Journal of Biomechanics 122 (2021) 110466

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The influence of cognitive load on balance control during steady-state walking

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ARTICLE INFO

Article history:
Accepted 15 April 2021

Keywords:
Dual-task
Gait
Balance control
Cognitive performance
Biomechanics

ABSTRACT

For an individual to successfully walk, they must maintain control of their dynamic balance. However, situations that require 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 specifically on the influence of cognitive load on balance control. The purpose of this study was to assess how individuals prioritize their cognitive resources and control dynamic balance during dual-task conditions of varying difficulty. Young healthy adults (n = 15) performed two single-task conditions (spelling-while-standing and treadmill walking with no cognitive load) and three dual-task conditions (treadmill walking with increasing cognitive load: attentive listening and spelling short and long words backwards). Cognitive performance did not change between the single- and dual-task as measured by spelling percent error and response rate ($p = 0.300$). Balance control, assessed using the range of whole-body angular momentum, did not change between the no load and listening conditions, but decreased during the short and long spelling conditions ($p < 0.001$). These results highlight that in young adults balance control decreases during dual-task treadmill walking with increased cognitive loads, but their cognitive performance does not change. The decrease in balance control suggests that participants prioritized cognitive performance over balance control during these dual-task walking conditions. This work offers additional insight into the automaticity of walking and task-prioritization in healthy young individuals and provides the basis for future studies to determine differences in neurologically impaired populations.

1. 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

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https://doi.org/10.1016/j.jbiomech.2021.110466
0021-9290/

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 of 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). Balance control in 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.

2. Methods

2.1. 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 s 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
Mass (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.

2.2. 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.

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.

2.3. 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:

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

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 maximum and minimum 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).

2.4. 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 × 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 × 3 levels). If the ANOVA revealed significant effects, Tukey HSD post-hoc tests were performed to identify pairwise differences between the DTs and to correct for errors due to multiple comparisons. The significance level was set at $p < 0.05$. All statistical analyses were performed using the statistical toolbox in MATLAB (Mathworks, Natick, MA).

3. Results

3.1. 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, Tables 2 and 3), indicating a decrease in balance control during the spelling DT. H_R did not reach significance 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.

3.2. Spatiotemporal measures

Step width increased from the no load walking to DT spelling ($p < 0.001$) (Tables 2 and 3). 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, Table 2). This difference was not seen in the SS conditions ($p = 0.290$) (Fig. 2b, Table 3).

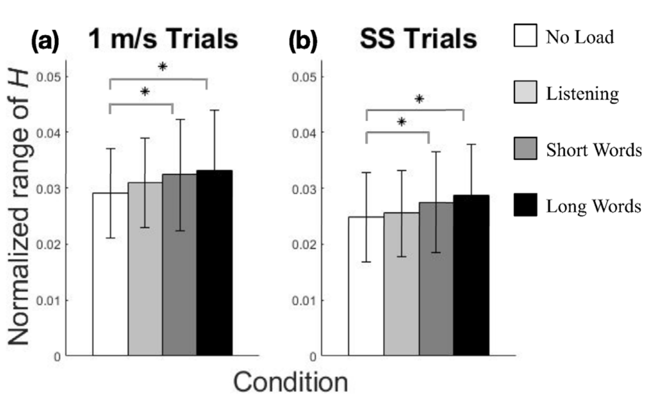

Fig. 1. Peak-to-peak differences in whole-body angular momentum (H_R, normalized by height, mass and speed of each individual) in the frontal plane for the no load and the three dual-task conditions at the 1 m/s speed (a) and the self-selected (SS) speed (b). * indicates a significant difference between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

Differences in step length did not reach significance between conditions at the SS speed ($p = 0.062$) (Table 3). 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 ($p = 0.002$) (Table 2).

Stance time decreased with cognitive load only at 1 m/s (Table 2). 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 ($p = 0.032$) (Table 2).

3.3. GRF measures

There were no differences in the vertical peak GRFs in the 1 m/s ($p = 0.097$) or SS speed trials ($p = 0.121$) (Fig. 3a and 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 and 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).

3.4. 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 4). 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 ($p < 0.001$).

4. 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 DTs. 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.

Table 2
Results for gait measures for 1 m/s speed trials. 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.

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	0.99
	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	0.83
	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	0.05
				e	**<0.001**
				f	0.587

4.1. 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 also consistent with previous DT studies that used other measures of balance, such as coefficient of variation of step length, step time and step 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.

4.2. Cognitive performance

There were no changes in spelling responses between ST and DT in either the percent error or the response rate measures (Table 4). 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).

4.3. 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 diffi-

Table 3
Results for gait measures for self-selected speed trials. 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.

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

culty 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 trial in the short word task (Table 4).

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 (Tables 2 and 3). 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.

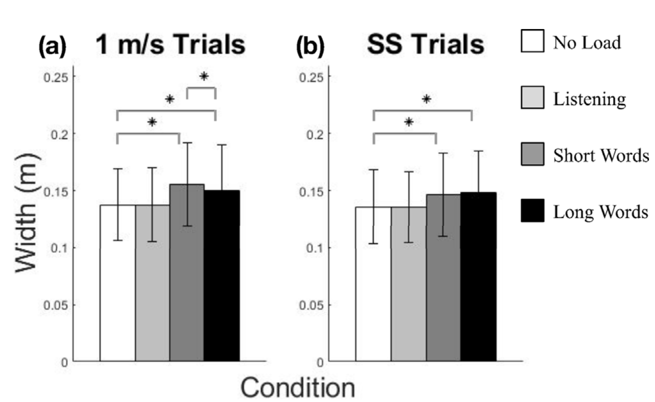

Fig. 2. Average step width (m) for the no load and the three dual-task conditions for the 1 m/s speed (a) and the self-selected (SS) speed (b). * indicates a significant difference between the two conditions ($p < 0.05$). Error bars represent ± 1 standard deviation.

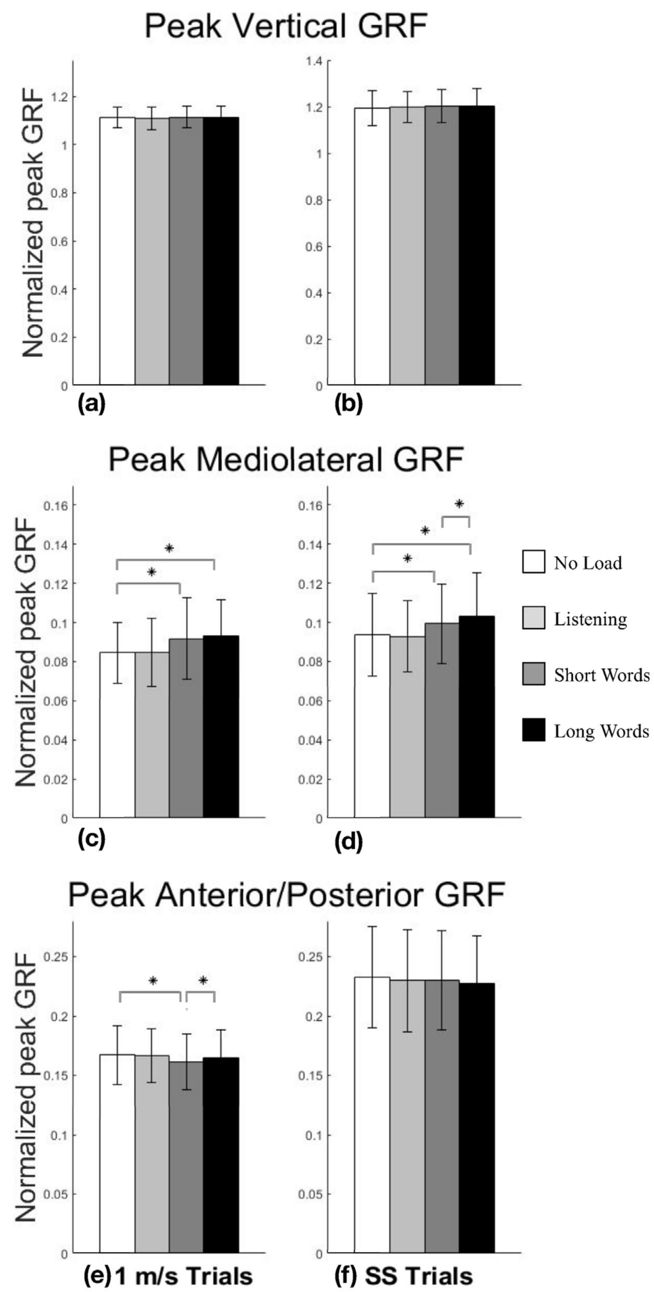

Fig. 3. Peak 3-dimensional ground reaction forces (GRFs) in the mediolateral direction (a and b), anterior/posterior direction (c and d), and vertical direction (e and f) normalized by body weight. a, c and e are at 1 m/s and b, d and f are at the self-selected speed. * indicates a significant difference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

4.4. 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). Some spatiotemporal results had p-values that came close to reaching the chosen alpha level of 0.05, and might have proved significant if a larger sample size was evaluated. Future studies with larger sample sizes should investigate these quantities further. 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).

5. 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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 4
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

Acknowledgements

The authors would like to acknowledge Lindsey Lewallen, Shelby Walford and Aude Lefranc for their help with data collection, and Dr. Dave Clark and Dr. Sarah Roelker for their helpful feedback on the manuscript.

Appendix A

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

References

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., Cockburn, J., 2011. Cognitive motor interference while walking: A systematic review and meta-analysis. Neurosci. Biobehav. Rev. 35, 715–728.

Armieri, A., Holmes, J.D., Spaulding, S.J., Jenkins, M.E., Johnson, A.M., 2009. Dual task performance in a healthy young adult population: results from a symmetric manipulation of task complexity and articulation. Gait Posture 29, 346–348.

Bauby, C.E., Kuo, A.D., 2000. Active control of lateral balance in human walking. J. Biomech. 33, 1433–1440.

Bock, O., 2008. Dual-task costs while walking increase in old age for some, but not for other tasks: an experimental study of healthy young and elderly persons. J. NeuroEng. Rehabil. 5, 27.

Bonetti, L.V., Hassan, S.A., Kasawara, K.T., Reid, W.D., 2019. The effect of mental tracking task on spatiotemporal gait parameters in healthy younger and middle- and older aged participants during dual tasking. Exp. Brain Res. 237, 3123–3132.

Bruce, H., Aponte, D., St-Onge, N., Phillips, N., Gagné, J.-P., Li, K.Z.H., 2019. The Effects of Age and Hearing Loss on Dual-Task Balance and Listening. J. Gerontol. Ser. B Psychol. Sci. Soc. Sci. 74, 275–283.

Clark, D.J., 2015. Automaticity of walking: Functional significance, mechanisms, measurement and rehabilitation strategies. Front. Hum. Neurosci. 9, 1–13.

Dault, M.C., Yardley, L., Frank, J.S., 2003. Does articulation contribute to modifications of postural control during dual-task paradigms?. Cogn. Brain Res. 16, 434–440.

Ebersbach, G., Dimitrijevic, M.R., Poewe, W., 1995. Influence of Concurrent Tasks on Gait: A Dual-Task Approach. Percept. Mot. Skills 81, 107–113.

Fallahtafti, F., Boron, J.B., Venema, D.M., Kim, H.J., Yentes, J.M., 2020. Task specificity impacts dual-task interference in older adults. Aging Clin. Exp. Res.

Hinton, D.C., Conradsson, D., Bouyer, L., Paquette, C., 2020. Does dual task placement and duration affect split-belt treadmill adaptation?. Gait Posture 75, 115–120.

Hollman, J.H., Childs, K.B., McNeil, M.L., Mueller, A.C., Quilter, C.M., Youdas, J.W., 2010. Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals. Gait Posture 32, 23–28.

Hollman, J.H., Kovash, F.M., Kubik, J.J., Linbo, R.A., 2007. Age-related differences in spatiotemporal markers of gait stability during dual task walking. Gait Posture 26, 113–119.

Jordan, K., Challis, J.H., Newell, K.M., 2007. Walking speed influences on gait cycle variability. Gait Posture 26, 128–134.

Kemper, S., McDowd, J., Pohl, P., Herman, R., Jackson, S., 2006. Revealing language deficits following stroke: the cost of doing two things at once. Neuropsychol. Develop. Cogn. Sect. B Aging Neuropsychol. Cogn. 13, 115–139.

Kimura, N., van Deursen, R., 2020. The Effect Of Visual Dual-Tasking Interference On Walking In Healthy Young Adults. Gait Posture 79, 80–85.

Krampe, R.T., Schaefer, S., Lindenberger, U., Baltes, P.B., 2011. Lifespan changes in multi-tasking: Concurrent walking and memory search in children, young, and older adults. Gait Posture 33, 401–405.

Laessoe, U., Voigt, M., 2008. Anticipatory postural control strategies related to predictive perturbations. Gait Posture 28, 62–68.

Li, C., Verghese, J., Holtzer, R., 2014. A comparison of two walking while talking paradigms in aging. Gait Posture 40, 415–419.

McIsaac, T.L., Lamberg, E.M., Muratori, L.M., 2015. Building a Framework for a Dual Task Taxonomy. Biomed Res. Int. 2015, 591475.

Mersmann, F., Bohm, S., Bierbaum, S., Dietrich, R., Arampatzis, A., 2013. Young and old adults prioritize dynamic stability control following gait perturbations when performing a concurrent cognitive task. Gait Posture 37, 373–377.

Montero-Odasso, M., Muir, S.W., Speechley, M., 2012. Dual-task complexity affects gait in people with mild cognitive impairment: the interplay between gait variability, dual tasking, and risk of falls. Arch. Phys. Med. Rehabil. 93, 293–299.

Neptune, R.R., Vistamehr, A., 2019. Dynamic Balance During Human Movement: Measurement and Control Mechanisms. J. Biomech. Eng. 141.

Nott, C.R., Neptune, R.R., Kautz, S.A., 2014. Relationships between frontal-plane angular momentum and clinical balance measures during post-stroke hemiparetic walking. Gait Posture 39, 129–134.

Paran, I., Nachmani, H., Melzer, I., 2020. A concurrent attention-demanding task did not interfere with balance recovery function in standing and walking among young adults – An explorative laboratory study. Hum. Mov. Sci. 73, 102675.

Plummer-D'Amato, P., Altmann, L.J.P., Saracino, D., Fox, E., Behrman, A.L., Marsiske, M., 2008. Interactions between cognitive tasks and gait after stroke: a dual task study. Gait Posture 27, 683–688.

Plummer, P., Altmann, L., Feld, J., Zukowski, L., Najafi, B., Giuliani, C., 2020. Attentional prioritization in dual-task walking: Effects of stroke, environment, and instructed focus. Gait Posture 79, 3–9.

Sheridan, P.L., Hausdorff, J.M., 2007. The role of higher-level cognitive function in gait: executive dysfunction contributes to fall risk in Alzheimer's disease. Dement. Geriatr. Cogn. Disord. 24, 125–137.

Silverman, A.K., Neptune, R.R., 2011. Differences in whole-body angular momentum between below-knee amputees and non-amputees across walking speeds. J. Biomech. 44, 379–385.

Simoni, D., Rubbieri, G., Baccini, M., Rinaldi, L., Becheri, D., Forconi, T., Mossello, E., Zanieri, S., Marchionni, N., Di Bari, M., 2013. Different motor tasks impact differently on cognitive performance of older persons during dual task tests. Clin. Biomech. 28, 692–696.

Siragy, T., Nantel, J., 2020. Absent Arm Swing and Dual Tasking Decreases Trunk Postural Control and Dynamic Balance in People With Parkinson's Disease. Front. Neurol. 11, 213.

Spaccavento, S., Marinelli, C.V., Nardulli, R., Macchitella, L., Bivona, U., Piccardi, L., Zoccolotti, P., Angelelli, P., 2019. Attention Deficits in Stroke Patients: The Role of Lesion Characteristics, Time from Stroke, and Concomitant Neuropsychological Deficits. Behav. Neurol. 2019, 7835710.

Strayer, D.L., Johnston, W.A., 2001. Driven to distraction: dual-task studies of simulated driving and conversing on a cellular telephone. Psychol. Sci. 12, 462–466.

Szturm, T., Maharjan, P., Marotta, J.J., Shay, B., Shrestha, S., Sakhalkar, V., 2013. The interacting effect of cognitive and motor task demands on performance of gait, balance and cognition in young adults. Gait Posture 38, 596–602.

Tamura, I., Kikuchi, S., Kitagawa, M., Otsuki, M., Tashiro, K., 2003. Age-related working memory decline in patients with Parkinson's disease. No to shinkei = Brain Nerve 55, 335–340.

Tisserand, R., Armand, S., Allali, G., Schnider, A., Baillieul, S., 2018. Cognitive-motor dual-task interference modulates mediolateral dynamic stability during gait in post-stroke individuals. Hum. Mov. Sci. 58, 175–184.

Vistamehr, A., Kautz, S.A., Bowden, M.G., Neptune, R.R., 2016. Correlations between measures of dynamic balance in individuals with post-stroke hemiparesis. J. Biomech. 49, 396–400.

Yogev-Seligmann, G., Hausdorff, J.M., Giladi, N., 2012. Do we always prioritize balance when walking? Towards an integrated model of task prioritization. Mov. Disord. 27, 765–770.

Zhang, C., Song, Q., Sun, W., Liu, Y., 2020. Dynamic Stability of Older Adults Under Dual Task Paradigm During Stair Descent. Mot. Control 24, 113–126.