The Influence of Cognitive Load on Balance Control During Steady-State Walking

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by

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Abstract

Background: For an individual to walk, they must maintain control of their dynamic balance. However, situations that present an increased cognitive load may impair an individual's ability to 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.

Methods: Young healthy adults (n = 15) performed two single-task conditions (spelling while standing and walking with no cognitive load) and three dual-task conditions (walking with increasing cognitive load: attentive listening, spelling short words backwards and spelling long words backwards). Repeated measures analysis of variances were used to assess differences in balance outcome measures and cognitive performance.

Results: Cognitive performance did not change between the single- and dual-task conditions as measured by percent error and response rate ($p = 0.3$). Balance control, assessed as 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 ($p < 0.001$).

Conclusions: These results showed that balance control decreases during dual-task treadmill walking with increased cognitive loads, but that 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 individuals and provides the basis for future studies to determine differences in neurologically impaired populations.

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Background

Maintaining proper balance control during walking is essential to prevent falling. However, the addition of a cognitive load during gait, such as listening to music or talking on the phone, may impair the ability to control dynamic balance during gait [1]. Altered balance control puts those with balance impairments at an even higher risk of falling [2], which may result in injuries and mortality [3]. The influence of cognitive loads on walking performance and dynamic balance 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 [e.g., 4]. Studies involving DT walking have become increasingly common to measure cognitive-motor interference [5]. A variety of DT paradigms have been used to exacerbate motor impairments and influence gait performance, especially in impaired populations such as the elderly [e.g., 6-8] and individuals post-stroke [e.g., 1,9,10], with Parkinson's disease [e.g., 11] or with mild cognitive impairment [e.g., 12]. Studies examining the effects of DTs on gait performance have shown that overground walking is less automatic than previously thought [2,13]. Studies that have compared single-task (ST) and DT walking have shown that healthy adults do not necessarily prioritize gait performance over a cognitive task [4,14]. The trade-offs between the automaticity and executive control of walking have important consequences in impaired populations because less attention placed on walking may lead to more falls and resulting injuries [15]. Thus, there exists a need to investigate how DTs affect dynamic balance.

The majority of DT studies have focused on gait speed as the primary outcome measure [5], with few studies focusing on balance control [e.g., 1,11,16]. Whole-body angular momentum (*H*) provides a useful measure of balance control that has been validated in a number of populations

and walking tasks [17]. However, *H* has not been assessed in DT conditions. Higher ranges of whole-body angular momentum (H_R) correlate to lower clinical balance scores and consequently poorer balance control [18]. Furthermore, the frontal plane requires more active control than the sagittal or transverse planes during walking [19]. Thus, DT effects during gait are often seen in the frontal plane, such as changes in step width [20], mediolateral (ML) margin of stability [21] and ML trunk motion [16]. However, it remains unclear how frontal plane *H* is influenced during DT conditions.

Walking DT studies have used a variety of cognitive tasks [5] such as counting backwards by *n* [22], reciting alternating letters of the alphabet [13], reading [23], word fluency [20], spelling backwards [24] and memorization [25]. Spelling words backwards is a cognitive task with real-world applications to conversation as it involves listening, processing the information and then verbalizing the answer [24]. These steps involve attention and working memory, which are also executive functions required during walking [26]. Reciting information backwards is a harder cognitive task than reciting information forwards, which requires increased working memory [27] and leaves fewer cognitive resources for controlling gait. Individuals also have less experience performing a backwards spelling task, which is more novel and challenging [28]. In contrast to spelling, attentive listening is a low novelty and low complexity task, and thus should produce little DT interference [29]. However, spelling short five letter words backwards is a high novelty but low complexity task, while spelling longer ten letter words backwards is a high novelty and high complexity task. These differences in spelling tasks provide a range of DT interference to assess their influence on balance control.

The purpose of this study was to assess how healthy individuals prioritize their cognitive resources and control dynamic balance during DT walking conditions with increasing difficulty. We hypothesize that as the DT load increases from attentive listening to spelling short and long words backwards, the control of dynamic balance will decrease. We further hypothesize that cognitive performance will not change between the single- and dual-task conditions, which would suggest that the participants prioritize cognitive performance over balance control during walking. Understanding how 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 informed, written 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 the participants "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 from a split-belt instrumented treadmill (Motek, Amsterdam, Netherlands). Trials consisted of 30 seconds of steady-state treadmill walking performed at 1) a fixed speed of 1.0 m/s and 2) their SS walking speed.

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

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 ST control trial (spelling while standing) to provide a cognitive baseline. Participants 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) for a total of eight walking trials (2 speeds, 4 loads). Spelling responses were recorded through a microphone. Walking trial 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 trials, participants were instructed to listen carefully to the story they heard through the headphones because they would be quizzed on what they heard after the trials finished. However, this instruction was only given to ensure they listened carefully, and no other task-prioritization instructions were given. After the experiment concluded, the participants signed a debriefing form clarifying no quiz would be provided.

During the spelling trials, the 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 (see Additional file 1), and each spelling trial consisted of

only short or only 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 they could 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 three-dimensional (3D) 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. H_R was defined as the difference between the highest positive and lowest negative peaks of H. Cross-over steps were identified and removed from the kinetic analyses.

To help interpret any observed changes in dynamic balance, differences in spatiotemporal parameters and peak 3D GRFs between the different conditions were determined. Step width was defined as the ML distance between the left and right heel markers at consecutive heel strikes. Step length was defined as 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 a heel strike and the toe off of one leg while swing time was the time between the toe off and next heel strike. Double support time was determined as the time between one foot's heel strike to the other foot's toe off. GRFs were normalized by body weight. Recorded audio data was examined to determine percent spelling error (number of

incorrect letters divided by total letters) and correct response rate (correct letters per second) for the cognitive responses. To examine the effects of task-prioritization, a dual-task effect (DTE) was calculated for balance control and correct response rates as a percent change from the ST to the DT condition. Negative DTE indicated a worse performance in the DT than ST.

Statistics

A mixed repeated measures analysis of variance (ANOVA) was 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 DT conditions across the two 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). If the ANOVA revealed significant effects, Tukey post-hoc tests were performed to identify pairwise differences between the DT conditions. One sample t-tests were used to determine if DTE was significantly different from zero. The significance level was set at $p < 0.05$. All statistical analyses were performed in MATLAB (Mathworks, Natick, MA).

Results

Balance Control

Frontal plane H_R increased between the no load and short word spelling trials ($p < 0.001$) and between the no load and long word spelling trials ($p < 0.001$) at both speeds (Fig. 1), indicating a decrease in balance control during the spelling trials. However, H_R did not change between the no load and listening trials for both the 1.0 m/s ($p = 0.065$) and SS ($p = 0.121$) trials. In contrast,

there were no differences in the sagittal and transverse plane H_R between the ST walking and DT conditions.

Spatiotemporal Measures

Step width increased from the ST walking to DT spelling conditions ($p < 0.001$). No differences were found between the no load and listening conditions ($p = 0.99$ for both speeds). In both the 1 m/s and SS trials, step width increased from the no load to short word trials ($p < 0.001$) and from the no load to long words trials ($p < 0.001$). However, in the 1 m/s trials, step width was wider in the short word spelling DT trials than in the long word spelling DT trials ($p < 0.001$) (Fig. 2a). This difference was not seen in the SS trials ($p = 0.290$) (Fig. 2b).

There was no difference in step length between conditions in the SS speed trials ($p = 0.062$). The 1 m/s trials showed decreases in step length between the listening DT trials and short word DT trials ($p = 0.013$) and between the listening DT and long word DT trials ($p = 0.002$).

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

GRF Measures

There were no differences in the vertical peak GRFs in either the 1 m/s ($p = 0.097$) or in the SS speed trials ($p = 0.121$) (Figs. 3a & b). ML peak GRFs increased between the no load and the

short spelling trials ($p < 0.001$) and between the no load and the long spelling trials ($p < 0.001$) at both the 1 m/s (Fig. 3c) and the SS speeds (Fig. 3d). In the SS speed trial, peak ML GRFs also increased between the short and long word spelling conditions ($p < 0.001$) but did not change in the 1 m/s trials ($p = 0.537$). Finally, the AP GRFs did not change in the SS speed trials ($p = 0.094$) (Fig. 3f), but in the 1 m/s speed, the short word trials had a lower peak GRF than the no load ($p < 0.001$) and long word ($p = 0.005$) trials (Fig. 3e).

Cognitive Performance

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

Table 2: Cognitive performance (mean ± 1 SD)

	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

Table 2 Legend: The cognitive results for the short 5 letter word and long 10 letter word backwards spelling trials during the single-task, the 1m/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).

Dual-Task Effect (DTE)

Cognitive DTEs were not different from zero in either the short words DT trials ($p = 0.917$ for 1 m/s trials, $p = 0.721$ for SS trials) or in the long word DT trials ($p = 0.571$ for 1 m/s trials, $p = 0.132$ for SS trials) (Fig. 4). The balance control DTE was less than zero for both the short and long word trials at both the 1 m/s and SS speeds ($p < 0.001$), indicating there was a smaller DTE for the cognitive response rate than for balance control.

Discussion

This study assessed how healthy individuals prioritize their cognitive resources and control dynamic balance during DT walking conditions with varying degrees of difficulty. Our first hypothesis that as the DT load increased, the control of dynamic balance would decrease was supported by our finding that H_R increased from the ST walking to the DT spelling trials, but not between the no cognitive load and attentive listening trials. Furthermore, our second hypothesis that participants would prioritize cognitive performance over balance control was supported by the cognitive performance not changing between the ST to DT trials, suggesting that participants prioritized cognitive performance over balance control.

Balance Control

The participants demonstrated a decrease in frontal plane balance control as the DT became more difficult (Fig. 1), presumably because attentional resources decreased with the increased

cognitive demands. The changes in balance control were only present between the spelling and no load conditions, while H_R did not differ between the listening and no load conditions. While not significant, there was a trend of frontal plane H_R increasing between the short and long word conditions (Fig. 1 and Fig. 4). 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 than the sagittal and transverse planes [19]. 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 [11] and ML center of mass displacement [23]. These results add to these studies that DT conditions 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 those of Simoni et al. (2013), who saw no change in cognitive performance during DT conditions on a treadmill. However, some studies have observed changes in cognitive performance in DT conditions [1,14,30]. For example, the cognitive accuracy in counting backwards by *n* and reciting alternating letters of the alphabet can diminish in older adults during overground DT conditions [30], and individuals post-stroke have worsened speech production during overground walking [1,14]. The discrepancies in cognitive performance and prioritization throughout these studies suggest that both the type of DT and the constraint of a treadmill likely affects cognitive performance. Furthermore, impaired populations, such as individuals post-stroke, may have attention deficits that diminish the accuracy in cognitive performance observed in young healthy adults [31]. In the present study, the treadmill spelling task did not produce a cognitive DTE in

young healthy adults, further supporting the conclusion that our participants prioritized the cognitive task to maintain accuracy in the spelling task.

Task-Prioritization

During the two spelling conditions, participants prioritized their cognitive performance over their balance control (Fig. 4), but there was no change in DTE between the no load walking and listening DT conditions. These results are consistent with others who found little to no change in motor performance when passive listening was added to an additional motor task due to the ease of the secondary task in young healthy adults [29,32]. Conversely, some 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 [33] and during perturbed walking [8]. However, both of these studies involve motor tasks that are more complex than steady-state walking. Thus, the discrepancies between our results showing a prioritization of the cognitive task and others showing prioritization of motor performance are likely due to the complexity of the cognitive and motor tasks being studied, with attentional focus being prioritized for more complex tasks.

Studies investigating whether individuals post-stroke prioritize cognitive tasks over walking performance have also demonstrated mixed results. Individuals post-stroke have been shown to focus their attention more on walking than the cognitive task in steady-state overground conditions [1]. Conversely, other studies of steady-state walking have shown both healthy adults and adults post-stroke prioritize cognitive tasks over walking [e.g., 9,14,34]. 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 [4]. In the present study, the automaticity of steady-state treadmill walking [15] and the high level of difficulty of the cognitive task appeared to have caused the participants to place more attention on the cognitive task. However, this allocation of attention resulted in poorer balance control, even though the motor task was not complex. If balance control was impaired to the point of an impending fall, subjects would likely then shift their prioritization to control their balance.

Spelling backwards is a cognitive task with real-world applications as it involves multiple attentional components, including listening, processing the information and then verbalizing the response [24]. The lack of DTE in the listening trials 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 articulation and information processing can cause DT interference [25,35]. 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 the time processing the information in the long word task, while they spent more time verbalizing the answers by completing more words per trials in the short word task (Table 2). This difference between the processing and verbalizing aspects of the long and short word tasks may indicate that the differences in spatiotemporal measures seen in short word trials that are absent from the long word trials could be due to the relative increase in verbalization. For example, both spelling DT trials had wider step widths than the ST no load trial ($p < 0.001$).

However, step width was wider in the short word DT trials than in the long word DT trials at the 1 m/s speed ($p < 0.001$). This difference suggests that step width, especially at slow speeds, may be more sensitive to articulation. Other measures might be more sensitive to the processing aspect of working memory, such as step timing for which there were shorter swing and stance times in the long word DT trials than the no load ST trials (see Additional file 2).

The increase in the ML GRF peaks and changes in step width during the spelling trials together lead to the observed changes in H_R and thus decreased balance control during the spelling DT trials, as the ML GRFs and foot placement directly influence H_R through their contributions to the external moment [36]. Furthermore, we observed greater differences in spatiotemporal metrics in the 1 m/s trials than in the SS trials (see Additional file 2). These spatiotemporal differences between speeds might be because walking on a treadmill at one's SS speed is fairly automatic, while walking at a slower than normal speed requires more active control [16,37] 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 conditions. However, the use of steady-state treadmill walking allowed for the collection of a greater number of consecutive steps in each trial, providing a more accurate assessment of our primary measure of balance control (H_R). Another limitation was the potential confounding influence of spelling articulation on walking performance, such as its impact on gait rhythm [14,35]. Future work should focus on separating articulation 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 DT conditions. Finally, the cognitive results may have been influenced by a learning effect from repeating the spelling backwards tasks. However, a post-hoc regression 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, which requires active control, decreases as the cognitive load increases in young healthy adults. However, in healthy young adults 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 conditions, which suggests that healthy adults may prioritize these cognitive tasks over their 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.

List of Abbreviations

DT: Dual-task; ST: Single-task; H: Whole-body angular momentum; H_R: Range of whole-body angular momentum; ML: Mediolateral; SS: Self-selected; GRF: Ground reaction force; SD: Standard deviation; 3D: Three-dimensional; AP: Anterior/posterior; DTE: Dual-task effect; ANOVA: Analysis of Variance

Declarations

Ethics approval and consent to participate

The present study was approved by the University of Texas at Austin Institutional Review Board. All participants provided written informed consent to participate.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

GS: Concept and design, acquisition of data, analysis and interpretation of data, preparation of manuscript. LB: Concept and design, acquisition of data, editing of manuscript. RN: Concept

and design, interpretation of data, editing of manuscript. All authors read and approved the final manuscript.

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Figure Legends

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 ($p < 0.05$).

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 ($p < 0.05$).

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 the 1 m/s speed trials and b, d and f are the self-selected speed trials. * indicates a significant difference between the two conditions ($p < 0.05$).

Figure 4: Dual-task effect (DTE) for the spelling trials at the 1 m/s and the self-selected (SS) speeds. Positive values indicate a performance improvement in the measure from the single- to the dual-task conditions, while negative values indicate the measure getting worse. The balance performance measure is peak-to-peak range of frontal plane whole-body angular momentum (H_R) and the cognitive performance measure is correct response rate.

Figures

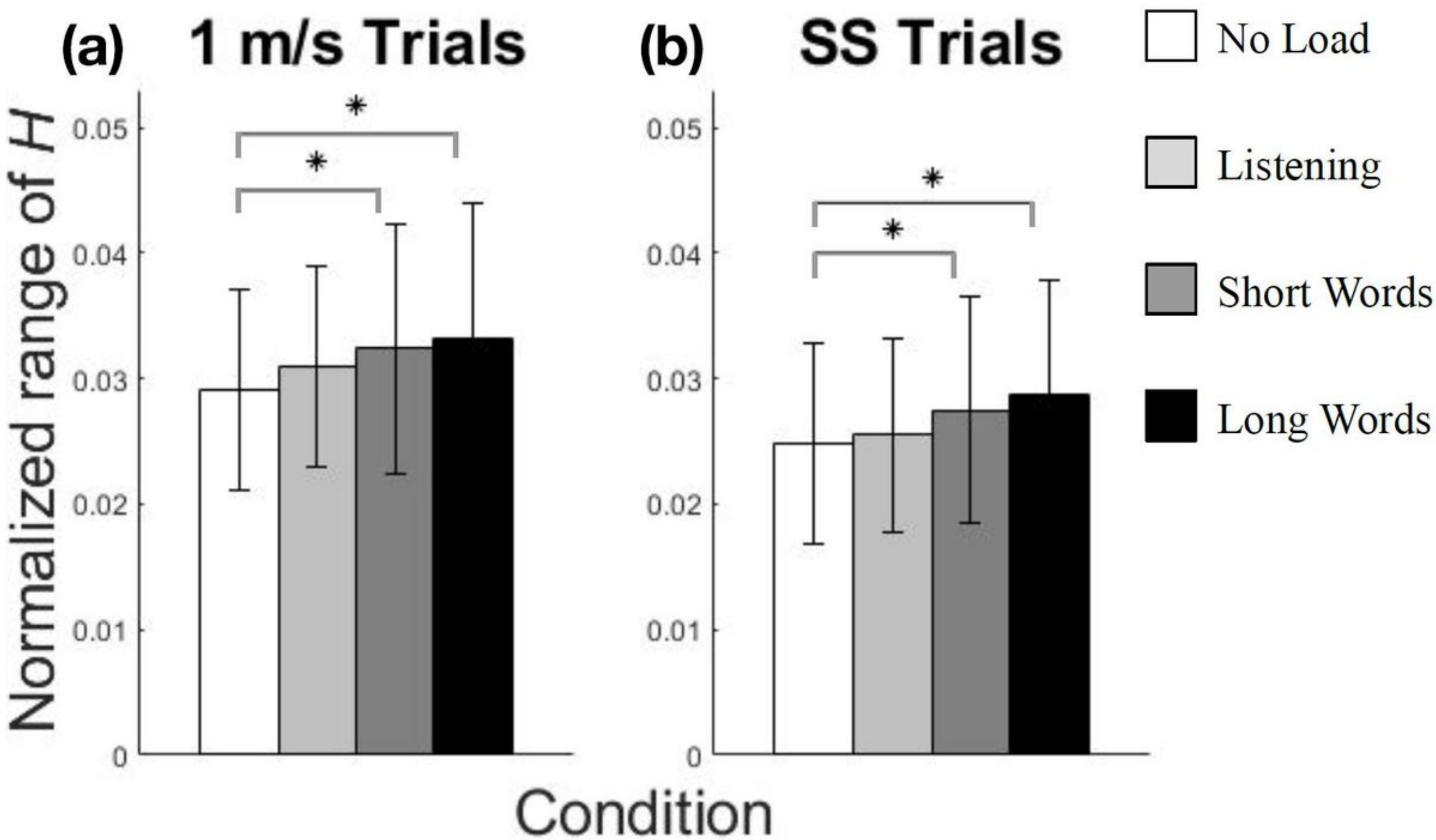

Figure 1

Peak-to-peak differences in whole-body angular momentum (HR, 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 ($p < 0.05$).

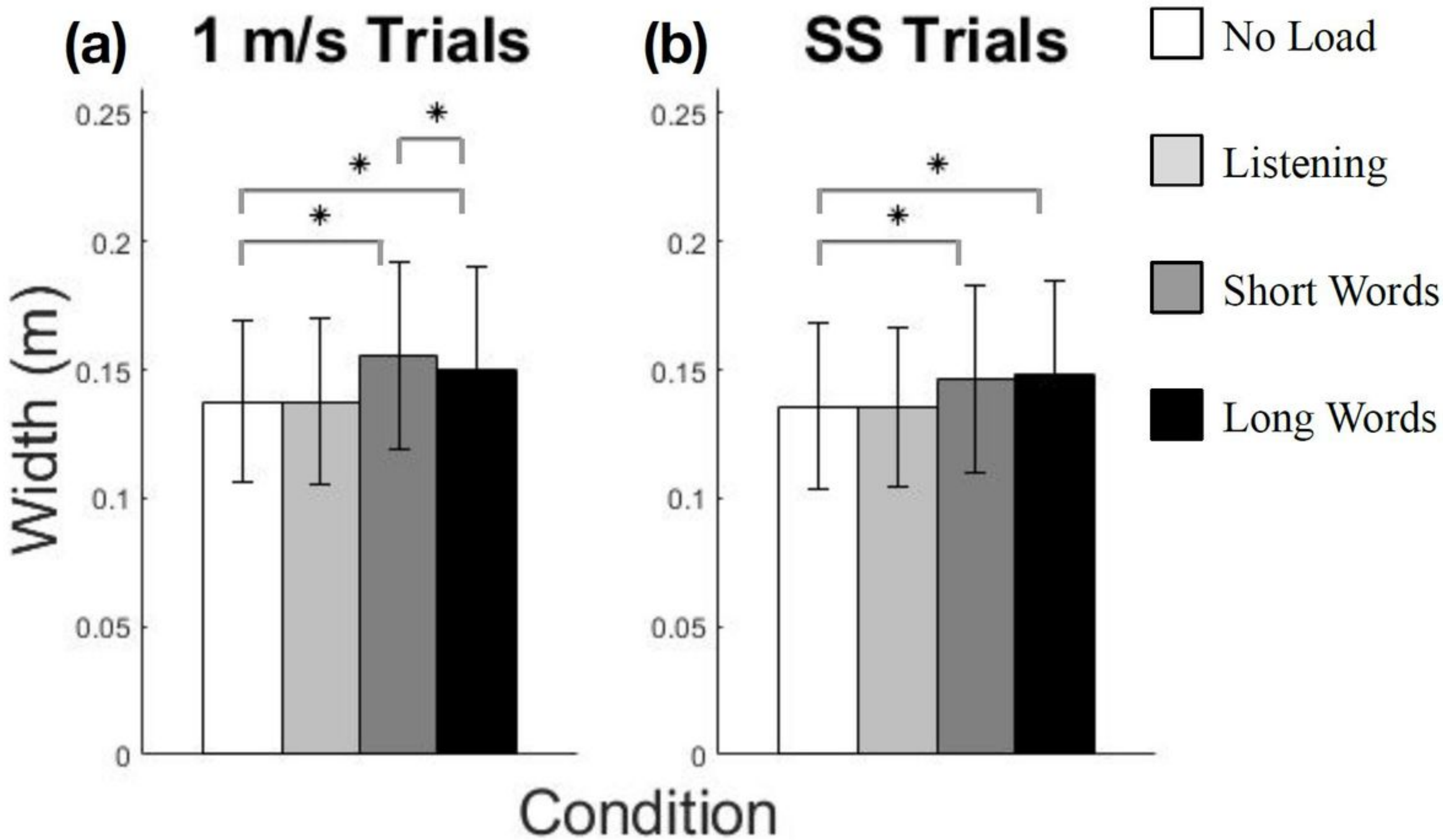

Figure 2

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 ($p < 0.05$).

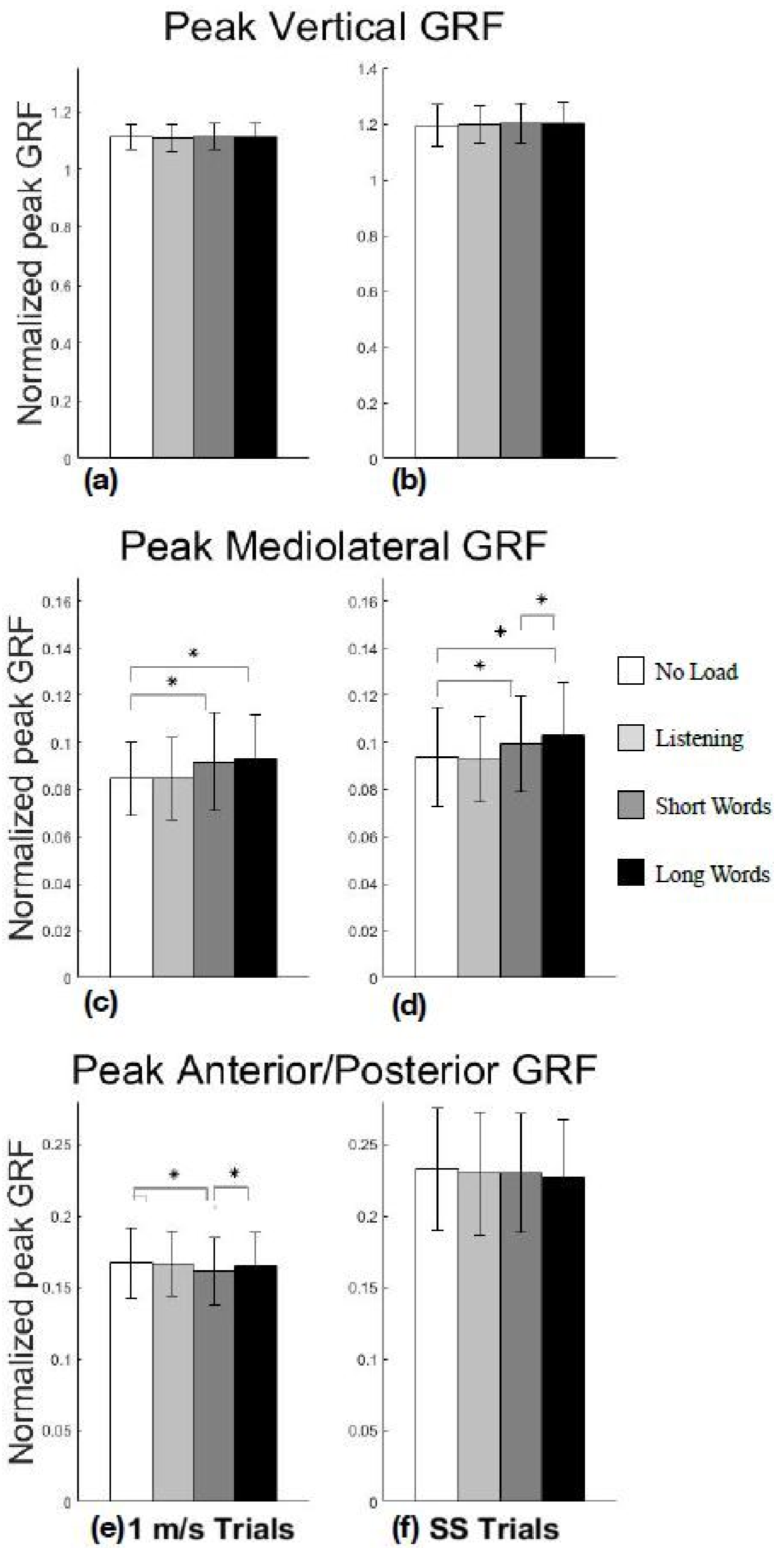

Figure 3

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 the 1 m/s speed trials and b, d and f are the self-selected speed trials. * indicates a significant difference between the two conditions ($p < 0.05$).

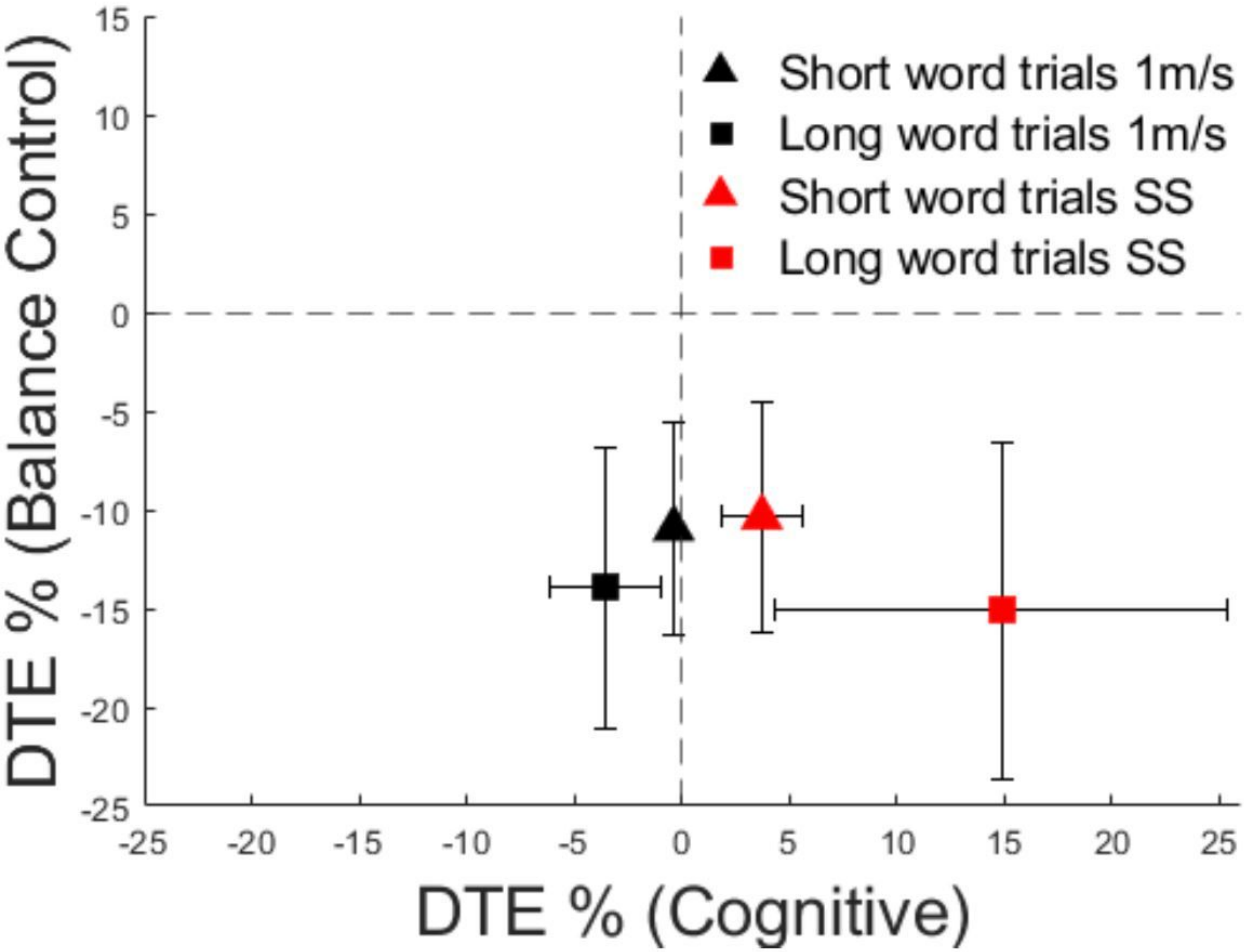

Figure 4

Dual-task effect (DTE) for the spelling trials at the 1 m/s and the self-selected (SS) speeds. Positive values indicate a performance improvement in the measure from the single- to the dual-task conditions, while negative values indicate the measure getting worse. The balance performance measure is peak-to-peak range of frontal plane whole-body angular momentum (HR) and the cognitive performance measure is correct response rate.

Supplementary Files

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- Additionalfile1.pdf
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