other groups for consistency purposes. In the baseline epoch, two baseline blocks were collected: one for overground and another for treadmill walking to measure subjectsô regular walking in these two contexts. During the overground baseline block, subjects walked along an 8-m walkway continuously for 10 min at a self-selected speed. During the treadmill baseline block, subjects walked on the treadmill when the belts moved at the same speed (i.e., tied condition) at 1.125 m/s for 300 strides. A stride was defined as the time between two consecutive heel strikes (i.e., foot landing) of the same leg. In the adaptation epoch, subjects walked on the split-belt treadmill while the speed difference between the feet was gradually introduced (Fig. 1*B*). The general speed profile is illustrated in Fig. 1*B*. In total, subjects walked for 1,200 strides, which were counted in real time using an automated process (see *Data Collection*). First, both belts moved at 1.125 m/s for 300 strides, and then one belt started to gradually speed up and the other to slow down. This ramp phase lasted 600 strides, and at the end of this period the belts (Fig. 1*B*, green dotted line) reached a 2:1 belt speed ratio (i.e., fast belt moving at 1.5 m/s and slow belt moving at 0.75 m/s). We selected this particular speed profile, rather than changing the speed of one belt only (Alc©ntara et al. 2018; Torres-Oviedo and Bastian 2010), because we were interested in maintaining the same cadence (i.e., stepping frequency) across the baseline and adaptation epochs, which is achieved by keeping the same averaged speed across the belts during these two experimental periods. Thus our speed profile eliminated the possibility for subjects to use changes in cadence across conditions as a cue about a change in the walking environment. The dominant leg (i.e., self-reported leg to kick a ball) walked on the fast belt, as in our previous studies (Gonzalez-Rubio et al. 2019; Sombric et al. 2017, 2019b). Last, the 2:1 split-belt ratio was maintained for 300 strides. In the postadaptation epoch, subjects walked overground and on the treadmill to assess the generalization and washout of the split-belt pattern, respectively (Fig. 1*C*). During the overground postadaptation block, subjects walked on a walkway for 10 min at a self-selected speed. Importantly, subjects were transported to the beginning of the walkway in a wheelchair to ensure we could record the initial overground steps following adaptation. Finally, during the treadmill postadaptation block, participants walked with the two belts moving at the same speed of 1.125 m/s for 600 strides (Fig. 1*A*). The initial steps (i.e., first 5 strides) during this epoch were used to quantify the remaining aftereffects that were not washed out by overground walking, and hence the remaining motor memory specific to the treadmill context (i.e., washout in Fig. 1*C*). All individuals successfully completed the entire protocol.

For safety purposes, subjects held to a handrail during the very first few steps of the baseline, adaptation, and postadaptation epochs on the treadmill until they felt comfortable walking with their arms unrestricted (as they did during overground walking). Also, a plastic divider was placed between the treadmill belts to ensure that subjects could not step on the wrong belt when walking on the treadmill. Finally, all individuals wore a harness on the treadmill that only provided support in the event of a fall.

To investigate the effect of attention on the generalization of locomotor adaptation, we tested three groups: distraction group (n ^ 10, 7 women; mean age 26.28 ^ 5.65 yr.), awareness group (n ^ 10, 6 women; mean age 25.21 ^ 3.73), and control group (n ^ 10, 4 women; mean age 27.61 ^ 6.34). The distraction and awareness groups were compared with the control group in which subjects adapted their gait without any instruction (Fig. 1*A*, gray). Subjects in the distraction group (Fig. 1*A*, blue) had altered attention by performing a secondary task unrelated to split-belt walking. Specifically, they were required to count (with a handheld counter) the number of times the word ñthirtyò was mentioned in a TV show. Subjectsô median accuracy was 3.5 (interquartile range ^ 1.75). Accuracy was defined as the absolute difference between each subjectôs report of the total number times the word ñthirtyò appeared and the 18 times that the word was truly mentioned. This TV task was selected because it has been shown to successfully alter subjectsô attention during the split-belt task (Malone and Bastian 2010). In addition, it resulted in slower adaptation and deadaptation rates in subjects experiencing an abrupt split-belt condition. Thus we selected this task to determine if it would also lead to longer lasting aftereffects over ground (i.e., untrained context). Subjects in the awareness group (Fig. 1*A*, red) observed the evolution of the speed difference between their feet during the entire adaptation epoch. More specifically, these participants watched two vertical progression bars displayed on the left and right side of a screen placed in front of them (see snapshots of the screen in Fig. 1*D*). These bars indicated the stance time duration for each leg, which has

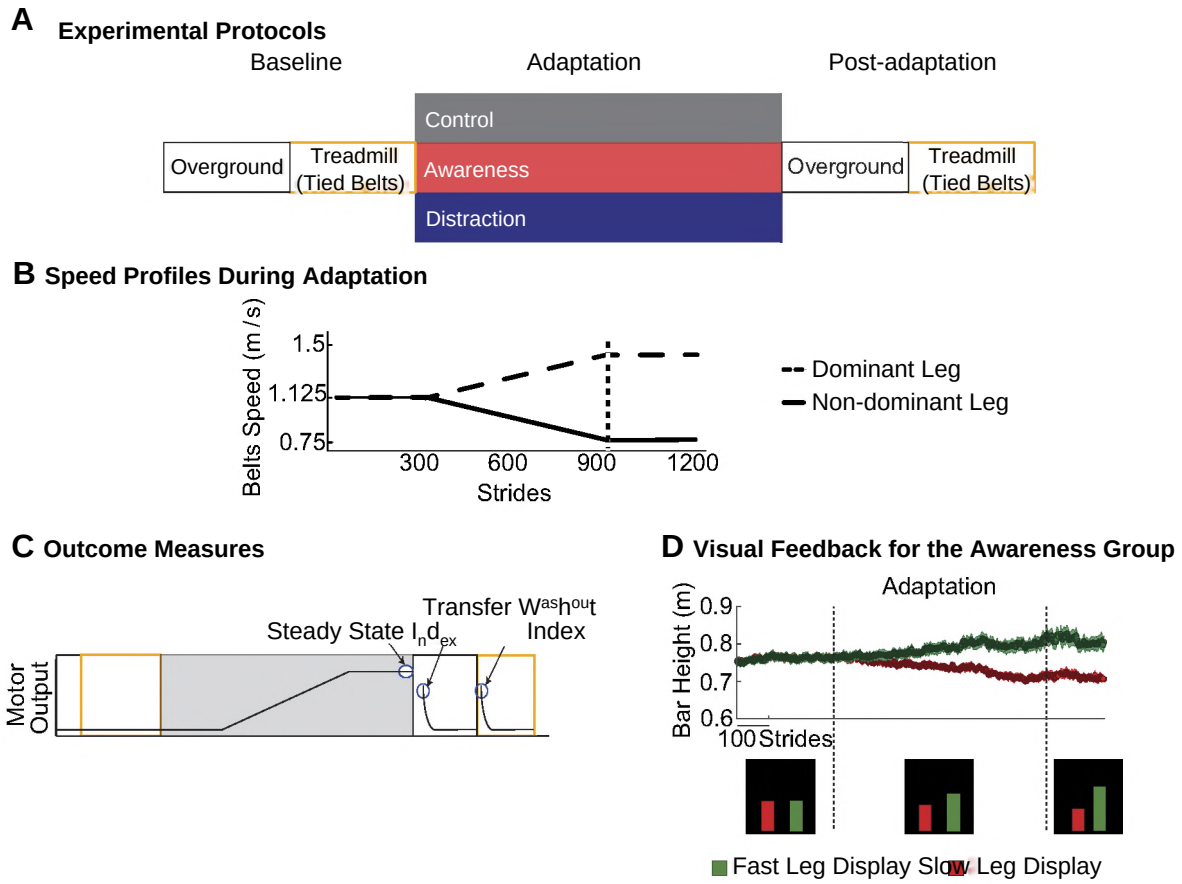

Fig. 1. *A*: experimental protocols. These consisted of 3 epochs: baseline, adaptation, and postadaptation, each of which had distinct epochs outlined with distinct colors. Orange rectangles on the treadmill trials represent both belts moving at 1.125 m/s. The adaptation epoch is further divided into 3 colors to indicate the distinct levels of attention experienced by each group: control (without altered attention), awareness (with attention altered by receiving information about speed difference between the feet), and distraction (with attention altered by performing a secondary task unrelated to split-belt walking). *B*: speed profiles. Graph illustrates the time course of the speed at which the dominant (dotted line) and nondominant legs (line) walked during the adaptation epoch. The end of the ramp phase is marked by the green dotted line. *C*: outcome measures. Steady state, transfer index, and washout index were collected at time periods indicated of interest. *D*: visual feedback that the awareness groups received during adaptation. Subjects observed progression bars that informed them about each foot speed. The averaged time courses (^SE) are displayed for each bar. Also shown are snap shots of images that subjects observed during the preramp, ramp, and hold phases during adaptation.

been shown to directly reflect the belt speed difference between the legs during the split-belt condition (e.g., Malone et al. 2012; Gonzalez-Rubio et al. 2019; Reisman et al. 2005). Each barôs height increased in real time as the duration of the foot in contact with the ground increased. Figure 1*D* illustrates the time courses of the barsô heights. These show that they were of the same height when the speed difference was zero and they were of distinct heights as the speed difference increased. We chose to display a biometric parameter instead of the speed commanded to each belt because we wanted to give subjects a measure that encompassed the walking speed variability. Furthermore, we chose to display stance duration for each leg, rather than foot speed, because stance duration is a speed-related measure (Reisman et al. 2005) that could be displayed reliably, whereas foot speed was susceptible to marker occlusion. This visual feedback was created using a custom program coded with Vizard (WorldViz, Santa Barbara, CA). Individuals were familiarized to the visual feedback with two short trials (~10 strides each) with the visual display while they walked at 1.5 m/s and at 0.75m/s, which were the speeds for each foot in the full-split condition. In addition, subjects also experienced a preramp phase, lasting 300 strides, with visual feedback and tied walking that served as a familiarization period before the two legs moved at different speeds. Lastly, individuals in the control and distraction groups wore a drape around their neck that was extended out all the way to the handrail located in front of the participants. This was done to prevent the individuals in the control and distraction groups from looking at their feet, whereas subject in the awareness group walked without this visual restriction. This was done to allow individuals in the awareness group to confirm the displayed speed difference by looking at their feet. All participants groups walked under the same conditions (i.e., without the screens and without the drape) during the baseline and postadaptation epochs. This was done so that all groups were tested similarly pre- and postadaptation. Also, participants chose to look straight ahead, but their gaze was not restricted to look in a particular direction.

Data Collection

Kinematic and force data were recorded to characterize subjectsô gait. Kinematic data were recorded at 100 Hz with a Vicon Motion System (Oxford, UK), and force data were recorded at 1,000 Hz with an instrumented split-belt treadmill (Bertec, Columbus, OH). Kinematic data were collected by measuring the position of reflective markers located bilaterally on the ankle (lateral malleolus) and hip (greater trochanter). Gaps in raw kinematic data due to marker occlusions were filled with a spline interpolation (Woltring; Vicon Nexus Software, Oxford, UK). Force data were used for detecting foot landing (i.e., heel strike) and foot lifting (i.e., toe off) in real time to count strides and to determine the stance duration used in the visual feedback of the awareness group. On the other hand, kinematic data

were used to detect gait events on the treadmill and overground as in previous work (Torres-Oviedo and Bastian 2010, 2012). This was done such that the data analysis of these two walking contexts was more comparable given that we could not collect force data overground.

Data Analysis

Gait parameters. Step length asymmetry, known to robustly adapt during split-belt walking (e.g., Reisman et al. 2005), was used as a global measure to characterize gait adaptation and its generalization to overground walking. Step length asymmetry, S_a, is defined as the difference of step lengths (anterior-posterior distance between ankle markers at heel strike) of two consecutive heel strikes and normalized by the sum of the step lengths (*Eq. 1*). SL_f represents the step length when the fast leg is leading, and SL_s represents the step length when the slow leg is leading. Zero S_a values indicate symmetric step lengths, positive values indicate that the leg walking on the fast belt (i.e., fast leg) is taking longer steps than the slow leg, and vice versa for negative values.

$$S_a = \frac{SL_f - SL_s}{SL_f + SL_s} \quad (1)$$

We also characterized spatial and temporal components of step length asymmetry (*Eq. 2*; Finley et al. 2015) because previous studies have shown distinct adaptation (Malone et al. 2012; Malone and Bastian 2010) and generalization (Sombric et al. 2017; Torres-Oviedo and Bastian 2010) of spatial and temporal gait features. Briefly explained, step length asymmetry can be decomposed into spatial (StepPosition, S_p), temporal (StepTime, S_t), and velocity (StepVelocity, S_v) components of two consecutive steps (*Eq. 2*).

$$S_a = S_p + S_t + S_v \quad (2)$$

StepPosition, S_p, quantifies how far the foot lands away from the body when a step is taken with one leg versus the other. This is formally expressed in *Eq. 3*, where Δ_{fast} indicates the difference in distances between the fast legôs landing position and the body at fast heel strike and the previous slow legôs landing position and the body at slow heel strike. Similarly, Δ_{slow} compares the distances between the slow legôs landing position and the previous fast legôs landing position (both with respect to the body location at slow and fast heel strike, respectively).

$$S_p = \frac{(\Delta_{fast} - \Delta_{slow})}{SL_f + SL_s} \quad (3)$$

StepTime compares the time to take a step (i.e., duration between two subsequent heel strikes) with one leg versus the other. This difference is scaled by the average velocity of the legs (*Eq. 4*).

$$S_t = \frac{\frac{V_{slow} + V_{fast}}{2} * (t_{slow} - t_{fast})}{SL_f + SL_s} \quad (4)$$

t_{slow} indicates the duration between the fast legôs heel strike and the previous slow legôs heel strike, and t_{fast} the duration between the slow legôs heel strike and the previous fast legôs heel strike. V_{fast} and V_{slow} represent the step velocity quantified as the relative velocity of the body with respect to the ankle in contact with the ground (i.e., fast ankle for V_{fast} and slow ankle for V_{slow}). Lastly, StepVelocity quantifies the difference in speeds at which the foot moves with respect to the body when a step is taken with one leg versus the other. This difference is scaled by the averaged step time across the legs (*Eq. 5*).

$$S_v = \frac{\frac{t_{slow} + t_{fast}}{2} * (V_{slow} - V_{fast})}{SL_f + SL_s} \quad (5)$$

Note that step length asymmetry and all its components are normalized by the sum of step lengths to account for differences in step sizes across individuals. Consequently, all measures are unitless.

Outcome measures. Measures of subjectsô adaptation and generalization were computed for each of the gait parameters described above (i.e., S_a, S_p, S_t, and S_v). Subjectsô adaptation performance was characterized with the steady state (SS) for each parameter and a global measure of extent of adaptation (AdaptExt). The steady state (SS) characterized subjectsô behavior at the end of the split-belt condition before they walked overground. This was computed using the average of the last 40 strides of adaptation ($Adapt_{late}$) without the baseline bias (mean of last 40 strides of the treadmill baseline, TM_{base}) as indicated in *Eq. 6*.

$$SS = Adapt_{late} - TM_{base} \quad (6)$$

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

$$AdaptExt = SS_a - SS_v \quad (7)$$

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

Generalization was characterized with two measures: *1*) transfer index and *2*) washout index. The transfer measure indicates the carryover of movements from the treadmill to the overground context. This measure was defined as the difference between the initial steps (averaged of the first 5 strides) overground after the adaptation epoch (OG_{after}) and the baseline overground behavior (OG_{base}; mean of last 40 strides of overground baseline) (*Eq. 8*). Large values of transfer indicate a big change in the gait pattern overground after the adaptation period on the treadmill, whereas small values indicate that the adapted pattern on the treadmill is not carried over to the overground context.

$$Transfer = OG_{after} - OG_{base} \quad (8)$$

On the other hand, washout indicates the remaining aftereffects specific to the treadmill environment following overground walking. This outcome was quantified by the difference between the initial steps (first 5 strides) on the treadmill during the postadaptation block (TM_{post}) and the baseline behavior on the treadmill (TM_{base}). Large values indicate little washout by the overground steps, whereas small values indicate substantial washout.

$$Washout = TM_{post} - TM_{base} \quad (9)$$

Statistical Analysis

Planned analysis. Prior to our statistical analysis we performed the Shapiroï Wilk test to determine if our outcome measures were normally distributed. After our data were shown to be normally distributed, we performed separate one-way ANOVAs on the distinct outcome measures (SS, AdaptExt, Transfer, Washout). This was done to determine the effect of attention on the adaptation and generalization of the gait parameters of interest (S_a, S_p, and S_t). If a main effect of group was observed, we performed a post hoc analysis with Dunnettôs corrections (Dunnett 1955). We used this statistical correction be-

cause, as in previous work (e.g., Roemmich and Bastian 2015), our primary focus was to determine the difference between the control group and each of the experimental groups with altered attention. We set the acceptable threshold for type I errors to 5% in all statistical tests. Statistical analyses were performed with Stata (StataCorp LLC, TX).

Power analysis. The number of subjects per group was determined using the overground aftereffects of step length asymmetry from three groups of young subjects experiencing different adaptation conditions (de Kam et al. 2018). We specifically used between-group variance of 0.05, within-group variance of 0.83, and an effect size of ^2 ^ 0.78 obtained from a one-way ANOVA of the aforementioned unpublished data. Our power analysis indicated that an estimated sample size of n ^ 7 subjects per group would allow us to detect this effect size with a significance level of ^ ^ 0.05 and a statistical power of 80%. We adopted a target sample size of 10 subjects per group to be more in line with the number of subjects on existing literature assessing the generalization of sensorimotor adaptation in locomotion (Sombric et al. 2017). All statistical analyses were done using STATA (StataCorp LLC, TX).

Post hoc analysis. Our planned analysis showed an effect of attention on the generalization of the adapted StepTime (S_t), but not StepPosition (S_p) or StepAsymmetry (S_a). StepAsymmetry (S_a) is, however, a function of StepTime (S_t). To reconcile these findings, we analyzed the asymmetry in limb positions at heel strike, which have a distinct impact on these variables (S_a, S_p, and S_t): the trailing legôs position (X) affects S_a and S_t, whereas the leading legôs position (^) only affects S_a and S_p (Sombric et al. 2019a; Sombric and Torres-Oviedo 2019). Thus we tested the relation between StepTime (S_t) and limb position asymmetries to determine the impact of StepTime (S_t) aftereffects on peopleôs movements overground.

More specifically, we computed asymmetries overground in the trailing legsô positions when a step was taken with either foot (X_{asym}) and those in the leading legsô positions ($^{}_{asym}$). We then tested the relation between each of these variables with StepPosition (S_p) and StepTime (S_t). X_{asym} (*Eq. 10*) and $^{}_{asym}$ (*Eq. 11*) were calculated as follows:

$$X_{asym} = \frac{X_{fast\ slow}X}{SL_f ^ SL_s} \quad (10)$$

$$^{}_{asym} ^ \frac{^{}_{fast} ^ ^{}_{slow}}{SL_f ^ SL_s} \quad (11)$$

In these equations, the leading legôs position (^) was defined as the ankleôs marker position in the sagittal plane of the leg in front of the body at heel strike, and the trailing legôs position (X) was defined as that of the leg behind the body. Both of these positions are computed with respect to the body, which is defined as the averaged position of the two hip markers at heel strike. Moreover, the trailing legôs position X_{fast} was the position of the fast leg when this was the trailing leg at slow heel strike and vice versa for X_{slow}. By convention, negative X_{asym} values indicate that the fast leg was farther behind the body compared with the slow leg when they were trailing legs. Similarly, the leading legôs position $^{}_{fast}$ was the position of the fast leg when this was the leading leg at fast heel strike, whereas $^{}_{slow}$ was the same, but when the slow leg was the leading leg. By convention, positive $^{}_{asym}$ values indicate that the fast leg landed farther forward from the body compared with when the slow leg landed forward when a step was taken.

We tested the association between the mean asymmetries in either the trailing and leading legôs position and aftereffects in StepTime (S_t) and StepPosition (S_p). To this end, we performed separate linear regressions between the mean X_{asym} and $^{}_{asym}$ over the first five steps overground (dependent variables) and the aftereffects in StepTime (S_t) and StepPosition (S_p) (independent variables). In other words, we ran two separate regressions with the equations:

$$Transfer_{Xasym} ^ ^{}_0 ^ ^{}_1 Transfer_{Sp} ^ ^{}_2 Transfer_{St} \quad (12)$$

$$Transfer_{^{}_{asym}} ^ ^{}_3 ^ ^{}_4 Transfer_{Sp} ^ ^{}_6 Transfer_{St} \quad (13)$$

RESULTS

Altered Attention Did Not Affect the Adaptation of Gait

We observed that all subjects reached the same adapted state, regardless of their attention condition. This is qualitatively indicated by the time courses for all parameters during adaptation (Fig. 2*A*). Specifically, we did not find an effect of attention on the subjectsô steady state of step length asymmetry ($F_{2,27}$ ^ 2.31, P ^ 0.12, effect size: ^2 ^ 0.15), step position ($F_{2,27}$ ^ 1.24, P ^ 0.30, effect size: ^2 ^ 0.08), or step time ($F_{2,27}$ ^ 0.05, P ^ 0.95, effect size: ^2 ^ 0.003). These findings were further supported by the similar ability across groups in counteracting the speed difference imposed by the split condition (AdaptExt: $F_{2,27}$ ^ 2.05, P ^ 0.15, effect size: ^2 ^ 0.13; Fig. 2*B*). In sum, subjectsô attention state did not affect their ability to counteract gradual split-belt perturbations.

Altered Attention to Split-Belt Walking Increased the Generalization of Adapted Step Timing to Overground Walking

Attention altered the aftereffects of step time overground. This is qualitatively shown by the distinct time courses of overground aftereffects (Fig. 3*A*). Note that the distraction and awareness curves (blue and red, respectively) have larger values than those in the control group (gray curve) for step time. This difference is also observed to a lesser extent in the time courses of step length asymmetry, but not of step position, which curves overlapped across groups. Consistently, we found a significant effect of attention condition on overground aftereffects of step time ($F_{2,27}$ ^ 3.72, P ^ 0.037, effect size: ^2 ^ 0.22), but not for those of step length asymmetry ($F_{2,27}$ ^ 2.39, P ^ 0.11, effect size: ^2 ^ 0.15) or step position ($F_{2,27}$ ^ 0.31, P ^ 0.74, effect size: ^2 ^ 0.02). Furthermore, protected post hoc analysis indicated that the distraction and awareness groups had larger aftereffects overground in step time than the control group (control vs. distraction, P ^ 0.049; control vs. awareness, P ^ 0.045). From the multiple linear regression analysis, we found that subjectsô step position (P ^ 0.001; Fig. 3*B*, *right*) but not their step time (P ^ 0.93; data not shown) can predict asymmetries in the leading position between the legs ($^{}_{asym}$: $F_{2,27}$ ^ 38.56, P ^ 0.001, r ^ 0.86). On the other hand, both step time (P ^ 0.001; Fig. 3*B*, *left*) and step position (P ^ 0.001; data not shown) were predictors of asymmetries in the trailing position between the legs (X_{asym}: $F_{2,27}$ ^ 25.02, P ^ 0.001, r ^ 0.81). Thus the trailing and leading legsô positions with respect to the body are respectively associated to the temporal or spatial control of the limb during overground walking. In sum, altering attention during split-belt walking led to greater overground aftereffects in step time but did not significantly change the overground aftereffects of step length asymmetry.

Effect of Attention to Split-Belt Walking on the Washout of Treadmill-Specific Aftereffects

Altering attention during split-belt walking also changed the washout of treadmill aftereffects in step time by over-

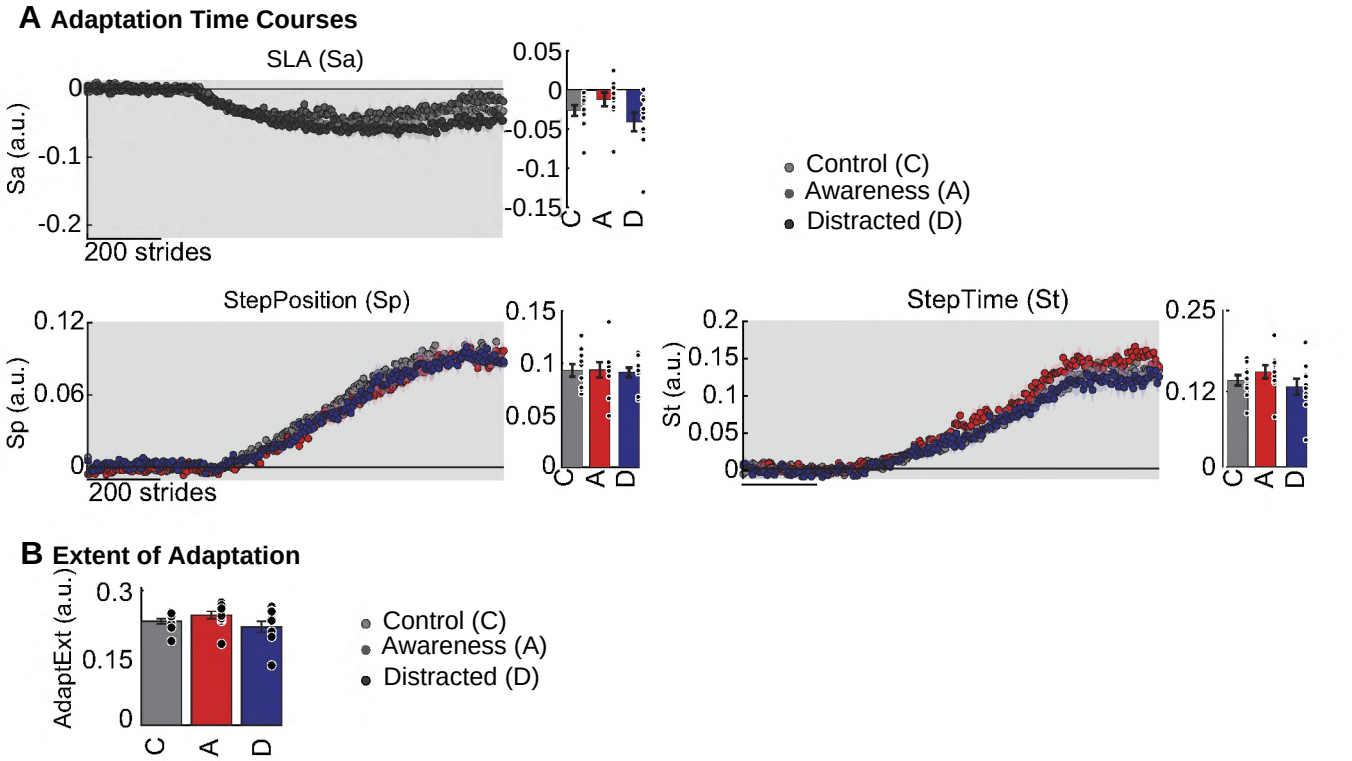

Fig. 2. *A*: time courses for each parameter (in arbitrary units, a.u.) during the adaptation epochs; each dot represents the average of 5 consecutive strides, and colored shaded areas indicate the SE for each group. Bar plots next to the time courses represent steady state at the end of the adaptation epochs; bar height indicates the mean adapted steady state per group (^SE), and black dots indicate individual subjectsô data. Note that we did not find a group effect for any gait parameter, indicating that attention did not have an impact on the steady-state behavior before overground walking. *B*: measure of adaptation extent for all groups. All groups adapted their gait similarly. AdaptExt, extent of adaptation; SLA, step length adaptation.

ground walking. Figure 4*A* illustrates the time courses for subjects walking under different attention conditions. Note that groups adapted with altered attention during adaptation (i.e., distraction and awareness groups) showed smaller step time aftereffects when they returned to the treadmill, while their step length asymmetry and step position was similar across groups. Accordingly, we found a significant effect of attention condition on subjectsô remaining treadmill aftereffects following overground walking for step time ($F_{2,27}$ ^ 5.34, P ^ 0.011, effect size: ^2 ^ 0.28), but not for step length asymmetry ($F_{2,27}$ ^ 0.21, P ^ 0.81, effect size: ^2 ^ 0.02) or step position ($F_{2,27}$ ^ 0.65, P ^ 0.53, effect size: ^2 ^ 0.05). Moreover, subjects with altered attention during adaptation had smaller remaining aftereffects when they went back to the treadmill than those without it (Fig. 4*A*). This reduction is qualitatively observed in both groups, but it was only significant in the distraction vs. control group (control vs. distraction, P ^ 0.007; control vs. awareness, P ^ 0.072). This indicates that the distraction and awareness groups were more susceptible to washout from overground walking than controls. These results further support that the visual feedback in the awareness group reduced, rather than facilitated, the context-specificity of locomotor adaptation, even if the visual information provided explicit information about the unique split condition. Overall, our washout findings were consistent with our transfer results, in the sense that the groups transferring the most were also those that had the least remaining aftereffects when returning to the treadmill. In sum, motor memories were more general when attention was altered during adaptation not only because these memories carried over to an untrained situation but also because they were susceptible to walking in the untrained context (i.e., overground).

DISCUSSION

Summary

We investigated how altering attention during split-belt walking affects subjectsô ability to adapt and generalize gait movements. We found that attention does not modulate subjectsô steady state in the split condition and the subsequent treadmill aftereffects. In contrast, attention had an impact on the generalization of temporal gait features adapted during split-belt walking. More specifically, reducing attention to subjectsô movements during adaptation increased the generalization of aftereffects across walking contexts, even if the visual distractor brought awareness to context-specific changes in the training condition. In sum, we find that a more general recalibration of walking occurs when attention to oneôs movements during sensorimotor adaptation is altered.

Attention Does Not Impact the Sensorimotor Adaptation to a Gradual Perturbation

We found that subjectsô performance during the adaptation epoch and subsequent aftereffects on the treadmill were not altered by attention. These observations contrast previous findings indicating that divided attention limits subjectsô steady-state performance (Ingram et al. 2000) or their ability to adjust movements from one trial to the next (Taylor and Thoroughman 2007). Altered attention during locomotor adaptation has

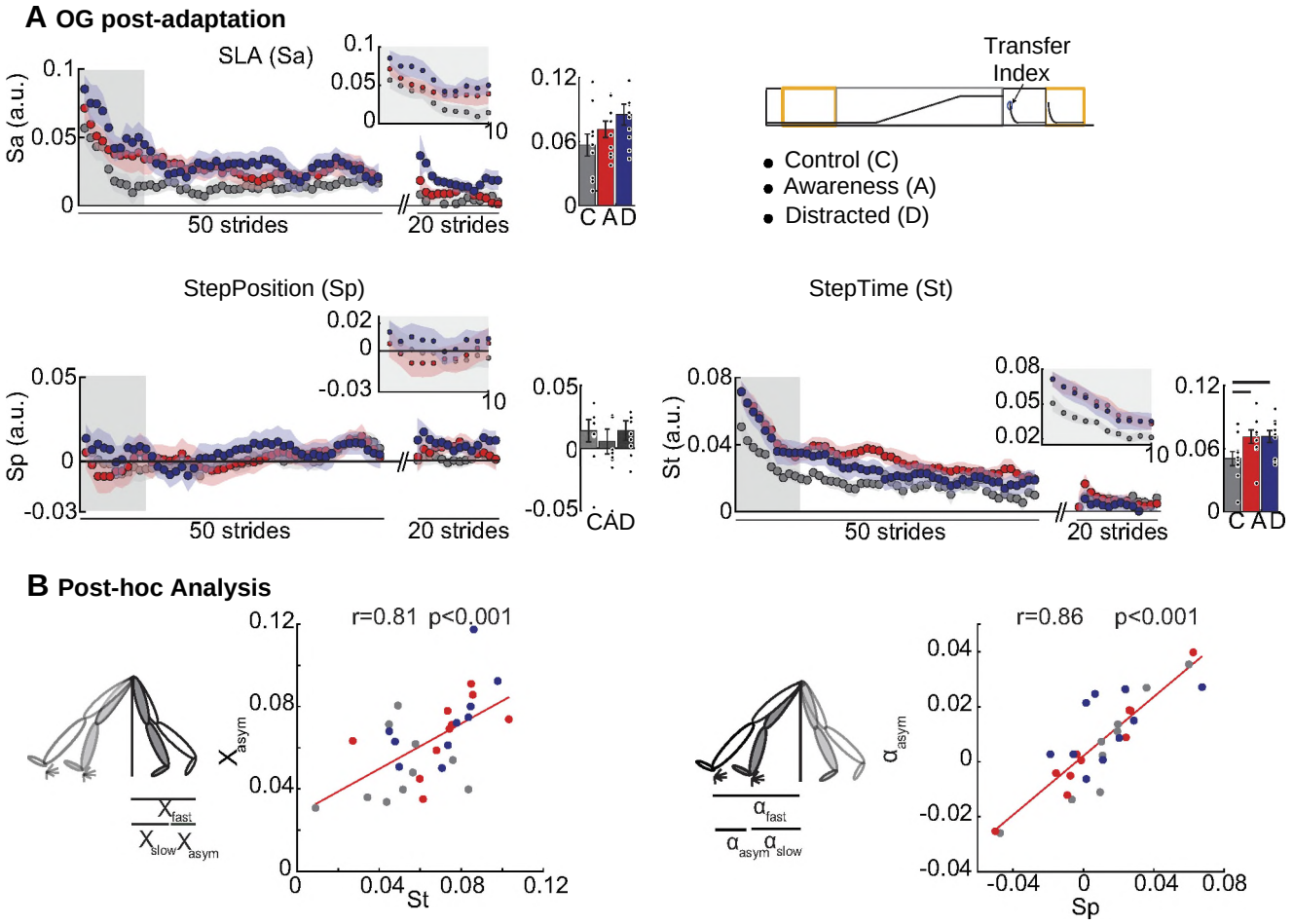

Fig. 3. *A*: stride-by-stride time courses and mean transfer values (i.e., overground aftereffects) are shown for all parameters (in arbitrary units, a.u.) during the postadaptation epoch overground. Gray shaded areas indicate the strides that are zoomed-in in the *insets*. Each dot represents the average of 5 consecutive strides, and colored shaded areas indicate the SE for each group. Bar plots indicate the mean transfer value for each group (^SE), black dots indicate individual subjectsô data, and black horizontal lines indicate significant statistical differences between groups. *B*: we found a correlation between step time aftereffects and asymmetries in the trailing, but not the leading, legôs position (*left*). The more step time aftereffects overground, the more asymmetric trailing positions. Step position aftereffects were associated with both the leading and the trailing (data not shown) legôs position (*right*). $\hat{}_{asym}$, asymmetries overground in the leading legsô positions when a step is taken with either foot, where $\hat{}_{fast}$ is the ankle marker position of the leading leg at fast heel strike and $\hat{}_{slow}$ is the ankle marker position of the slow leg when it is the leading leg. X_{asym}, asymmetries overground in the trailing legsô positions when a step is taken with either foot, where X_{fast} is the position of fast leg when it is the trailing leg at slow heel strike and X_{slow} is the position of slow leg when it is the trailing leg. OG, overground.

also been shown to slow down the adaptation and deadaptation rates when the split perturbation is introduced abruptly (Malone and Bastian 2010). We believe that these differences stem from the distinct adaptation schedules in our study compared with previous work. More explicitly, our participants experienced a gradual perturbation, whereas the referenced studies were done in response to abrupt perturbations. Recent work indicates that cognitive-driven strategies, such as re-aiming, contribute more to motor performance when abrupt perturbations are large compared with when they are small (Bond and Taylor 2015; Morehead et al. 2015). Perhaps we find that subjectsô performance to gradual perturbations is not susceptible to divided attention because motor adaptation in this case requires less cognitive-based strategies.

Reduced Attention to Split-Belt Walking Facilitates the Generalization of Motor Adaptation

We found that altering attention to split-belt walking facilitates the transfer of adapted step timing from the treadmill to overground, even when the visual distractor brings awareness to the external perturbation specific to the training context. Notably, the aftereffects of step timing adapted on the treadmill were larger not only in the distraction group but also in the awareness group, who received explicit information about the speed difference induced by the treadmill. Our findings are consistent with previous work showing that explicit knowledge about the perturbation during adaptation does not disrupt generalization patterns from one limb to another (Wang et al. 2011). It is also possible that the variable nature of the feedback influenced our results. Notably, the visual information given to subjects in the awareness group varied as they walked, which could have acted as a distractor. Thus the variable feedback possibly reduced subjectsô attention to their movements during the split-belt condition, and this reduction led to greater generalization as in the distraction group. Taken together, our results suggest that distracting subjects during locomotor adaptation leads to greater generalization of recalibrated movements beyond the training environment.

We believe distractors might result in more generalized motor memories for two potential reasons. First, distractors might alter what is learned. We hypothesize that divided

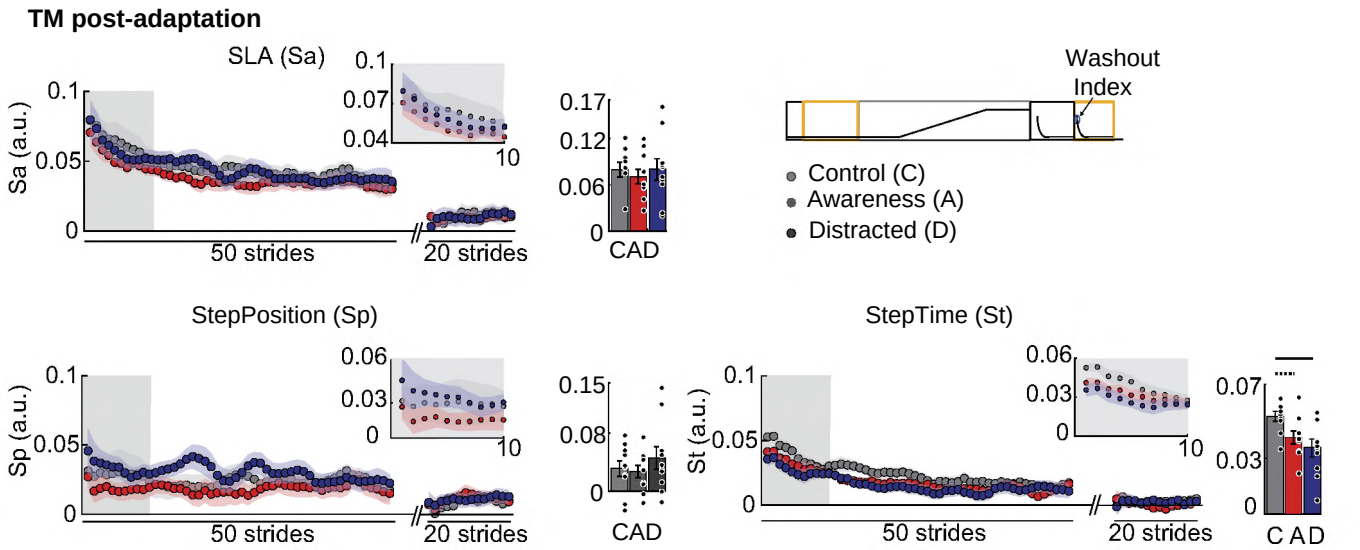

Fig. 4. *A*: stride-by-stride time courses and mean washout values (i.e., remaining treadmill aftereffects) are shown for all parameters (in arbitrary units, a.u.) during the postadaptation block on the treadmill. Each dot represents the average of 5 consecutive strides, and colored shaded areas indicate the SE for each group. Bar plots indicate the mean washout value for each group (^SE), black dots indicate individual subjectsô data, horizontal solid line indicates significant statistical differences between groups, and horizontal dotted line indicates a strong trend between the groupsô (P ^ 0.072) trials. TM, treadmill.

attention reduces the explicit component of motor adaptation, which is tied to the environment, relative to the implicit one, which is tied to subjectsô actions and can be applied to other contexts. Namely, explicit components of motor adaptation are developed based on cognitive constructs of the task. For example, one can learn to change the aiming direction to counteract the visual rotation and hit a target in visuomotor adaptation protocols (B®lard and Song 2013; Day et al. 2016; Krakauer 2009; Mazzoni and Krakauer 2006; Neville and Cressman 2018) and change the re-aiming angle as soon as subjects receive contextual cues that the perturbation has been removed (Mazzoni and Krakauer 2006). This explicit change is, therefore, tied to the environment in which subjects develop the cognitive construct of the perturbation. Conversely, implicit adaptation results from the mismatch between predicted and actual sensory consequences, despite use of explicit strategies to improve oneôs performance (Long et al. 2016; Mazzoni and Krakauer 2006; Neville and Cressman 2018). These implicit changes are, then, tied to subjectsô actions and therefore could be more likely carried over to situations in which the same task (e.g., walking) is being executed in distinct environments (e.g., treadmill vs. overground). It is known that divided attention, such as having a visual stimulus during walking (Herold et al. 2017), increases the cognitive load associated to locomotion (Holtzer et al. 2011; Mirelman et al. 2014). Thus we speculate that divided attention could alter the relative contribution of explicit and implicit components to counteract the split perturbation as shown by preliminary work in reaching (Abraham et al. 2019; Avraham et al. 2019). Future studies are however needed to test this possibility.

Second, altering attention could also lead to changes in credit assignment of errors during adaptation from the environment to oneself, which would also result in greater generalization of movements. Notably, individuals are more variable when they walk under divided attention conditions (Beauchet et al. 2005; Lin and Lin 2016). Changes in variability have been shown to alter credit assignment (Kelly and Sober 2014), which has an impact on the generalization of sensorimotor recalibration (Berniker and Kording 2008; Fercho and Baugh 2014). In sum, reducing attention to oneôs movements during adaptation increases the generalization of learned movement across contexts, possibly because divided attention might alter the encoding of adaptation tied to subjectsô actions, rather than explicit corrections associated with the training environment.

We also found that attention did not modulate the generalization of adapted step position. This observation is consistent with prior work showing that spatial and temporal aspects of gait generalize differently, and that the generalization of temporal gait features is easier to manipulate (Torres-Oviedo and Bastian 2010). This could be explained by the fact that during overground walking, subjects control their movements through feedback and feedforward processes, the latter of which rely on internal models (Wolpert et al. 1995). While adaptation aftereffects during the catch trial indicate that internal model predictions are updated for both spatial and temporal features of gait (Reisman et al. 2005), online feedback during overground walking can override these internal predictions. Namely, several studies have shown that visual feedback during walking strongly contributes to the control of the leading footôs location (Maeda et al. 2017; Marigold and Patla 2008; Matthis et al. 2017; Matthis and Fajen 2014), but not step timing. Consequently, we reasoned that spatial aftereffects overground, and not temporal ones, are immediately corrected through feedback processes. This is consistent with previous generalization studies in locomotion (Sombric et al. 2017; Torres-Oviedo and Bastian 2010). Thus we suggest that greater generalization of spatial features may be observed if online feedback is diminished in the untrained context (Gordon et al. 1995; Torres-Oviedo and Bastian 2010). However, future studies are needed to test this prediction.

Limitations

While we observed an effect on the generalization of recalibrated movements when subjects had altered attention to the split-belt condition, we acknowledge that our TV task is not a

conventional test to manipulate attention. We selected it for consistency with a prior study that successfully distracted subjects during split-belt walking (Malone and Bastian 2010). However, future work with formal cognitive tasks [such as California Verbal Learning Test, verbal paired associates test, and action (verbal) fluency] (Bolcekov§ et al. 2017; Hoche et al. 2018; Woods et al. 2005) are needed to identify specific neuropsychological processes influencing locomotor adaptation, particularly corticocerebellar and frontostriatal processes. We consider our results as a proof of principle that cognitive factors might be involved in the sensorimotor recalibration process induced by split-belt walking. Moreover, our study was focused on investigating the impact of awareness on motor behavior; however, it is possible that split-belt walking interfered with subjectsô ability to perform the TV task. In other words, we observed cognitive-motor interference in the motor domain, but it is possible that this interference is also appreciated in the cognitive domain (Beauchet et al. 2005; Lin and Lin 2016; Patel et al. 2014). Future studies are needed to determine the potential bidirectionality of cognitive-motor interference during locomotor adaptation.

Clinical Implications

Our results might have an impact on the rehabilitation of hemiparetic gait because error-augmentation protocols, such as the one presented here, can induce gait improvements in stroke survivors (Reisman et al. 2007; Savin et al. 2014) that persist with repeated exposure (Lewek et al. 2018; Reisman et al. 2013). However, if treadmills and robots are to be used for correcting patientsô movements, it is critical that the learned movements carry over to ñreal-lifeò situations beyond the training context. In this study, we show that altering attention to the perturbed environment during sensorimotor adaptation facilitates the generalization of adapted behavior to different environments. These findings are promising for two reasons. First, individuals with motor disorders are often trained by either bringing self-awareness to their motions and explicit instructions on how to move (Lewek et al. 2018). Our results suggest that this large awareness to the training condition will not limit the generalization of motor improvements. However, it remains an open question whether individuals would form more context-specific motor memories than our subjects if the feedback instructed them where or when to place their feet (French et al. 2018; Gonzalez-Rubio et al. 2019; Long et al. 2016). Second, our results suggest that sensorimotor adaptation protocols, such as split-belt walking, might lead to more general motor improvements if patients adapt their movements while their attention to the split-belt perturbation is reduced. Furthermore, we find that the overground aftereffects in step time are associated to changes in the asymmetry of the trailing legôs position when a step is being taken. This is relevant since poststroke individuals could primarily exhibit between-leg differences in where they place their leading leg (i.e., step position asymmetries) or between-leg differences in when they lift their foot to take a step (i.e., step time asymmetries) (Finley et al. 2015; de Kam et al. 2020). Our study suggests that altering attention can change the generalization of movements, correcting the latter one (i.e., step time asymmetries leading to between-leg differences in where subjects lift their foot). However, future work is needed to test this hypothesis.

In conclusion, our results suggest that increased cognitive load during rehabilitation therapies might lead to encoding more general motor memories, whereas errors specific to the training environment tied them to the training situation.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

D.M.M., P.A.I., and G.T.-O. conceived and designed research; D.M.M. and P.A.I. performed experiments; D.M.M. analyzed data; D.M.M., P.A.I., and G.T.-O. interpreted results of experiments; D.M.M. prepared figures; D.M.M., P.A.I., and G.T.-O. drafted manuscript; D.M.M., P.A.I., and G.T.-O. edited and revised manuscript; D.M.M., P.A.I., and G.T.-O. approved final version of manuscript.

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