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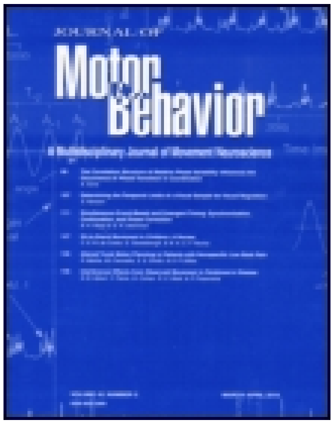

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RESEARCH ARTICLE

Effects of Gradual Versus Sudden Training on the Cognitive Demand Required While Learning a Novel Locomotor Task

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ABSTRACT. The cognitive demand required for a range of locomotor tasks has been described for a variety of populations. However, the effect of different training strategies on the cognitive demand required while learning novel locomotor tasks is not well understood and may inform physical rehabilitation. The authors examined whether two training strategies, gradual and sudden training, influenced the cognitive demand required while practicing a novel locomotor task, asymmetric split-belt treadmill walking. Simple reaction times and whole-body kinematics were recorded throughout practice. Gradual training resulted in significantly lower reaction times during much of training, suggesting that gradual training is less cognitively demanding than sudden training, possibly due to a reduction in error feedback or movement planning demands.

Keywords: cognitive demand, locomotion, rehabilitation, training, variability

Dual-task methodologies (Abernethy, 1988; Fraizer & Mitra, 2008) are frequently used to assess the cognitive demand required to perform locomotor tasks (Abernethy, Hanna, & Plooy, 2002; Brown, McKenzie, & Doan, 2005; Lajoie, Teasdale, Bard, & Fleury, 1993; Ojha, Kern, Lin, & Winstein, 2009), examine the effect of a secondary task on locomotor performance (Beauchet, Dubost, Gonthier, & Kressig, 2005; Ebersbach, Dimitrijevic, & Poewe, 1995; Grabiner & Troy, 2005; Weerdesteyn, Schillings, van Galen, & Duysens, 2003), and determine how the relationship between cognitive demand and physical performance is influenced by a variety of factors including age (Brown et al., 2005; Lajoie et al., 1996; Marsh & Geel, 2000) and physical impairment (Lamoth, Stins, Pont, Kerckhoff, & Beek, 2008; Parker, Osternig, Lee, Donkelaar, & Chou, 2005; Smulders, van Swigchem, de Swart, Geurts, & Weerdesteyn, 2012). In contrast, dual-task methodologies are rarely used to assess how the cognitive demand required while learning a novel motor skill is influenced by common practice conditions or training strategies (Lam, Maxwell, & Masters, 2010; Li & Wright, 2000; Wulf, McNevin, & Shea, 2001). While the efficacy of different practice conditions for learning motor skills has been well documented (Wulf, Shea, & Lewthwaite, 2010), the cognitive demand associated with their use remains largely unknown. This may be particularly relevant to the relearning of motor skills during physical rehabilitation. Specifically, the cognitive demand required by a training strategy may be among a host of factors that impact the response to that training strategy. This would in turn influence the feasibility of its implementation in promoting skill acquisition, retention, and transfer among individuals with cognitive impairments or when relearning a cognitively demanding skill such as walking.

Gradual training incrementally introduces task requirements over the course of a practice session. This results in the production of small movement errors that often go unnoticed by the learner and a reduction in practice difficulty (Criscimagna-Hemminger, Bastian, & Shadmehr, 2010). Historically it has been assumed that large movement errors and increased practice difficulty, characteristics of sudden training, facilitate motor learning (Christina & Bjork, 1991; Schmidt & Bjork, 1992; Wolpert & Ghahramani, 2000). However, gradual training has been shown to improve or preserve the adaptation to, and retention or generalization of, novel motor skills when compared to sudden training (Kagerer, Contreras-Vidal, & Stelmach, 1997; Klassen, Tong, & Flanagan, 2005; Kluzik, Diedrichsen, Shadmehr, & Bastian, 2008; Malfait & Ostry, 2004; Torres-Oviedo & Bastian, 2012). Several studies suggest that the efficacy of gradual training may be due to subthreshold increments that reduce awareness of the changes taking place and the contribution of conscious adjustments during training (Criscimagna-Hemminger et al., 2010; Hatada, Rossetti, & Miall, 2006). This lack of conscious adjustments may engage an implicit rather than explicit learning mechanism, resulting in reduced cognitive demand (Buch, Young, & Contreras-Vidal, 2003). Conversely, sudden training is thought to require explicit cognitive strategies to deal with the larger movement errors and increased practice difficulty, which may increase cognitive demands. However, the cognitive demand required while learning a motor skill using either gradual or sudden training is unknown. A better understanding of whether gradual versus sudden training influences the cognitive demand required while learning a novel locomotor skill may facilitate the selection of motor learning strategies during physical rehabilitation, and provide additional insight into whether gradual versus sudden training engages implicit rather than explicit learning mechanisms.

The objective of this study was to compare the cognitive demands associated with gradual versus sudden training in a novel locomotor task. Specifically, we were interested in the influence of training strategies on cognitive demand during training, not the influence of a cognitive task on motor performance (i.e., rate of adaptation, final level of adaptation). This

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was accomplished by examining probe reaction times (RTs) to a visual stimulus on a simple RT task, and whole-body sagittal plane kinematics while practicing a novel locomotor task, asymmetric split-belt treadmill walking (Dietz, Zijlstra, & Duysens, 1994). While previous work has examined the cognitive burden associated with performing this novel locomotor task (McFadyen, Hegeman, & Duysens, 2009), it remains unknown whether specific training conditions impact the degree of cognitive demand. Such information may assist in the selection of motor learning strategies during the physical rehabilitation of individuals with and without cognitive impairments. It was hypothesized that the cognitive demand required while learning the novel locomotor task would be reduced when using a gradual rather than a sudden training strategy.

Method

Recruitment

Twenty participants were recruited from a population of adults without impairment. Inclusion criteria were age between 18 and 50 years, the ability to walk continuously for 20 min on a treadmill without assistance, and no prior split-belt treadmill experience. Exclusion criteria were self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions. The University of Washington and VA Puget Sound Institutional Review Boards approved all protocols. Written informed consent was obtained prior to enrollment.

Experimental Protocols

Walking Task (Primary Task)

Participants walked on a Bertec split-belt treadmill (Bertec, Columbus, OH) under two conditions: 1:1 walking, where both legs are driven at the same velocity (0.7 m/s), and novel asymmetric split-belt walking where the dominant leg is driven at a velocity that is faster than that of the nondominant leg (Dietz et al., 1994). Half of the participants practiced the novel asymmetric walking task under sudden training conditions, while the other half received gradual training. For participants allocated to sudden training, asymmetric walking was introduced via a single abrupt change in belt velocity. The belt under the dominant leg was accelerated at 10.0 m/s^2 to reach a velocity two times that of the nondominant leg (0.7 vs. 1.4 m/s) between consecutive heel-strikes. The condition of 2:1 walking was maintained for the entire training period, 720 consecutive strides in the sudden cohort. The gradual training group was introduced to asymmetric walking by incrementally increasing the belt velocity under the dominant leg such that every 20 strides the dominant leg belt velocity was increased by 0.02 m/s using an acceleration of 0.001 m/s^2. This continued until the dominant leg belt velocity reached 1.4 m/s, a transition which took 700 strides (35 blocks of 20 strides), and full 2:1 walking was reached for the final twenty strides of gradual training, for a total of 720 strides. The magnitude of the velocity changes and the acceleration were chosen to minimize the detection of each incremental adjustment and represent the lower limits of treadmill control. All participants were given the same instructions to "maintain or restore a comfortable, rhythmic walking pattern." Participants were naïve to the novel locomotor task, asymmetric walking, as well as their allocation to gradual or sudden training. Because the asymmetric walking task had to remain novel during dual-task conditions to accurately assess the cognitive demands of each training approach, single-task asymmetric walking (i.e., asymmetric walking with no secondary cognitive task) was performed by a separate, comparable group ($n = 10$ per cohort) as part of a different study (Sawers & Hahn, in press). If the same subjects performed the asymmetric walking task on its own (single-task performance) and then again during dual-task performance it would no longer be considered novel and would thus alter the nature of the question being asked in the present experiment.

Cognitive Task (Secondary Task)

The cognitive task consisted of a simple RT task. This was selected over more demanding tests (i.e., choice RT task or Stroop test) to prevent the cognitive task from becoming so demanding as to induce attention switching. Simple RT tasks have also proven to be sufficiently sensitive to detect differences in the cognitive demand of simple and challenging motor tasks (Abernethy et al., 2002; Gage, Sleik, Polych, McKenzie, & Brown, 2003; Lajoie et al., 1996; Ojha et al., 2009). The simple RT task consisted of a series of visual cues (+) followed by stimuli (O) presented on the center of a 32-inch LCD screen 4 ft from the participants using SuperLab (version 4.5; Cedrus, San Pedro, CA). Participants were asked to respond as quickly as possible following stimulus onset by depressing a handheld trigger (Microsoft Corp., Redmond, WA). The visual cue and stimulus were selected to minimize perceptual content that could help anchor balance and attenuate any influence of the dual-task component (e.g., a vertical line as stimulus could offset challenge to balance control; Fraizer & Mitra, 2008).

To minimize stimulus predictability, anticipatory strategies, and the possibility that response measures were walking phase specific, the visual stimuli were presented in an unpredictable fashion at various points throughout the gait cycle (Hirschfeld & Forssberg, 1991). This was accomplished by randomly selecting time intervals between each visual cue and stimulus onset from a list of six possible times (500, 1500, 2000, 3500, 4500, and 5000 ms). The frequency of stimulus presentations was set to 12 stimuli per 20 strides as recommended by Salmoni, Sullivan, and Starkes (1976) and any responses less than 100 ms were rejected as anticipatory responses (Gage et al., 2003). In this study RT was defined as the time (ms) between onset of visual stimulus and onset of the motor response (Maki & McIlroy, 1996). Absolute RTs were selected over relative RTs because no difference was expected between groups in baseline RT values, and previous studies have successfully used absolute RTs to identify differences in cognitive demand across a variety of motor tasks (Abernethy et al., 2002; Gage et al., 2003; Lajoie et al., 1993, 1996; Ojha et al., 2009).

Dual-Task Conditions

Following 20 seated practice trials of the cognitive task to ensure familiarity with the RT procedure, baseline processing speed was assessed as the average of 20 seated trials on the simple RT task. These data were used to confirm equivalent processing speeds between groups to ensure fair comparisons during subsequent phases of the experiment. Following 15 min of single-task 1:1 walking to promote treadmill acclimation (Zeni & Higginson, 2010), and an additional 20 strides to characterize baseline 1:1 walking performance, participants continued 1:1 walking at 0.7 m/s for another 180 strides while performing the RT task in order to determine 1:1 walking RTs. Over the course of the 180 1:1 walking strides, 108 visual stimuli were presented. These data provided a record of the cognitive demand required for 1:1 walking prior to the introduction of asymmetric walking. Participants were then randomly allocated to either gradual or sudden training for 2:1 walking.

During dual-task asymmetric walking, the gradual and sudden groups were presented with the same number of stimuli and the same time intervals between the visual cue and the stimulus onset. This was done to ensure comparable presentation of stimuli. Over the duration of the training protocol (~720 strides), 432 visual stimuli were presented. Four hundred and twenty were presented over the first 700 strides and 12 over the last 20 strides (full 2:1 walking in both cohorts). In an effort to reduce interpretive difficulties that could arise due to attentional switching from the primary locomotor task to the secondary cognitive task, participants were instructed to maintain focus on and afford priority to the primary locomotor task (Siu, Chou, Mayr, van Donkelaar, & Woollacott, 2008). The likelihood of attentional switching with the introduction of the secondary cognitive task was further reduced by the substantial challenge of the primary locomotor task (Kelly, Janke, & Shumway-Cook, 2010).

Data Collection

Fifty-seven reflective markers were placed on participants' bony landmarks (Sawers & Hahn, 2012). Throughout all walking conditions, three-dimensional marker coordinate data were collected at 120 Hz using a 12-camera Vicon MX motion capture system (Vicon, Oxford, England) and synchronized with ground reaction force data collected from the treadmill force platforms at 1200 Hz and later down-sampled to match that of the marker coordinate data. Reaction times were recorded using SuperLab (version 4.5; Cedrus, San Pedro, CA). Demographics including age, height, mass, gender, self-selected walking speed (SSWS), and limb dominance, identified as the preferred kicking leg (Kramer & Balsor, 1990), were recorded.

Data Analysis

Following the principles of the dual-task paradigm as described by Kahneman (1973), performance on the cognitive task (absolute RTs), while performing either of the primary locomotor tasks (1:1 or asymmetric walking) were compared and any differences in RTs between the tasks were interpreted as a difference in the required cognitive demand (Kahneman, 1973). To examine whether gradual or sudden training influenced the cognitive demand required while learning asymmetric walking, the 420 RT responses during the first 700 strides of dual-task training were separated into four sequential and equal bins of 105 RTs (Q1, Q2, Q3, Q4). For each of the four dual-task RT bins, the mean RT for the gradual and sudden training groups were compared. The last 12 reaction times over the final 20 strides of training, where both cohorts were performing the identical locomotor task (2:1 walking), were also compared.

To determine whether any changes in walking occurred from single- to dual-task conditions, we compared the amount of variability in the whole-body sagittal plane kinematic movement pattern during single- and dual-task locomotor performance of asymmetric walking. The whole-body sagittal plane kinematic movement pattern was described by the sagittal inclination angle (SIA). The SIA is a measure of limb endpoint control relative to the whole body center of mass (COM), which can be defined as the angle formed by a vector from the COM to the lateral malleolus with respect to the vertical in the sagittal plane (Chen & Chou, 2010). It was chosen as the metric of locomotor performance on the basis of previous biomechanical (Griffin, Main, & Farley, 2004; McMahon & Cheng, 1990), neurophysiological (Bosco, Eian, & Poppele, 2005; Bosco, Poppele, & Eian, 2000; Bosco, Rankin, & Poppele, 1996), and behavioral (Chang, Auyang, Scholz, & Nichols, 2009; Lacquaniti, Le Taillanter, Lopiano, & Maioli, 1990) evidence for the importance of whole limb function to locomotion, specifically with respect to the whole body COM (Balasubramanian, Neptune, & Kautz, 2010; Redfern & Schumann, 1994). Additionally, asymmetric walking imposes task specific requirements on limb orientation (Reisman, Block, & Bastian, 2005) that necessitate changes in the SIA. Marker coordinate data were filtered with a dual-pass fourth-order Butterworth 5 Hz low-pass cutoff frequency and combined with participant-specific anthropometric data adapted from Dempster (Winter, 2009) to build a 15-segment whole-body model in Visual 3D (C-Motion, Germantown, MD; Sawers & Hahn, 2012). Whole-body COM position was calculated using the weighted sum approach.

Using custom MATLAB (The MathWorks, Natick, MA) code, discrete values for the SIA were calculated on a stride by stride basis at ipsilateral heel strike for the fast (dominant) and slow (nondominant) legs. To quantify the amount of variability in the sagittal plane movement pattern among the two different cohorts performing single- and dual-task 2:1 walking, the standard deviation of the SIA was calculated for every 20 strides during single- and dual-task asymmetric walking. During asymmetric walking this resulted in 36 values (i.e., from 720 strides). The standard deviation reflects the amount of variability in a movement pattern (Stergiou, 2004), which in turn reflects the challenge or difficulty of a locomotor task (Bauby & Kuo, 2000; Donelan, Shipman, Kram, & Kuo, 2004; Gates, Wilken, Scott, Sinitski, & Dingwell, 2012; Owings & Grabiner, 2004). The difference between each of the 36 standard deviation values and the variability (standard deviation) of the SIA during baseline 1:1 walking, similarly calculated over 20 strides, was then computed. The mean of these 36 residual values was then calculated to quantify the average variability in the whole-body sagittal plane kinematic movement pattern during training, the average uncertainty residual (AuR; Supplemental Material). The AuR was then compared between the single- and dual-task asymmetric walking conditions. A lack of significant difference was taken to indicate that the variability in the sagittal plane movement pattern was not different between single- and dual-task conditions, suggesting that no shift in attentional focus away from the primary locomotor task occurred under dual-task conditions, ensuring an accurate assessment of cognitive demand.

Statistical Analysis

To evaluate the effect of gradual versus sudden training on the cognitive demand required while practicing asymmetric walking, a two-factor split-plot (mixed) analysis of variance (ANOVA; $\alpha = .05$) was performed on the average reaction time data. Training was the between-subjects factor with two levels (gradual and sudden), and time was the within-subjects factor with six levels (1:1 baseline walking, training bins Q1, Q2, Q3, Q4, and the RTs over the final 20 strides of full 2:1 walking). Post hoc comparisons were adjusted using a Bonferroni correction. To ensure that cognitive performance was equivalent across the two training cohorts, seated reaction times were compared with an additional single sided *t* test ($\alpha = .05$).

To ensure that priority was afforded to the primary locomotor task of asymmetric walking during dual-task conditions, a MANOVA was used to compare motor performance between the single- and dual-task cohorts as assessed by the AuR of the SIA of the fast and slow legs. All statistical tests were conducted using SPSS (version 19).

Results

Demographics of the 20 participants who were recruited are presented in Table 1. Averaged locomotor and reaction time data from participants in the gradual and sudden training cohorts are provided in Figure 1.

Locomotor Performance

The AuR during dual-task 2:1 walking was found to be equivalent to that during single-task 2:1 walking for the fast and slow legs among both the gradual (fast leg, $p = .469$; slow leg, $p = .278$) and sudden (fast leg, $p < .355$; slow leg, $p = .307$) training groups (Figure 2).

Cognitive Performance

Box's M test and Levene's test of equality were not significant ($p = .340$ and $p > .10$) indicating that the reaction time data demonstrate homogeneity of covariance and variance for the between-subjects and the within-subjects analysis, respectively. Sphericity assumptions were not met for RT data (Mauchly's test of sphericity, $p < .05$); therefore, Greenhouse-Geisser corrections were applied. There was no significant difference in the average seated RT between the gradual and sudden training groups ($p = .435$; Table 1). The split-plot ANOVA revealed a significant between-subjects main effect for training ($p = .006$), a significant within-subjects main effect of time ($p < .01$), as well as a significant ordinal interaction between time and training ($p < .01$). Post hoc pairwise comparisons for time revealed significant differences in RT between baseline 1:1 walking and all other

TABLE 1. Participant Demographics and Probe Reaction Times

Cohort		Height (m)	Mass (kg)	Age (years)	Sex	SSWS (m/s)	Dominant leg	Seated RT	1:1 Walking RT	2:1 Walking RT
Gradual training	*M*	1.70	62.09	33.6	5M, 5F	1.56	9R, 1L	329	368	395
($n = 10$)	*SD*	0.10	9.11	8.03		0.11		23	20	25
	Range	1.60–1.85	54.25–89.61	24–50		1.23–1.67		296–359	338–405	368–452
Sudden training	*M*	1.72	69.45	31.4	6M, 4F	1.50	9R, 1L	332	372	459
($n = 10$)	*SD*	0.13	11.20	6.91		0.20		57	44	59
	Range	1.55–1.91	60.33–88.9	23–44		1.19–1.83		246–433	300–464	371–558

Note. SSWS = self-selected walking speed; RT = reaction time; M = male; F = female; R = right; L = left.

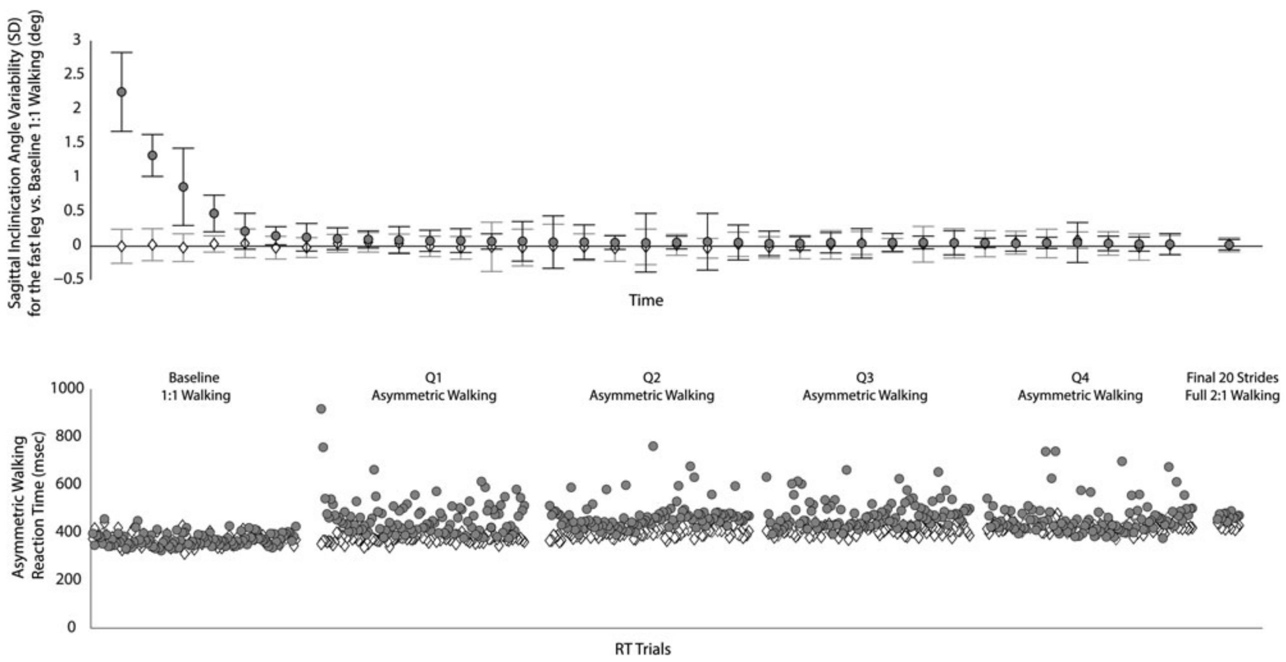

FIGURE 1. Locomotor (**A**) and reaction time (RT; **B**) data from the gradual (◇) and sudden (●) cohorts during asymmetric walking training. Variability values in A are with respect to baseline 1:1 walking variability. As a result, the timescales of A and B differ slightly. In A the data represent asymmetric walking and the final 20 strides at full 2:1 walking, while in B data from 1:1 baseline, asymmetric walking, and the final 20 strides at full 2:1 walking are provided. Each data point in A is the mean ± 1 *SD* of 20 strides.

time points ($p < .001$), between Q1 and Q3 ($p = .006$) and Q1 and Q4 ($p = .005$).

To examine the significant ordinal interaction term of time x training, simple effects were calculated to examine training differences within each level of time, and time differences with each level of training. Overall simple effects examining the effect of training within each time period revealed that there were significant differences in reaction time between gradual and sudden training during Q1 ($p < .001$), Q2 ($p = .002$), and Q3 ($p = .015$) of practice, as well as during the final 20 strides when both training cohorts were performing the same full 2:1 locomotor task ($p = .030$). Reaction times were not statistically different between gradual and sudden training during baseline 1:1 walking ($p = .796$), nor during Q4 ($p = .076$). Overall simple effects examining time within each training cohort revealed a significant overall effect ($p < .001$) of time for each training cohort. Pairwise comparisons revealed significant differences in reaction time within the gradual cohort between baseline 1:1 walking and Q3, Q4 and the last 20 strides of full 2:1 walking, as well as between Q1 and Q2, Q3 and Q4, and Q3 and the last 20 strides of full 2:1 walking. Within the sudden cohort, pairwise comparisons revealed significant differences between baseline 1:1 walking and all other time points ($p < .001$; Figure 3).

Discussion

This study sought to compare how gradual versus sudden training influences the cognitive demand required while learning a novel locomotor task. This was accomplished by examining RT values on a simple RT task and whole-body sagittal plane kinematics during single- and dual-task conditions. During both seated and 1:1 walking conditions, both training groups had similar average RTs (Table 1), indicating that the cognitive performance of the two groups was comparable at baseline. Furthermore, 2:1 walking performance, as assessed by the AuR of the fast and slow legs, was not significantly different between single- and dual-task conditions for either the gradual or sudden training groups. This indicates that the addition of the secondary cognitive task did not degrade locomotor performance and that attentional switching away from the primary locomotor task, asymmetric walking, did not occur, ensuring that the primary locomotor task was afforded priority. This was further corroborated by the observed increase in the average RT during asymmetric with respect to 1:1 walking for the gradual (27 ms) and sudden (89 ms) groups. Together these results suggest that the addition of the simple RT task did not affect locomotor performance and as such, any changes in RT reflect changes in the cognitive demand required by the primary motor task (Abernethy, 1988).

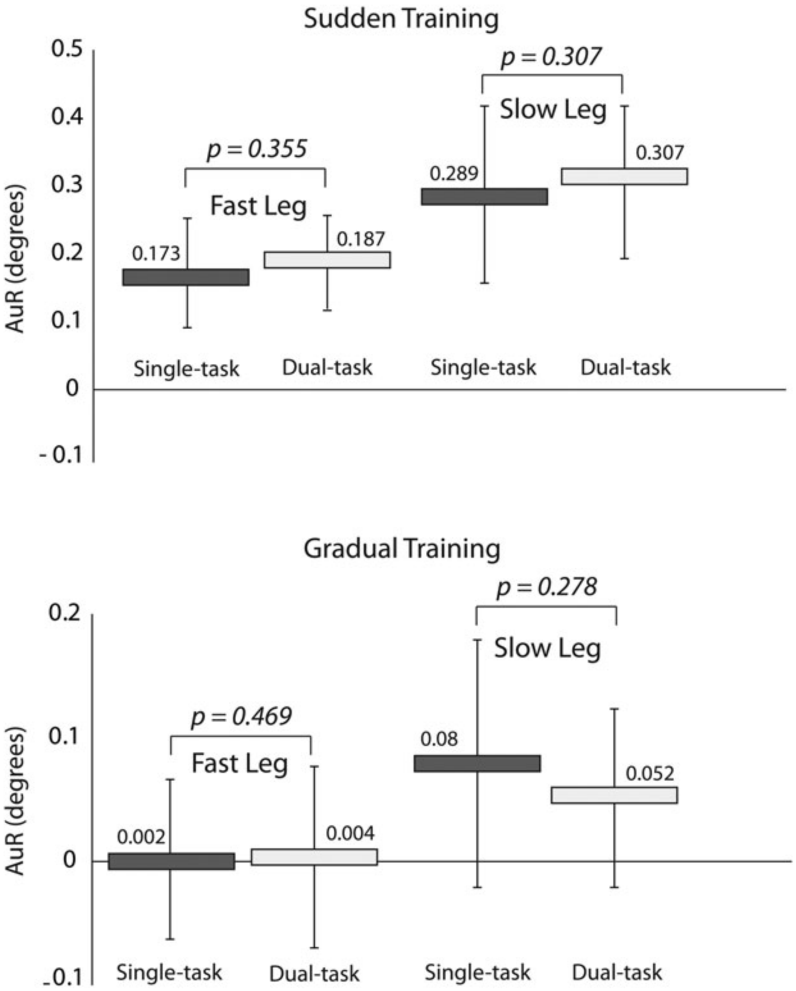

FIGURE 2. Average uncertainty residual (AuR) of the sagittal inclination angle for the fast and slow legs during gradual and sudden training under single- and dual-task conditions. Error bars equal ±1 *SD*. For both the gradual and sudden training cohorts, the AuR of the fast and slow legs were equivalent between single- and dual-task conditions ($p > .05$), indicating that there was no decrement in locomotor performance with the addition of the secondary cognitive task. Given the need to preserve the novelty of 2:1 walking, single-task walking was performed by a separate but equivalent sample of participants (Sawers & Hahn, in press).

During dual-task asymmetric walking, the RT was significantly greater among participants who received sudden (459 ms) rather than gradual (395 ms) training (Table 1). This suggests that ignoring all other variables (i.e., time), the cognitive demand required during practice was modulated by the training strategy; gradual training demanded less cognitive demand than sudden training. The difference in RT between the two training strategies, 64 ms, is greater than previously reported differences between level ground walking and ascending (43 ms) or descending (34 ms) stairs (Ojha et al., 2009) as well as crossing obstacles (∼ 40 ms; Brown et al., 2005) among young adults without impairment, suggesting a functional meaningful difference in cognitive demand. Further inspection revealed a significant main effect of time, indicating that cognitive demand increased over the course of training. As a function of time, cognitive demand was significantly greater during all four training quarters (Q1, Q2, Q3, Q4) compared to baseline 1:1 walking, as well as between Q1 and Q3, and Q1 and Q4 (Figure 3).

A significant ordinal interaction between time and training was observed, indicating that although RT and thus cognitive demand was affected by time, the manner in which it was affected by time was different for the gradual and sudden training cohorts. Interestingly, while the RT and thus cognitive demand associated with learning asymmetric walking increased over specific intervals during gradual training (Figure 3), cognitive demand during sudden training increased between baseline 1:1 walking and Q1, and then

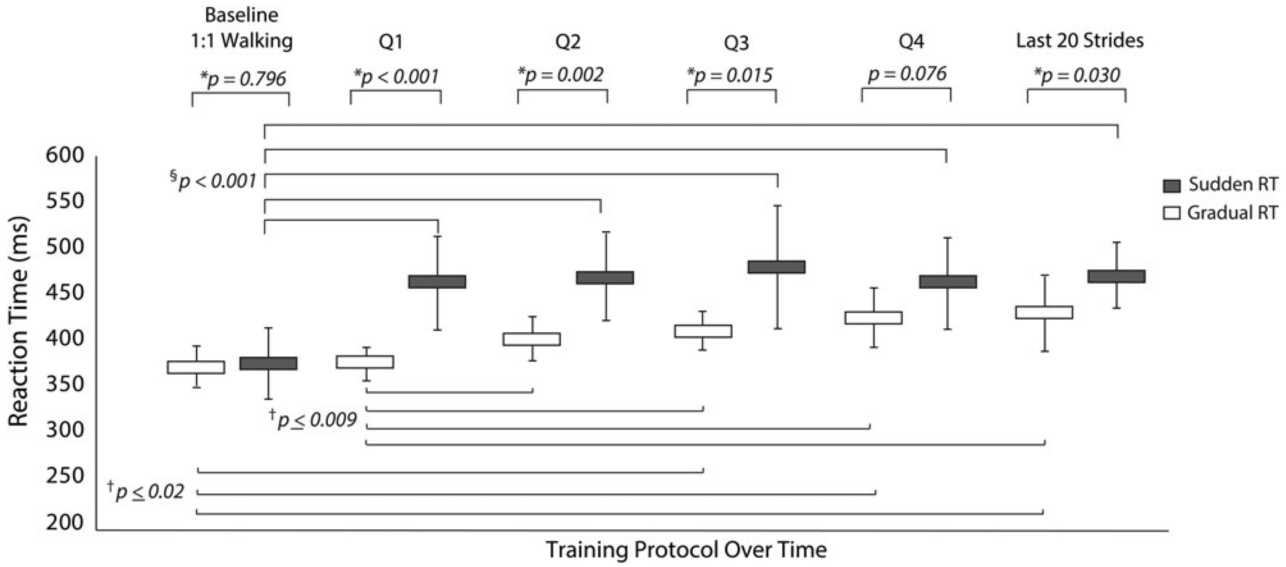

FIGURE 3. Reaction times (RT) during baseline 1:1 walking, dual-task asymmetric walking, and the final 20 strides of full 2:1 walking. Data points (white box = gradual training, gray box = sudden training). Error bars equal ±1 *SD*. Significant interaction effects of training within each level of time (*), significant interaction effect of time within sudden training (§), and significant interaction effect of time within gradual training (†).

remained elevated, failing to change or diminish over the course of training (Q1–Q4). Additionally, examining the effect of training within each level of time, the sudden cohort was found to require significantly greater cognitive demand compared to the gradual cohort during the training periods Q1, Q2, and Q3. Perhaps most importantly, this increase in cognitive demand for the sudden versus the gradually trained cohorts was also present over the last 20 strides of training, when they were both performing the same locomotor task, full 2:1 walking. This suggests that in addition to modulating the cognitive demand required during practice, gradual training reduced the cognitive demand required after practice. While RT was significantly different between the gradual and sudden cohorts during the final 20 strides when both groups were performing 2:1 walking, there was no significant difference during Q4. Examining figure 1 it appears that the RTs for the gradual subjects over the first half of Q4 are greater than during Q3 as well as the second half of Q4. This elevated RT at the start of Q4 may explain the lack of statistical difference during Q4. It may have been that over this time period (first half of Q4) was when the motor task was particularly challenging or when the difference in the belt speeds became most apparent to those participants that received gradual training. While it remains unknown whether similar differences in cognitive demand would be observed during subsequent performance of the novel locomotor task hours or days later, the lack of change in cognitive demand in the sudden cohort throughout practice, coupled with the reduction in cognitive demand after practice, when both cohorts were performing the same motor task, suggests that selection of the training strategy used during practice may play a role in determining the cognitive resources that are allocated to the performance of a motor skill beyond practice. A similar hypothesis has been tested for a novel balance task. Wulf et al. (2001) found that practicing a balance task using an external rather than internal focus reduced the cognitive demand during training as well as subsequent performance of the same task 24 hr later. These results lend support to the idea that the training strategy used during practice may influence more than just how well a motor skill is learned. Training strategies may modulate the cognitive demand required during practice as well as during subsequent performance, a potentially important consideration given the limited dual-task capabilities of many patient populations (Geurts, Mulder, Nienhuis, & Rijken, 1991; Kelly, Eusterbrock, & Shumway-Cook, 2012; Smulders et al., 2012).

A number of studies have suggested that the adaptation and learning that occur with gradual training may be due to a reduced awareness of ongoing changes which lead to a reduction in the contribution of cognitive strategies and thus the use of different learning mechanisms (Buch et al., 2003; Kluzik et al., 2008). Specifically, the transfer of reaching tasks between arms following sudden but not gradual training has been attributed to an increased cognitive effort due to the sudden introduction and related movement errors (Malfait & Ostry, 2004). In contrast, greater adaptation and within-limb transfer of the same reaching tasks following gradual training has been attributed to the minimization of explicit cognitive strategies (Buch et al., 2003; Kluzik et al., 2008). This suggests that sudden training requires explicit cognitive strategies to deal with the larger movement errors and increased practice difficulty, while gradual training engages implicit learning mechanisms, reducing cognitive demand (Buch et al., 2003). The results of this study support the idea proposed in previous work that gradual training may act to reduce cognitive demand required during practice to perform a novel motor task. This is particularly highlighted by the reduced cognitive demand over the last 20 strides where both the sudden and gradual cohorts were performing the same locomotor task. It remains unknown whether this observation indicates that gradual training drives motor learning through an implicit rather than explicit mechanism. However, considering the reduction in cognitive demand and the inability of many of the gradually trained participants to demonstrate an explicit understanding of the changes in treadmill conditions that occurred during practice, it would appear that gradual training might promote motor learning through implicit rather than explicit mechanisms.

The differences in cognitive demand between the two training strategies, specifically over the first three quarters of training (Q1–Q3), may be related to the idea that processing error feedback is more cognitively demanding than processing feedback indicating success (Koehn, Dickinson, & Goodman, 2008; Lam, Masters, & Maxwell, 2010). Greater movement errors and increased practice difficulty define sudden training (Torres-Oviedo & Bastian, 2012). Greater practice difficulty for the sudden training cohort was apparent from the increased variability observed in the sagittal plane movement pattern during training, particularly over the first half of training (Figure 1), when the difference in cognitive demand was also greatest between the two training strategies (Figure 3). Given the increase in practice difficulty, the sudden training group likely had to process more error feedback than the gradual training group, potentially contributing to the increased cognitive demand observed with sudden training. Additionally, greater cognitive demand is thought to be required during movement preparation versus execution (Ells, 1973; Fisher, 1997; Lam, Masters, & Maxwell, 2010). Considering the need of participants in the sudden training group to respond to the abrupt introduction of task demands, it would stand to reason that while both groups must execute stepping movements, the sudden training group may have required additional movement planning or preparation in order to adapt to the sudden changes in walking conditions, thereby necessitating an increase in cognitive demand to plan these adjustments. Future work is necessary to manipulate the magnitude and duration of movement errors and probe the resulting cognitive demand.

Learning or relearning motor skills with a cognitive component, such as walking (Woollacott & Shumway-Cook, 2002), may be limited when the cognitive demands associated with training are increased. A motor learning or relearning strategy that minimizes cognitive demands may be particularly advantageous during physical rehabilitation for individuals that experience challenges with cognitive demand or when the skill being practiced is particularly cognitively demanding. One specific example of this may be the use of powered exoskeletons (Herr, 2009) or prostheses (Herr & Grabowski, 2012). A unique feature of these devices is that the level of assistance that they provide must be turned on and restored at a specified rate. Based on the results of the current study, it is plausible that by gradually restoring powered function with these rehabilitation devices, the attentional demand required during training and subsequent use of the device may be reduced.

This study used a simple RT task to assess cognitive demand. Use of a more challenging cognitive task such as a choice RT task or a Stroop task may have provided a more sensitive measure, enabling a more precise assessment of cognitive demand (i.e., not just RT, but also correct or incorrect responses). The simple RT task made use of a visual stimulus and physical response. The presentation of a visual stimulus and the lack of optic flow while walking on a treadmill may have affected locomotor performance, while the use of a common mechanical effector to generate the RT response and the (i.e., arms are also used in locomotion) might have influenced the results. To minimize the effect of these limitations, all participants were given time to acclimate to the treadmill, the secondary cognitive task and dual-task conditions. In future work, the use of an auditory stimulus and verbal response along with the addition of virtual reality environment would further serve to address these issues. The delivery of the stimulus was not paired to specific gait events. Therefore it is possible that the stimulus may have been presented more frequently at certain points in the gait cycle for some participants than others. In future work the presentation of the stimulus should be linked to specific gait events to ensure consistency in the timing of stimulus presentation across participants. While debate exists regarding the number of strides required to capture the variability of a locomotor pattern (Owings & Grabiner, 2003), 20-stride increments were selected because that was the range over which the velocity of the fast treadmill belt was increased during gradual training. Extending the length of those increments would have increased the length of training, possibly inducing fatigue and confounding the results.

This study was limited to the examination of the cognitive demand required during training as a function of practice conditions, gradual versus sudden. Future researchers should employ dual-task approaches and conventional motor learning protocols to assess whether practice conditions such as gradual versus sudden training influence the cognitive demand required after practice, the automaticity of the acquired locomotor pattern and how this is linked to movement errors during practice. Additionally, future researchers should include the use of noninvasive imaging techniques such as functional near-infrared spectroscopy (Suzuki, Miyai, Ono, & Kubota, 2008) to confirm the results of traditional dual-task methodologies.

Conclusion

In the present study we found that the cognitive demand required during practice could be modulated by the selection of training strategies. Specifically, the use of gradual training reduced the cognitive demand required while learning a novel locomotor task when compared to sudden training. This difference in cognitive demand may have arisen due to an increase in error processing or movement planning during sudden training, thereby requiring the use of an explicit rather than implicit learning mechanism. Future work is required to examine the interaction between other motor learning strategies and the cognitive demand required during training, as well as the impact on subsequent motor performance among individuals with and without locomotor impairments.

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