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The Influence of Cognitive Load on Balance Control During Walking

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Abstract

The Influence of Cognitive Load on Balance Control During Walking

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Maintaining dynamic balance is essential during walking, with foot-placement playing a critical role. Situations requiring increased cognitive attention may impair an individual's ability to actively control their balance. While dual-task studies have analyzed walking-while-talking conditions, few studies have focused on how cognitive loads impact balance control during steady-state walking and more difficult motor tasks, such as walking with foot-placement perturbations. Individuals recover from a loss of balance using an ankle or hip strategy, but how cognitive loads effect these recovery strategies remains unknown. The overall goal of this research was to investigate the influence of cognitive loads on balance control using two aims. The first aim assessed how individuals prioritize cognitive resources and control balance during steady-state walking with increasing cognitive loads. Aim 2 investigated how individuals prioritize cognitive resources to control their balance during dual-task walking while experiencing foot-placement perturbations. Fifteen young healthy adults performed a cognitive single-task condition (spelling-while-standing) and four treadmill walking conditions (no cognitive load, attentive listening, spelling short words backwards and spelling long words backwards), each performed during steady-state (Aim 1) and perturbed conditions (Aim 2). No specific task-prioritization instructions were given. During the perturbed trials, medial and lateral foot-placement perturbations were applied before heel-strike during random steps. Aim 1 showed that cognitive performance did not change between single- and dual-task conditions, but balance control decreased during the spelling dual-tasks. Aim 2 found that cognitive performance decreased between unperturbed and perturbed conditions. While balance control decreased during perturbed relative to unperturbed walking, the additional cognitive load had little effect during the perturbations. Lastly, the balance recovery strategy was unaffected by the addition of a cognitive load. The results from Aim 1 highlight that in steady-state walking, balance control decreases during treadmill walking with increased cognitive loads, but cognitive performance does not change, suggesting that participants prioritized cognitive performance over balance control. In contrast to steady-state walking, Aim 2 found that individuals prioritize their balance over cognitive task performance when faced with foot-placement perturbations. Overall, these results emphasize the flexibility of task-prioritization in young adults and provide a foundation for future studies analyzing neurologically impaired populations.

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INTRODUCTION

Maintaining proper balance control during walking is essential to prevent falling, which requires cognitive resources to maintain. However, the addition of a cognitive load during gait may decrease the resources available and potentially impair the ability to control dynamic balance (Hollman et al., 2007). This competition for cognitive resources could put those with balance impairments at an even higher risk of falling (Sheridan and Hausdorff, 2007). The influence of cognitive loads on dynamic balance during gait can be evaluated using a dual-task (DT) paradigm, which requires participants to perform multiple tasks simultaneously, commonly pairing steady-state walking with an additional cognitive task (Ebersbach et al., 1995; Yogev-Seligmann et al., 2012). Automaticity indicates the ability to control movements without taxing cognitive resources. The trade-offs between automaticity and the cognitive control of walking have important consequences in impaired populations since reaching attentional demand limits during walking may lead to more falls and resulting injuries (Clark, 2015). Thus, there exists a need to investigate how DTs affect dynamic balance during gait.

Studies involving DT walking have become increasingly common to measure cognitive-motor interference and use a variety of cognitive tasks (Al-Yahya et al., 2011) such as counting backwards by *n* (Laessoe and Voigt, 2008), reciting alternating letters of the alphabet (Simoni et al., 2013), reading (Kimura and van Deursen, 2020), word fluency (Fallahtafti et al., 2020), spelling backwards (Hollman et al., 2010) and memorization (Armieri et al., 2009). DT paradigms have also been used as a probe to investigate the cognitive demands of gait in impaired populations such as the elderly (e.g., Bock, 2008; Krampe et al., 2011; Mersmann et al., 2013) and individuals post-stroke (e.g., Kemper et al., 2006; Plummer et al., 2020; Tisserand et al., 2018), and those with Parkinson's disease (e.g., Siragy and Nantel, 2020) or mild cognitive impairment (e.g., Montero-Odasso et al., 2012). Studies examining the effects of DTs on gait have shown that overground walking becomes slower, suggesting that walking is more demanding of cognitive resources than previously thought (Sheridan and Hausdorff, 2007; Simoni et al., 2013). Walking performance has not necessarily been shown to take priority over cognitive performance, as some have observed successfully executed cognitive tasks at the expense of poorer gait performance (Plummer-D'Amato et al., 2008; Yogev-Seligmann et al., 2012), while others have seen a prioritization of gait performance (Hinton et al., 2020; Mersmann et al., 2013).

The majority of DT studies have focused on gait speed as the primary outcome measure (Al-Yahya et al., 2011), with few studies focusing on balance control (e.g., Siragy and Nantel, 2020; Szturm et al., 2013; Tisserand et al., 2018). Whole-body angular momentum (*H*), which is a mechanics-based measure relating the linear and angular momenta of the body segments, must be tightly regulated in order to maintain dynamic balance during walking, and thus provides a useful measure of balance control that has been used to investigate a number populations and walking tasks (Neptune and Vistamehr, 2019). Higher ranges of whole-body angular momentum (H_R) correlate with lower clinical balance scores and consequently poorer balance control (Nott et al., 2014; Vistamehr et al., 2016). The frontal plane requires more active control than sagittal or transverse planes during walking (Bauby and Kuo, 2000). Thus, DT effects are often seen in the frontal plane, such as changes in step width (Fallahtafti et al., 2020), mediolateral (ML) margin of stability (Zhang et al., 2020) and ML trunk motion (Szturm et al., 2013). However, H has not been assessed in DT conditions, and it remains unclear how the addition of a cognitive load would affect frontal plane H.

The purpose of this study was to assess how healthy individuals prioritize their cognitive resources and control dynamic balance during DT walking with increasing cognitive loads. We hypothesize that as the cognitive load increases from attentive listening to spelling short and long words backwards, H_R will increase, indicating the control of dynamic balance has decreased. We further hypothesize that cognitive performance will not change between the single- and dual-tasks, suggesting a prioritization of cognitive performance over balance control. Understanding how young healthy individuals prioritize cognitive resources and control dynamic balance during DT walking will provide a benchmark for assessing potential deficits in neurologically impaired populations.

METHODS

Human Subject Protocol

Fifteen young healthy adults (Table 1) were recruited from the local community. All subjects provided written informed consent to participate in this protocol approved by the University of Texas at Austin Institutional Review Board. All participants were free from any musculoskeletal or neuromuscular injuries. To determine their self-selected (SS) walking speed, three trials of 10-meter overground walking at a "comfortable, typical walking speed" were averaged. Data collection trials consisted of 30 seconds of steady-state treadmill walking performed at a fixed speed of 1.0 m/s and their SS walking speed. Three-dimensional (3D) full-body kinematic data were collected at 120 Hz using 65 reflective markers with a 10-camera motion capture system (Vicon, Oxford, UK). Three-dimensional ground reaction force (GRF) data were collected at 960 Hz from a split-belt instrumented treadmill (Motek, Amsterdam, Netherlands).

Table 1: Average demographic data of participants (mean ± 1 standard deviation).

Age (years)	25 ± 4
Gender (male/female)	6 male/9 female
Height (cm)	175 ± 11
Weight (kg)	67 ± 11
Self-selected walking speed (m/s)	1.3 ± 0.1

Participants first performed a cognitive ST control (spelling-while-standing) and then walked on the treadmill with four varying cognitive loads: a ST no load walking condition and three DT walking conditions (attentive listening, spelling short 5-letter words backwards and spelling long 10-letter words backwards) at each speed for a total of eight walking trials (4 tasks, 2 speeds). Spelling responses were recorded through a microphone. Walking conditions, speeds and the order the words were presented were randomized.

Cognitive Loads

Participants wore noise-cancelling headphones for all trials to prevent distractions. For the attentive listening condition, participants were instructed to listen carefully to the story they heard through the headphones. No other task-prioritization instructions were given in order to observe what strategy the participants would select.

During the spelling conditions, participants were instructed to spell each word backwards as quickly and accurately as possible. Thirty 5-letter and thirty 10-letter common words were selected from the English dictionary (Appendix A), and each spelling trial consisted of only short or long words as the cognitive load. Participants heard each pre-recorded word through the headphones with the next word playing immediately after they spelled the previous word, completing as many words as possible until the trial ended.

Data Analysis

Marker and force plate data were low-pass filtered at 6 Hz and 15 Hz, respectively, using a fourth-order Butterworth filter. A 13-segment inverse dynamics model was created for each subject using Visual 3D (C-Motion, Germantown, MD). Dynamic balance was quantified by analyzing 3D *H*, which was calculated by summing the angular momentum of each body segment about the whole-body center of mass (CoM) as follows:

$$\vec{H} = \sum_{i=1}^{n}[(\vec{r}_i^{COM} - \vec{r}_{body}^{COM}) \times m_i(\vec{v}_i^{COM} - \vec{v}_{body}^{COM}) + I_i\vec{\omega_i}] \tag{1}$$

where $\vec{r}_i^{COM}$, $\vec{v}_i^{COM}$ are the position and velocity vectors of the i^{th} segment's CoM, respectively. $\vec{r}_{body}^{COM}$ and $\vec{v}_{body}^{COM}$ are the position and velocity vectors of the whole-body CoM, m_i, I_i and $\vec{\omega_i}$ are the mass, moment of inertia and angular velocity vector of the i^{th} segment, respectively, and *n* is the number of body segments. *H* was normalized by subject mass, height and walking speed. H_R was defined as the difference between the peaks of *H* over the gait cycle. Steps where the participant's foot landed on the opposite force plate were identified and removed from the kinetic analyses.

Step width was defined as the ML distance between the left and right heel markers at consecutive heel-strikes. Step length was the anterior/posterior (AP) distance between the left and right heel markers at consecutive heel-strikes plus the distance the treadmill moved during that time. Stance time was defined as the time between heel-strike and toe-off of one leg while swing time was the time between toe-off and the next heel-strike. Double support time was the time between one foot's heel-strike and the other foot's toe-off. GRFs were normalized by body weight.

Recorded audio was examined to determine percent spelling error (number of incorrect letters divided by total letters) and correct response rate (correct letters per second).

Statistics

Multiple repeated measures analyses of variance (ANOVA) were used to assess differences in the balance outcome measures (H_R, step width, step length, stance time, swing time, double support time, peak 3D GRFs) between the ST and three DTs across the two speeds (4 conditions x 2 speeds). A two-way repeated measures ANOVA was used to assess differences in the cognitive performance by comparing the correct response rates of the two spelling tasks (short versus long words) and the three condition levels (standing versus 1 m/s walking versus SS walking) (2 tasks x 3 levels). If the ANOVA revealed significant effects, Tukey HSD post-hoc tests were performed to identify pairwise differences between the DTs. The significance level was set at $p < 0.05$. All statistical analyses were performed using the statistical toolbox in MATLAB (Mathworks, Natick, MA).

RESULTS

Balance Control

Frontal plane H_R increased between the no load and short word spelling ($p < 0.001$) and between the no load and long word spelling conditions ($p < 0.001$) at both speeds (Fig. 1), indicating a decrease in balance control during the spelling DT. H_R did not change between the no load and listening conditions at both 1 m/s ($p = 0.065$) and SS ($p = 0.121$) speeds. There were no differences in sagittal and transverse plane H_R between the ST and DT conditions.

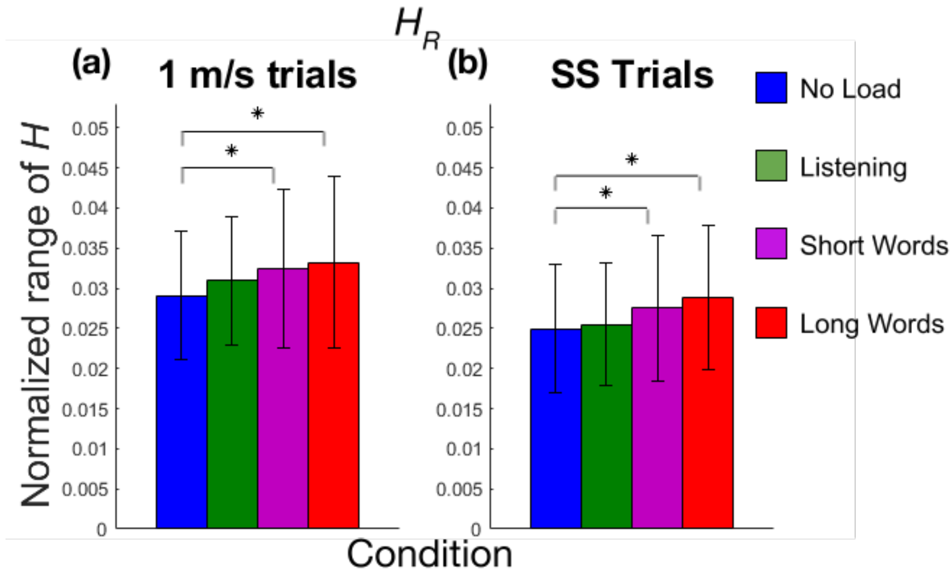


Figure 1: Peak-to-peak differences in whole-body angular momentum (H_R, normalized by height, mass and speed of each individual) in the frontal plane for the no load and the three dual-task conditions at the 1 m/s speed (a) and the self-selected (SS) speed (b). * indicates a significant difference between the two conditions ($p < 0.05$). Error bars represent ± 1 standard deviation.

Spatiotemporal Measures

Step width increased from the no load walking to DT spelling ($p < 0.001$). No differences were found between the no load and listening conditions ($p = 0.990$). At both speeds, step width increased from the no load to short word conditions ($p < 0.001$) and from the no load to long word conditions ($p < 0.001$). At the 1 m/s speed, step width was wider in the short word DT than in the long word DT ($p < 0.001$) (Fig. 2a). This difference was not seen in the SS conditions ($p = 0.290$) (Fig. 2b).

Step length did not change between conditions at the SS speed ($p = 0.062$). At 1 m/s, step length decreased between the listening and short word conditions ($p = 0.013$) and between the listening and long word conditions ($p = 0.002$).

Stance time decreased with cognitive load only at 1 m/s. The long word condition had shorter stance time than the no load ($p = 0.014$). Swing time also only changed at 1 m/s, slightly decreasing between the no load walking and long word DT ($p = 0.032$).

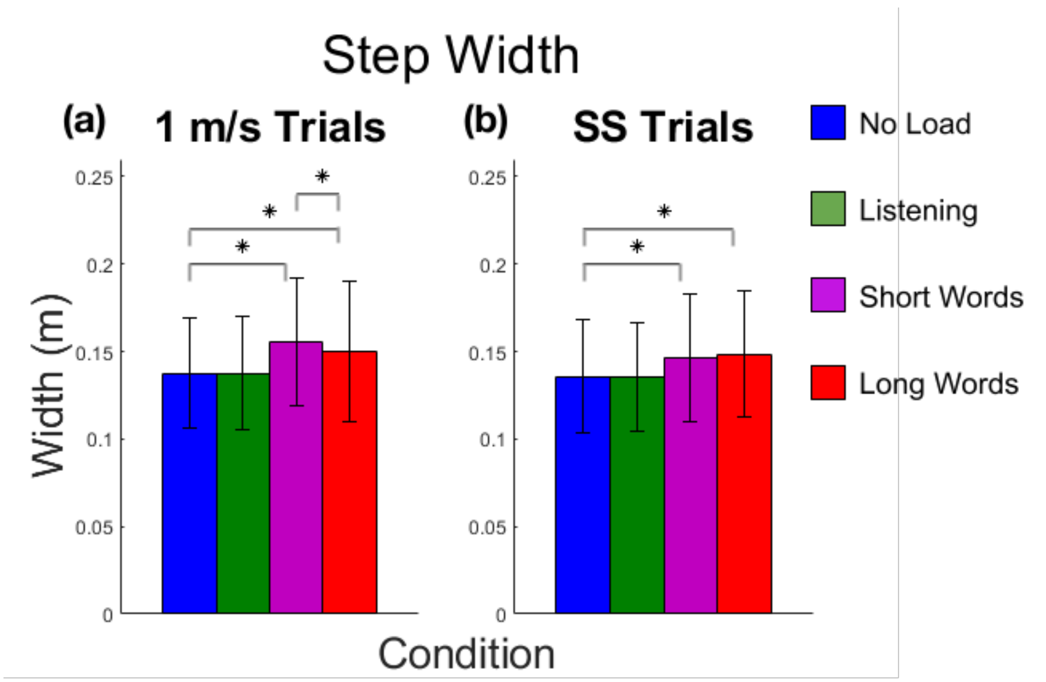
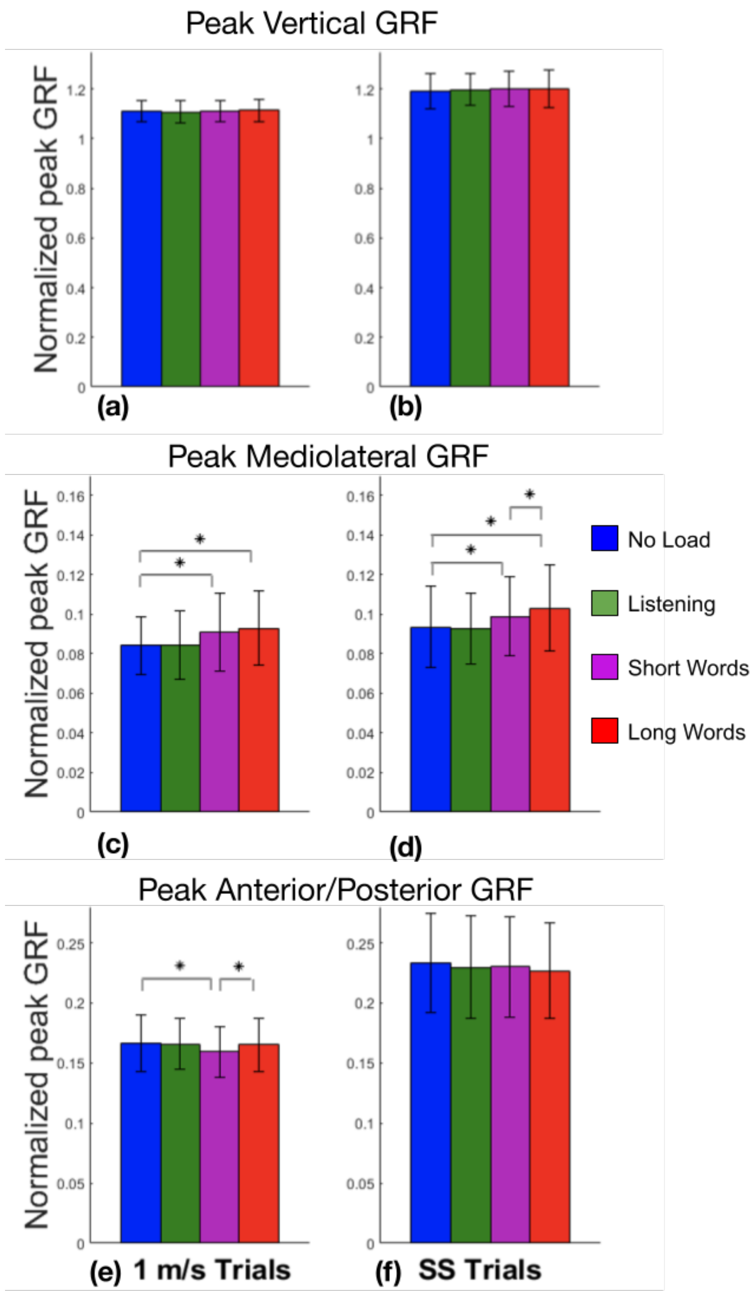


Figure 2: Average step width (m) for the no load and the three dual-task conditions for the 1 m/s speed (a) and the self-selected (SS) speed (b). * indicates a significant difference between the two conditions ($p < 0.05$). Error bars represent ± 1 standard deviation.

GRF Measures

There were no differences in the vertical peak GRFs in the 1 m/s ($p = 0.097$) or SS speed trials ($p = 0.121$) (Figs. 3a & b). ML peak GRFs increased between the no load and short word conditions ($p < 0.001$) and between the no load and long word conditions ($p < 0.001$) at both speeds (Fig. 3c & d). At the SS speed, peak ML GRFs also increased between the short and long word spelling conditions ($p < 0.001$) but did not change at 1 m/s ($p = 0.537$). Finally, the AP GRFs remained the same at the SS speed ($p = 0.094$) (Fig. 3f), but at 1 m/s, the short word conditions had a lower peak GRF than the no load ($p < 0.001$) and long word ($p = 0.005$) conditions (Fig. 3e).



Peak Vertical GRF
Normalized peak GRF
(a)
(b)
Peak Mediolateral GRF
Normalized peak GRF
(c)
(d)
No Load
Listening
Short Words
Long Words
Peak Anterior/Posterior GRF
Normalized peak GRF
(e) 1 m/s Trials
(f) SS Trials

Figure 3: Peak 3-dimensional ground reaction forces (GRFs) in the mediolateral direction (a and b), anterior/posterior direction (c and d), and vertical direction (e and f) normalized by body weight. a, c and e are at 1 m/s and b, d and f are at the self-selected speed. * indicates a significant difference between the two conditions ($p < 0.05$). Error bars represent ± 1 standard deviation.

Cognitive Performance

Spelling performance did not change between the ST and two spelling DTs as measured by the number of errors and response rate ($p = 0.300$) (Table 2). On average the response rate decreased by 59% ($p < 0.001$), and percent error increased from 2% to 10% between the short and long word tasks across the three conditions ($p < 0.001$).

Table 2: The cognitive results (mean ± 1 standard deviation) for the short 5-letter word and long 10-letter word backwards spelling conditions during the single-task, the 1 m/s speed dual-task and the self-selected (SS) speed dual-task. % error is the number of incorrect letters/total possible letters as a measure of accuracy. Correct response rate is the number of correct letters per second as a measure of response time. Bold indicates significant difference from the associated long word trial ($p < 0.05$).

	Single-Task		**1.0 m/s Dual-Task**		**SS Dual-Task**	
	Short	**Long**	**Short**	**Long**	**Short**	**Long**
% Error	**1 ± 3**	11 ± 10	**2 ± 4**	8 ± 11	**2 ± 5**	11 ± 11
Correct response rate (letters/s)	**1.9 ± 0.5**	1.0 ± 0.5	**1.9 ± 0.5**	1.0 ± 0.4	**1.9 ± 0.6**	1.1 ± 0.4
Number of words per trial	2.9 ± 0.3	2.9 ± 0.3	**3.9 ± 1.0**	2.2 ± 0.6	**4.9 ± 1.0**	2.5 ± 0.5

DISCUSSION

This study assessed how young healthy individuals prioritize their cognitive resources and control dynamic balance during DT walking with varying levels of cognitive demand. Our first hypothesis that as the DT load increased, the control of dynamic balance would become worse was supported by our finding that H_R increased in the frontal plane from the no load walking to the spelling DT. Furthermore, our second hypothesis that participants would prioritize cognitive performance over balance control was supported by the cognitive performance not changing between the ST and DT, suggesting that participants prioritized cognitive performance over balance control during steady-state treadmill walking.

Spelling words backwards is a cognitive task with real-world applications to conversation as it involves listening, processing information and then verbalizing an answer (Hollman et al., 2010). These steps involve attention and working memory, which are also executive functions required during walking (Bonetti et al., 2019). Reciting information backwards is a harder cognitive task than reciting information forwards, which requires increased working memory (Tamura et al., 2003) and leaves fewer cognitive resources for controlling gait. Individuals also have less experience performing a backwards spelling task, which is more novel and challenging (McIsaac et al., 2015). In contrast to spelling, attentive listening is a low novelty and low complexity task, and thus should produce little DT interference (Strayer and Johnston, 2001). Spelling short 5-letter words backwards is a high novelty but low complexity task, while spelling longer 10-letter words backwards is a high novelty and high complexity task. These differences in spelling tasks provided a range of DT interference to assess their influence on balance control.

Balance Control

Frontal plane balance control decreased as the cognitive load became more difficult (Fig. 1), presumably due to competition for attentional resources with the increased cognitive demands. There were changes in balance control between the spelling and no load conditions, but H_R did not differ between the listening and no load conditions. These results were consistent with others who found little to no change in motor performance when passive listening was added due to the ease of the secondary task in young healthy adults (Bruce et al., 2019; Strayer and Johnston, 2001). While not statistically significant, there was a trend of frontal plane H_R increasing between the short and long word conditions (Fig. 1). H_R did not change in the sagittal or transverse planes, which is consistent with previous work suggesting that the frontal plane requires more active control (Bauby and Kuo, 2000). These results are consistent with previous DT studies that used other measures of balance, such as coefficient of variation of step length, time and width (Siragy and Nantel, 2020) and ML CoM displacement (Kimura and van Deursen, 2020). These results add to these studies that challenging DTs reduce an individual's ability to control their dynamic balance during walking.

Cognitive Performance

There were no changes in spelling responses between ST and DT in either the percent error or the response rate measures (Table 2). These results are consistent with studies that saw no change in cognitive performance during DTs on a treadmill (Paran et al., 2020; Simoni et al., 2013). However, some studies observed changes in cognitive performance during DTs (Li et al., 2014; Plummer-D'Amato et al., 2008; Tisserand et al., 2018). For example, the cognitive accuracy in counting backwards by *n* and reciting alternating letters of the alphabet can diminish in older adults during overground DTs (Li et al., 2014), and individuals post-stroke have worsened speech production during overground walking (Plummer-D'Amato et al., 2008; Tisserand et al., 2018). The discrepancies in cognitive performance and prioritization throughout these studies suggest that the type of DT and the constraint of a treadmill may affect cognitive performance. Furthermore, impaired populations, such as individuals post-stroke, may have attention deficits that diminish the cognitive resources observed in young healthy adults (Spaccavento et al., 2019).

Task-Prioritization

During the two spelling conditions, participants prioritized cognitive performance over balance control. Other studies have produced conflicting results as to whether individuals prioritize their walking or cognitive performance. For example, young healthy adults prioritized walking over cognitive performance when adapting to split-belt treadmill walking when the belts move at different speeds (Hinton et al., 2020) and during perturbed walking (Mersmann et al., 2013). However, both of these studies involve motor tasks that are more complex than steady-state walking. One study found that young healthy adults were able to maintain both cognitive and motor performance during DT perturbed walking (Paran et al., 2020). While this study increased the difficulty of the motor task by increasing the surface perturbation magnitude, our study kept the motor task the same while increasing the difficulty of the cognitive load. Paran et al. (2020) found that young healthy adults have enough cognitive reserves to recover from perturbed walking and count backwards by 7. Spelling backwards appears to be a challenging enough task to cause a decrease in the motor performance, where counting backwards or attentive listening did not. Newer research suggests that the focus on maintaining posture is adjusted based on the difficulty of the cognitive or motor task, highlighting the flexible nature of prioritizing different attentional resources (Yogev-Seligmann et al., 2012). In the present study, the automaticity of steady-state treadmill walking (Clark, 2015) and the high level of difficulty of the cognitive task appeared to have caused the participants to place a higher priority on the cognitive task. This allocation of attention resulted in poorer balance control during steady-state walking.

The lack of performance decline in the listening condition suggests that the interference from the spelling tasks is more likely from the processing and verbalizing of the information instead of listening to the auditory cue. However, the interaction of the processing and verbalizing components of spelling in DTs remains unclear. There is evidence that both verbalization and information processing can cause DT interference (Armieri et al., 2009; Dault et al., 2003). Thus, the inability to fully separate these components is a limitation of our study. However, because the long word task was significantly more challenging than the short word task, participants likely spent a larger percentage of time processing the information in the long word task, while they spent relatively more time verbalizing the answers by completing more words per trials in the short word task (Table 2).

The increase in the ML GRF peaks and changes in step width during the spelling conditions together lead to the observed changes in H_R, as ML GRFs and foot-placement directly influence H_R through their contributions to the external moment (e.g., Silverman and Neptune, 2011). Furthermore, we observed greater differences in spatiotemporal metrics at the 1 m/s than at the SS speed (Appendix B). The differences between speeds might be because walking on a treadmill at one's SS speed is more automatic, while walking at a slower than one's SS speed requires more active control (Jordan et al., 2007; Szturm et al., 2013) and is more likely to be affected by cognitive interference.

Limitations

One potential limitation of this study was the constraints placed upon the spatiotemporal measures by the treadmill since participants could not alter their walking speed in response to the DT. However, the use of steady-state treadmill walking allowed for the collection of a greater number of consecutive steps in each condition, providing a more accurate assessment of our primary measure of balance control (H_R). Another limitation was the potential confounding influence of spelling verbalization on walking performance, such as its impact on gait rhythm (Dault et al., 2003; Plummer-D'Amato et al., 2008). Future work should focus on separating verbalization and word processing in a spelling task to determine the effects of each component on the DT. Furthermore, due to the method in which the spelling words were presented to the participants, we were not able to measure initial response time to the words. Future studies should look into the initial response time to learn about initiation of cognitive responses during DTs. Finally, the cognitive results may have been influenced by a learning effect from repeating the spelling backwards tasks. However, a post-hoc linear regression model applied to the data showed that no participants demonstrated any learning effect (average *R-squared* = 0.130, average *p*-value = 0.366).

CONCLUSION

In conclusion, our results suggest that during DT walking, frontal plane balance becomes worse as cognitive load increases in young healthy adults. However, there appears to be a cognitive load threshold that is exceeded before balance control is adversely affected. Furthermore, the participants' cognitive performance did not change between the ST and DT, suggesting that young healthy adults may prioritize these cognitive tasks over balance control during steady-state treadmill walking. These results provide additional insight into the automaticity of walking and task-prioritization in healthy young adults, which provides the basis for future studies to determine differences in aging and neurologically impaired populations.

Chapter 2: The Effect of Cognitive Load on Balance Recovery Strategies Used During Walking

INTRODUCTION

Maintaining dynamic balance during walking is critical to prevent falling and becomes more challenging when performing an additional cognitive task (Hollman et al., 2007). Dual-task (DT) studies, which require participants to perform multiple tasks simultaneously, often combine steady-state walking with an additional cognitive task (e.g., Ebersbach et al., 1995; Yogev-Seligmann et al., 2012). Some studies extend this paradigm to more challenging motor tasks, such as split belt gait adaptation (e.g., Hinton et al., 2020), obstacle avoidance (e.g., Yamada et al., 2011), perturbed standing (e.g., Brown et al., 1999) and perturbed walking (e.g., Mersmann et al., 2013; Nnodim et al., 2016). Foot-placement plays a critical role in balance control (Roelker et al., 2019). However, few studies have examined foot-placement perturbations in the context of a DT. Some DT studies found that individuals prioritize the cognitive task performance at the expense of their balance control (Plummer-D'Amato et al., 2008; Small et al., 2021; Yogev-Seligmann et al., 2012). However, other work found that individuals prioritize their balance control at the expense of cognitive performance (Tisserand et al., 2018), or have enough cognitive resources to maintain both balance and cognitive performance (Paran et al., 2020). The differences in results from these studies highlight that DT performance is highly dependent on the difficulty of the cognitive or motor task and available resources (Yogev-Seligmann et al., 2012). However, it remains unclear how cognitive performance and balance control are prioritized when confronted with a more challenging motor task such as walking with foot-placement perturbations. Understanding how young healthy adults prioritize cognitive resources when faced with challenging cognitive and motor tasks provides a benchmark for future studies in populations with cognitive and neuromotor impairments.

Maintaining frontal plane balance requires more active control than in the transverse or sagittal planes (Bauby and Kuo, 2000), and DT effects are most often seen in the frontal plane (Fallahtafti et al., 2020; Small et al., 2021; Szturm et al., 2013; Zhang et al., 2020). Thus, frontal plane balance could be affected by an additional cognitive load while experiencing a mediolateral (ML) foot-placement perturbation. Healthy adults can compensate for a loss of balance due to unexpected changes in ML foot-placement with a multitude of strategies (Brough et al., 2021; Hof et al., 2010). For example, a lateral ankle strategy uses produces an inversion moment that quickly moves the center of pressure to the outer limit of the foot to compensate for ML perturbations, but is constrained by the surface area of the foot. A hip strategy uses a hip abduction moments to assist in maintaining balance by counteracting the gravitational moment (Hof et al., 2010; Reimann et al., 2018). Any larger adjustments needed can only occur on subsequent steps (Hof et al., 2010). Previous studies analyzing DTs with perturbations have largely focused on quiet standing (Brauer et al., 2002; Brown et al., 1999; Laessoe and Voigt, 2008; Patel and Bhatt, 2015; Quant et al., 2004), and the few that have studied walking include either walking over a soft surface (Bohm et al., 2012; Mersmann et al., 2013) or walking with translating surfaces (Paran et al., 2020). Further, no study has analyzed the influence of a cognitive load on balance control in response to ML foot-placement perturbations, which would provide more insight into the task-prioritization involved in maintaining frontal plane balance.

The purpose of this study was to assess how healthy individuals prioritize cognitive resources in response to ML foot-placement perturbations while performing cognitive tasks of increasing difficulty. We hypothesize that as the cognitive load increases from attentive listening to spelling short and then long words backwards, individuals will focus more on the cognitive load, thus causing a delay in response time to the perturbation. Furthermore, we expect this delay will cause individuals to use the quicker ankle strategy rather than the hip strategy during recovery from the perturbation with more challenging cognitive loads in order to maintain their balance.

METHODS

Data Collection

Fifteen young healthy adults (Table 1) were recruited from the local community. All subjects provided informed written consent to participate in this institutionally approved protocol. All participants were free from any musculoskeletal or neuromuscular injuries. Data collection trials consisted of 30-45 seconds of steady-state and perturbed treadmill walking performed at a fixed speed of 1.0 m/s and their self-selected walking speed. Trial duration was determined by when the random perturbation was applied. To determine their self-selected walking speed, three trials of 10-meter overground walking at their "comfortable, typical walking speed" were averaged. Three-dimensional full-body kinematic data were collected at 120 Hz using 65 reflective markers with a 10-camera motion capture system (Vicon, Oxford, UK). Three-dimensional ground reaction force (GRF) data were collected at 960 Hz using a split-belt instrumented treadmill (Motek, Amsterdam, Netherlands).

Participants performed a cognitive single-task (ST) control (spelling-while-standing), and then steady-state unperturbed and perturbed treadmill walking trials at both speeds (Table 3). Walking trials were completed with four different cognitive loads: a ST no load walking condition and three DT walking conditions (attentive listening, spelling short 5-letter words backwards and spelling long 10-letter words backwards). Spelling responses were recorded through a microphone. Walking and cognitive load conditions, speeds and the order of the words presented were randomized.

Table 3: Trial conditions

<table>
<tr><td colspan="2">1 cognitive control for short words and 1 for long words
(spelling-while-standing)</td></tr>
<tr><td colspan="2">16 total walking trials (8 unperturbed, 8 perturbed)</td></tr>
<tr><td>Perturbed
Two medial and two lateral perturbations occur during each perturbed trial.
Each cognitive condition done at 1 m/s and at self-selected speed</td><td>Unperturbed
Each cognitive condition done at 1 m/s and at self-selected speed</td></tr>
<tr><td colspan="2">Cognitive Conditions
No cognitive load
Attentive listening
Spelling short words backwards
Spelling long words backwards</td></tr>
</table>

A total of 16 medial and 16 lateral perturbations will be applied to each subject.

Cognitive Loads

Participants wore noise-cancelling headphones for all trials to prevent acoustic distractions. For the attentive listening condition, participants were instructed to listen carefully to the story they heard through the headphones. No other task-prioritization instructions were given.

During the spelling conditions, participants were instructed to spell each word backwards as quickly and accurately as possible. Thirty 5-letter and 10-letter common words were selected from the English dictionary, and each spelling trial consisted of only short or long words as the cognitive load. Participants heard each pre-recorded word through the headphones with the next word playing immediately after they spelled the previous word, completing as many words as possible.

Perturbations

During each perturbed walking trial, a custom pneumatic device (Fig. 4) applied two lateral and two medial perturbations to the ankle just before heel-strike at random but non-consecutive steps throughout the trial (Brough et al., 2021). Briefly, the perturbations were generated by a valve releasing compressed air at the ankle 140 ms before heel-strike, producing a force of approximately 15 N that altered foot-placement medially or laterally (Brough et al., 2021).

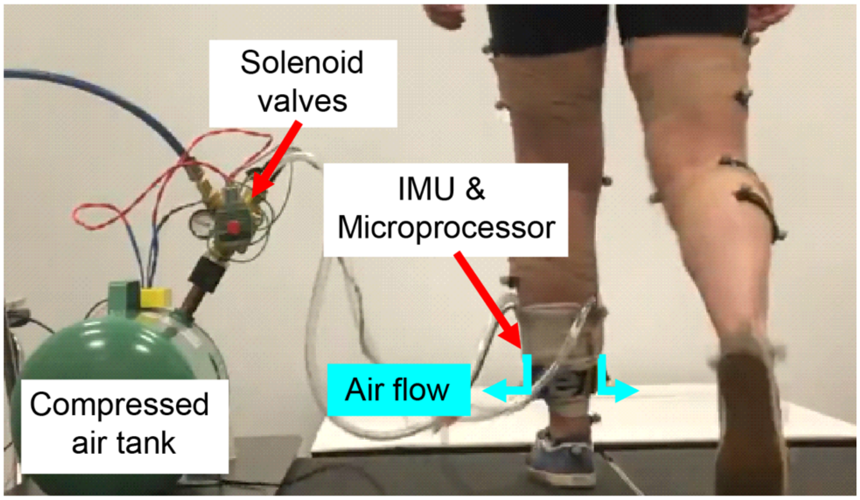


Figure 4: The perturbation device. Air flowed from a compressed air tank to solenoid valves and flexible hoses and out of elbow joints at the ankle. An IMU and microprocessor determined when to release the air (Brough et al., 2021).

Data Analysis

Marker and force plate data were low-pass filtered at 6 Hz and 15 Hz, respectively, using a fourth-order Butterworth filter. A 13-segment inverse dynamics model was created for each subject using Visual 3D (C-Motion, Germantown, MD). Dynamic balance was quantified by analyzing frontal plane whole body angular momentum (H), which was calculated by summing the angular momentum of each body segment about the whole-body center of mass. H was normalized by subject mass, height and walking speed. Balance control was quantified as the range of H (H_R), defined as the difference in the highest and lowest peaks of H over the gait cycle, where lower H_R indicates more tightly controlled balance (Herr and Popovic, 2008). Steps where the participant's foot landed on the incorrect force plate were identified and removed from the kinetic analyses. Joint moments at the ankle and hip were normalized by subject mass and moment impulses were defined as the time integral of the joint moment over the gait cycle and over each of the four regions of stance (first double support, first and second half of single leg stance, second double support). Recorded audio was examined to determine correct response rate (correct letters per second) as the measure of cognitive performance.

Statistics

A linear mixed effects model was used to assess differences in the outcome measures (H_R, peak ankle inversion moment, peak hip abduction moment, percent of the gait cycle when the peak moments occurred, ankle and hip moment impulse and cognitive response) between the unperturbed walking and perturbed DT walking conditions. Separate models were created for the medial and lateral perturbations over the entire gait cycle and within four regions of stance (first double support, first and second half of single leg stance, second double support). The self-selected and standardized walking speeds did not have differences in the outcome measures and were pooled for statistical analysis. The walking conditions (level of cognitive load and perturbation) were the fixed effects, and the study subjects were the random effects. If the linear mixed effects model revealed significant effects, Tukey HSD post-hoc tests were performed to identify pairwise differences between the DT conditions. The significance level was set at $p < 0.05$. All statistical analyses were performed using the statistical toolbox in MATLAB (Mathworks, Natick, MA).

Results

Cognitive Load

Spelling performance did not change between the ST and DT conditions (steady-state p = 0.994, perturbed p = 0.156 for both word lengths) (Table 4). However, within the DT conditions, correct response rate decreased between the steady-state unperturbed and perturbed DT for both the short and long word conditions (p = 0.003 for both). In all conditions, individuals performed worse in the long word task than in the short word task with a lower correct response rate ($p < 0.001$).

Table 4: Cognitive performance (mean ± 1 standard deviation). Bold indicates a significant difference from the steady-state dual-task of the corresponding length ($p < 0.05$)

	Single-Task		**Steady-State Dual-Task**		**Perturbed Dual-Task**	
	Short	**Long**	**Short**	**Long**	**Short**	**Long**
Correct response rate (letters/s)	1.91 ± 0.5	1.02 ± 0.5	1.87 ± 0.6	1.04 ± 0.4	**1.67 ± 0.4**	**0.90 ± 0.3**

Balance Control

Frontal plane H_R was higher for the medial perturbations compared to the lateral perturbations and steady-state unperturbed walking (Fig. 5). The only significant effect on frontal plane H_R when adding a cognitive load was a slight increase between the no load and long word condition (p = 0.045) and between the listening and long word condition for the medial perturbation (p = 0.006) (Fig. 5).

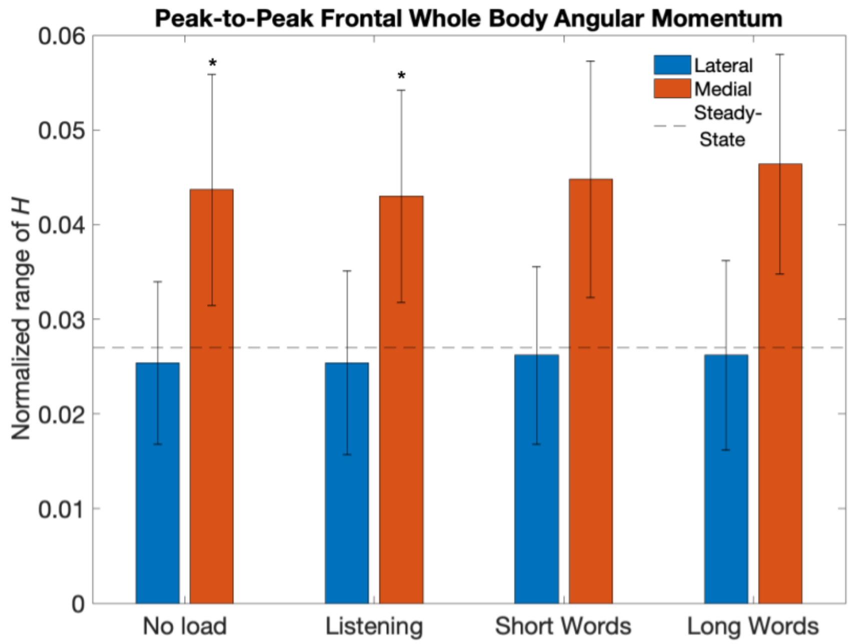


Figure 5: Peak-to-peak differences in frontal plane whole-body angular momentum (H_R, normalized by height, mass and speed of each individual) for the no load and three dual-task conditions. The horizontal dashed line represents H_R for steady-state unperturbed walking. * indicates a significant difference from the long word DT with a medial foot-placement perturbation ($p < 0.05$). Error bars represent ± 1 standard deviation.

Lateral Ankle Strategy

The addition of a cognitive load did not affect the ankle inversion moment peaks or timing over the gait cycle for either the lateral (Table 5) or medial (Table 6) perturbations (Fig. 6). There were also no differences in the ankle inversion moment impulse across the different cognitive loads in any of the four regions of stance.

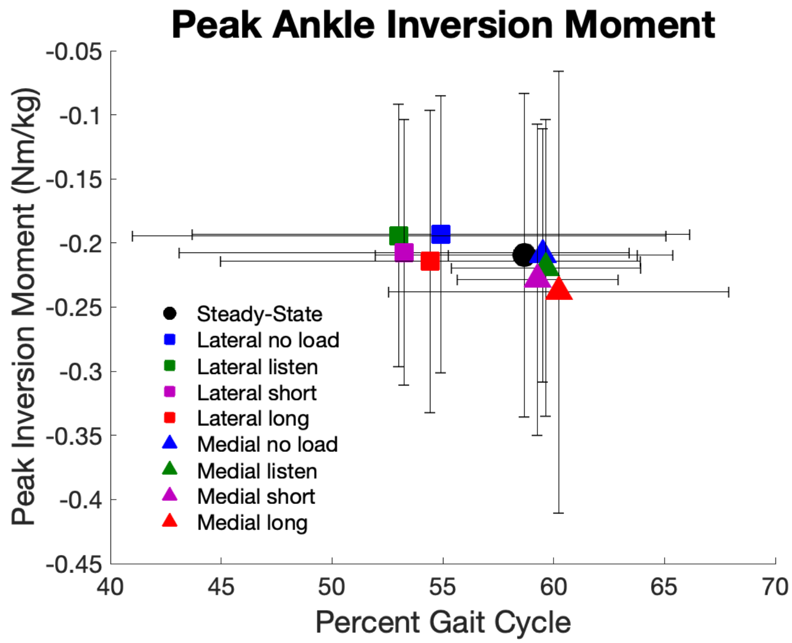


Figure 6: Peak ankle inversion moment for the lateral and medial perturbed conditions during the four cognitive loads (no load, listening and spelling short and long words backwards) and where in the gait cycle the peaks occurred. Error bars represent ± 1 standard deviation.

Hip Strategy

The addition of a cognitive load also did not affect the peak hip abduction moment or timing for either the lateral (Table 5) or the medial (Table 6) perturbations (Fig. 7). There were also no differences in the hip abduction moment impulse across the different cognitive loads in any of the four regions of stance.

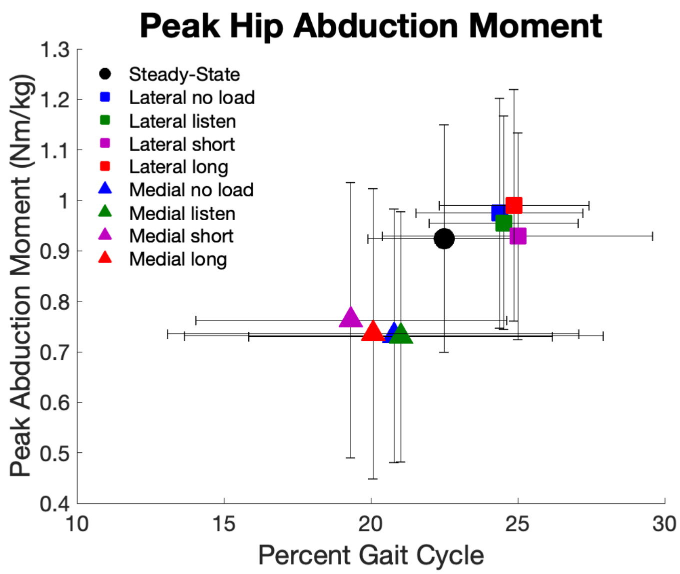


Figure 7: Peak hip abduction moment for the lateral and medial perturbed conditions during the four cognitive loads (no load, listening and spelling short and long words backwards) and where in the gait cycle the peaks occurred. Error bars represent ± 1 standard deviation.

Table 5: Lateral Perturbations (mean ± 1 standard deviation). a-f indicate pairwise Tukey post-hoc comparisons performed when the linear mixed effect model produced significant interactions ($p < 0.05$). a = between no load and listening DT, b = between no load and short words DT, c = between no load and long words DT, d= between listening DT and short words DT, e = between listening DT and long words DT, f = between short words DT and long words DT. Bold indicates significance.

Variable	Condition	Mean ± SD	Linear Mixed Effects Fixed *p*-value	Comparisons	*p*-value
H_R	Steady-State	0.0270 ± 0.008	**0.021**	a	0.999
	No Load	0.0254 ± 0.009		b	0.839
	Listen DT	0.0254 ± 0.010		c	0.843
	Short words DT	0.0262 ± 0.009		d	0.698
	Long words DT	0.0262 ± 0.010		e	0.716
				f	1.000
Ankle Inversion Moment Impulse (Nms/kg)	Steady-State	-0.63 ± 7.70	< **0.001**	a	0.931
	No Load	-3.76 ± 7.76		b	0.996
	Listen DT	-3.56 ± 7.97		c	0.999
	Short words DT	-4.46 ± 7.49		d	0.767

	Long words DT	-4.72 ± 7.76		e f	0.859 0.999
Peak Ankle Inversion Moment (Nm/kg)	Steady-State No load Listen DT Short words DT Long words DT	-0.209 ± 0.126 -0.193 ± 0.108 -0.194 ± 0.102 -0.207 ± 0.104 -0.214 ± 0.118	**0.005**	a b c d e f	0.999 0.998 0.975 0.976 0.907 0.999
Hip Abduction Moment Impulse (Nms/kg)	Steady-State No Load Listen DT Short words DT Long words DT	-47.79 ± 16.77 -46.47 ± 13.07 -45.07 ± 10.44 -45.16 ± 10.88 -46.83 ± 11.43	**0.002**	a b c d e f	0.985 0.990 0.998 1.00 0.999 1.00
Peak Hip Inversion Moment (Nm/kg)	Steady-State No Load Listen DT Short words DT Long words DT	0.924 ± 0.226 0.975 ± 0.229 0.956 ± 0.212 0.929 ± 0.205 0.990 ± 0.229	0.395		

Table 6: Medial Perturbations (mean ± 1 standard deviation). a-f indicate pairwise Tukey post-hoc comparisons performed when the linear mixed effect model produced significant interactions ($p < 0.05$). a = between no load and listening DT, b = between no load and short words DT, c = between no load and long words DT, d = between listening DT and short words DT, e = between listening DT and long words DT, f = between short words DT and long words DT. Bold indicates significance.

Variable	**Condition**	**Mean ± SD**	**Linear Mixed Effects Fixed *p*-value**	**Comparisons**	***p*-value**
H_R	Steady-State No Load Listen DT Short words DT Long words DT	0.0270 ± 0.008 0.0437± 0.010 0.0430 ± 0.010 0.0448 ± 0.010 0.0464 ± 0.010	**0.021**	a b c d e f	0.969 0.806 **0.045** 0.411 **0.006** 0.471
Ankle Inversion Moment Impulse (Nms/kg)	Steady-State No Load Listen DT	-0.63 ± 7.70 0.81 ± 9.79 0.26 ± 7.24	0.834		

	Short words DT	0.52 ± 8.79			
	Long words DT	-1.36 ± 11.11			
Peak Ankle Inversion Moment (Nm/kg)	Steady-State	-0.209 ± 0.126	**0.003**	a	0.956
	No Load	-0.210 ± 0.099		b	0.785
	Listen DT	-0.219 ± 0.116		c	0.313
	Short words DT	-0.229 ± 0.122		d	0.991
	Long words DT	-0.238 ± 0.173		e	0.736
				f	0.949
Hip Abduction Moment Impulse (Nms/kg)	Steady-State	-47.79 ± 16.77	< **0.001**	a	0.523
	No Load	-44.60 ± 15.60		b	0.987
	Listen DT	-41.61 ± 12.39		c	0.986
	Short words DT	-43.55 ± 13.54		d	0.845
	Long words DT	-46.27 ± 16.94		e	0.229
				f	0.850
Peak Hip Abduction Moment (Nm/kg)	Steady-State	0.924 ± 0.226	**< 0.001**	a	0.993
	No Load	0.731 ± 0.252		b	0.815
	Listen DT	0.730 ± 0.249		c	0.997
	Short words DT	0.762 ± 0.273		d	0.557
	Long words DT	0.736 ± 0.288		e	0.939
				f	0.947

DISCUSSION

This study assessed how young healthy adults prioritize cognitive resources to recover their balance when faced with a perturbation to foot-placement during DT walking conditions. Contrary to our hypothesis, there was not a delay in the response time to the perturbation with increased cognitive loads, and therefore individuals did not need to use the faster ankle strategy. The cognitive loads did not cause a change in the ankle or hip peak moment or in the timing of the peak during stance. Furthermore, cognitive performance decreased between steady-state walking and perturbed walking, suggesting that participants switched their attention to focus more on balance control when facing unexpected changes to foot-placement.

Cognitive Performance

Spelling words backwards has been used in DT paradigms in young and older healthy adults (Bonetti et al., 2019; Hollman et al., 2010) and individuals post-concussion (Howell et al., 2020), as it is a challenging cognitive task that can produce cognitive-motor interference during walking (Hollman et al. 2007; Small et al., 2021). When compared to steady-state unperturbed walking, cognitive performance decreased for both the short and long words during the perturbed trials (Table 4). This decrease in cognitive performance is consistent with other work showing that individuals prioritize a motor task over a cognitive one during more challenging walking tasks such as adapting to split-belt treadmill walking (Hinton et al., 2020), and stepping on an uneven surface (Mersmann et al., 2013). However, one study did not observe changes in cognitive performance during varying levels of surface translation perturbation when counting backwards by 7 (Paran et al., 2020). This discrepancy is likely due to differences in cognitive task difficulty. For simpler cognitive tasks such as counting backwards, young healthy adults likely have enough cognitive resources to maintain balance and cognitive performance. Therefore, the present finding of decreased cognitive performance suggests that perturbed DTs can cause cognitive-motor interference if the cognitive task is challenging enough to strain the attentional resources of the participants.

Joint Responses

Contrary to our hypothesis that individuals would focus on the cognitive task and thus have a delayed response to the perturbation, the cognitive loads did not cause a change in the ankle or hip joint moments for either the medial or lateral perturbations (Figs. 6 & 7).

This negligible change in ankle and hip joint moments indicates that subjects did not change their recovery strategy across the different cognitive loads. However, these results are consistent with other work showing that a cognitive load did not affect the type of strategy used in recovery during perturbed standing (e.g., Brauer et al., 2002; Brown et al., 1999). The lack of change in peak joint moments and moment impulses could be due to an automatic reflexive response to the perturbation. However, because cognitive performance decreased, the balance recovery response likely required cognitive resources and thus subjects focused more on motor performance than the cognitive load throughout the perturbation to maintain the same recovery strategy regardless of the cognitive load. While other DT perturbed standing studies also did not see changes in recovery strategy, they did find differences within a specific recovery strategy, including changes in timing (Patel and Bhatt, 2015), peak center of pressure (Quant et al., 2004), and distance between the center of mass and base of support (Brown et al., 1999) when an additional cognitive load is added. However, these studies were done during standing, and studies of perturbed walking did not see similar changes in motor performance during DT conditions (Mersmann et al., 2013; Paran et al., 2020), consistent with the present results.

Dynamic Balance

Dynamic balance can decrease during DT steady-state walking if the cognitive task is challenging enough, indicating that individuals focus more on the challenging cognitive task (Oh and LaPointe, 2017; Small et al., 2021). In the presence of unexpected balance perturbations, the present study showed balance decreases between steady-state and medially perturbed walking with only minor differences in the lateral perturbations. The addition of cognitive loads only decreased balance control slightly between medially perturbed walking without a cognitive task and the long word spelling condition, which was the most challenging DT (Fig. 5). The listening and spelling of short words backwards were likely not challenging enough DTs to produce a change in H_R during the perturbations compared with the no cognitive load condition. We previously showed spelling long words backwards causes a decrease in dynamic balance during steady-state treadmill walking (Small et al., 2021). Therefore, a change in H_R was present during the long word task before the perturbation and could have contributed to the decrease in balance control during the perturbation. However, this decrease in balance control was not seen in the lateral perturbations, which may indicate that the medial perturbation condition demanded more attentional resources due to the difficulty of the task. Regardless, these differences in balance control were small, and the overall lack of change across the cognitive loads agrees with other studies that saw no change in balance control during perturbed DT walking (Mersmann et al., 2013; Paran et al., 2020).

Limitations

One potential limitation of this study was that the cognitive performance could be influenced by a learning effect across the trials. However, a post-hoc linear regression model applied to the data showed that no participants demonstrated any learning effect in increased accuracy in cognitive performance (average *R-squared* = 0.130, average *p*-value = 0.366). Another limitation of this study was the constraints of the treadmill since participants could not alter their walking speed in response to the DT and thus these results may not hold for overground studies. Finally, due to the study design, cognitive responses could not be separated by the direction of the perturbation. Future work should compare cognitive performance across different types of perturbations.

CONCLUSION

In conclusion, adding a challenging cognitive load did not affect the magnitude, onset time or recovery strategy from a perturbation to ML foot-placement in young healthy adults during treadmill walking. During steady-state walking with a challenging cognitive load, young healthy adults focused on the cognitive load at the expense of their balance control (Small et al., 2021), but when faced with a foot-placement perturbation that threatens balance, they switch their attention from the cognitive task to the motor task. This change in task-prioritization results in decreased cognitive performance during the perturbations and little change in balance control across the increasing cognitive loads. These results provide additional insight into task-prioritization during balance recovery in young healthy adults and provides a benchmark for future studies to determine differences in aging and neurologically impaired populations.

Appendices

Appendix A: Words used in study

Short words	Long words
Ankle	Abominable
Arrow	Acceptable
Blaze	Accomplice
Block	Activation
Brown	Ambassador
Chase	Anesthesia
Clump	Asexualize
Crazy	Aspiration
Decaf	Benefactor
Depth	Biological
Dream	Boisterous
Exact	Brilliance
Fight	Cantaloupe
Forum	Capitalism
Frizz	Chimpanzee
Giant	Disqualify
Globe	Earthquake
Japan	Expectancy
Joker	Jackhammer
Juicy	Jaywalking
Knack	Kickboxing
Lucky	Mozzarella
Picky	Polarizing
Plaza	Puzzlement
Prize	Quadruplex
Quack	Quizmaster
Ready	Rejuvenate
Whack	Subjective
World	Sympathize
Zebra	Unequalize

APPENDIX B1: RESULTS FOR GAIT MEASURES FOR 1 M/S SPEED TRIALS.

Variable	Condition	Mean ± SD	Group ANOVA *p*-value	Comparisons	*p*-value
H_R	No load	0.0291 ± 0.008	< **0.001**	a	0.065
	Listen DT	0.0310 ± 0.008		b, c	< **0.001**
	Short words DT	0.0324 ± 0.01		d	0.268
	Long words DT	0.0332 ± 0.01		e	**0.016**
				f	0.659
Step Width (m)	No load	0.135 ± 0.03	< **0.001**	a	0.994
	Listen DT	0.136 ± 0.03		b, c, d, e, f	< **0.001**
	Short words DT	0.156 ± 0.04			
	Long words DT	0.149 ± 0.04			
Step Length (m)	No load	0.589 ± 0.04	< **0.001**	a	0.451
	Listen DT	0.593 ± 0.04		b	0.398
	Short words DT	0.585 ± 0.04		c	0.133
	Long words DT	0.584 ± 0.04		d	**0.013**
				e	**0.002**
				f	0.932
Swing Time (s)	No load	0.386 ± 0.02	< **0.001**	a	0.990
	Listen DT	0.386 ± 0.03		b	0.063
	Short words DT	0.382 ± 0.03		c	**0.032**
	Long words DT	0.381 ± 0.03		d	**0.027**
				e	**0.013**
				f	0.995
Double Support Time (s)	No load	0.406 ± 0.03	< **0.001**	a	0.830
	Listen DT	0.408 ± 0.03		b	0.999
	Short words DT	0.406 ± 0.03		c	0.621
	Long words DT	0.403 ± 0.03		d	0.809
				e	0.167
				f	0.647
Stance Time (s)	No load	0.792 ± 0.04	**< 0.001**	a	0.833
	Listen DT	0.795 ± 0.04		b	0.303
	Short words DT	0.789 ± 0.05		c	**0.014**
	Long words DT	0.786 ± 0.04		d	0.050
				e	**< 0.001**
				f	0.587

a-f indicate pairwise Tukey post-hoc comparisons performed when the ANOVA produced significant interactions ($p < 0.05$). a = comparison between no load and listening DT, b = between no load and short words DT, c = between no load and long words DT, d = between listening DT and short words DT, e = between listening DT and long words DT, f = between short words DT and long words DT. Bold indicates significance.

APPENDIX B2: RESULTS FOR GAIT MEASURES FOR SELF-SELECTED SPEED TRIALS.

Variable	Condition	Mean ± SD	Group ANOVA *p*-value	Comparisons	*p*-value
H_R	No load	0.0249 ± 0.008	< **0.001**	a	0.855
	Listen DT	0.0255 ± 0.008		b	**0.002**
	Short words DT	0.0275 ± 0.009		c, e	< **0.001**
	Long words DT	0.0288 ± 0.009		d	**0.030**
				f	0.263
Step Width (m)	No load	0.136 ± 0.03	< **0.001**	a	0.999
	Listen DT	0.136 ± 0.03		b, c, e, f	< **0.001**
	Short words DT	0.145 ± 0.04		d	0.290
	Long words DT	0.149 ± 0.04			
Step Length (m)	No load	0.696 ± 0.05	0.062		
	Listen DT	0.699 ± 0.05			
	Short words DT	0.698 ± 0.05			
	Long words DT	0.696 ± 0.05			
Swing Time (s)	No load	0.356 ± 0.03	< **0.001**	a	0.538
	Listen DT	0.358 ± 0.02		b	0.629
	Short words DT	0.358 ± 0.02		c	0.965
	Long words DT	0.356 ± 0.03		d	0.999
				e	0.267
				f	0.339
Double Support Time (s)	No load	0.338 ± 0.03	0.126		
	Listen DT	0.338 ± 0.03			
	Short words DT	0.336 ± 0.03			
	Long words DT	0.337 ± 0.03			
Stance Time (s)	No load	0.695 ± 0.05	**< 0.001**	a	0.823

Listen DT	0.697 ± 0.05	b	0.999
Short words DT	0.695 ± 0.05	c	0.926
Long words DT	0.693 ± 0.05	d	0.890
		e	0.448
		f	0.870

a-f indicate pairwise Tukey post-hoc comparisons performed when the ANOVA produced significant interactions ($p < 0.05$). a = comparison between no load and listening DT, b = between no load and short words DT, c = between no load and long words DT, d = between listening DT and short words DT, e = between listening DT and long words DT, f = between short words DT and long words DT. Bold indicates significance.

APPENDIX C1: STATISTICS FOR LATERAL PERTURBATIONS COMPARED WITH STEADY-STATE VALUES.

Variable	Linear Mixed Effects Fixed *p*-value	Comparisons	*p*-value
H_R	**0.021**	A	0.100
		B	**0.045**
		C	0.846
		D	0.835
Ankle Inversion Moment Impulse (Nms/kg)	< **0.001**	A, B, C, D	**< 0.001**
Peak Ankle Inversion Moment (Nm/kg)	**0.005**	A	0.142
		B	0.061
		C	0.381
		D	0.598
Hip Abduction Moment Impulse (Nms/kg)	**0.002**	A	0.602
		B	0.196
		C	0.241
		D	0.377
Peak Hip Inversion Moment (Nm/kg)	0.395		

A-D indicate pairwise Tukey post-hoc comparisons performed when the linear mixed effect model produced significant interactions ($p < 0.05$). A = comparison between steady-state and no load lateral perturbed walking, B = between steady-state and lateral listening DT, C = between steady-state and lateral short DT, D = between steady-state and lateral long DT. Bold indicates significance.

APPENDIX C2: STATISTICS FOR MEDIAL PERTURBATIONS COMPARED WITH STEADY-STATE VALUES.

Variable	Linear Mixed Effects Fixed *p*-value	Comparisons	*p*-value
H_R	**0.021**	A, B, C, D	**< 0.001**
Ankle Inversion Moment Impulse (Nms/kg)	0.834		
Peak Ankle Inversion Moment (Nm/kg)	**0.003**	A	1.00
		B	0.843
		C	0.505
		D	0.065
Hip Abduction Moment Impulse (Nms/kg)	< **0.001**	A	0.195
		B	**< 0.001**
		C	**0.045**
		D	0.594
Peak Hip Abduction Moment (Nm/kg)	**< 0.001**	A, B, C, D	**< 0.001**

A-D indicate pairwise Tukey post-hoc comparisons performed when the linear mixed effect model produced significant interactions ($p < 0.05$). A = comparison between steady-state and no load perturbed walking, B = between steady-state and listening DT, C = between steady-state and short DT, D = between steady-state and long DT. Bold indicates significance.

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