Coordination between Motor and Cognitive Tasks in Dual Task Gait

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Abstract

Background

Dual Task (DT) paradigms are frequently used by researchers and clinicians to examine the integrity of motor processes in many movement disorders. However, the mechanism of this interaction is not fully understood. Therefore, the aim of this study was to examine the within-stride interactions between cognitive and motor processes during dual task gait (DT).

Research question

Do healthy young adults coordinate gait with secondary task processing? If so, is cognitive task processing capability associated with the coordination observed?

Methods

Nineteen healthy young adults walked for two minutes on a motorized treadmill whilst counting backwards in sevens from three-digit numbers. The coordination of calculation verbalizations with gait parameters were assessed across six phases of the gait cycle. Mid verbalization time points (VER_{Mid}) were used as points of high cognitive processing of the dual task and compared with the end of the verbalizations (VER_{End}) as points of low cognitive processing.

Results

VER_{Mid} and VER_{End} did not systematically occur in any phase of the gait cycle. However, 10/19 and 9/19 participants showed non-random distributions of verbalizations for VER_{Mid} and VER_{End} time points respectively ($p<0.01$), indicating that these walkers coordinated gait with the cognitive task. Analysis of subgroups of Verbalization Coordinators and Non-Coordinators showed slower verbalization response durations (VRD) for VER_{Mid} Coordinators compared to VER_{Mid} Non-Coordinators, indicating that VER_{Mid} Coordinators found the cognitive tasks more demanding. No differences were found in VRD for VER*End* Coordinators and VER*End* Non-Coordinators.

Significance

It was found that cognitive processing is coordinated with gait phases in some but not all healthy young adults during DT gait. When demands on cognitive processes are high, healthy young adults coordinate cognitive processing with phases of gait. Analysis of within-stride coordination may be of use for studying clinical conditions where gait and attentional cognition performance breaks down.

Key words: *Dual task, divided attention, serial and parallel processing, bottleneck, gait, stride time variability*

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Important discoveries about cognitive and motor processes have been made by considering attentional cognition and gait together[1,2]. It has provided important early insights into a number of neuropathological conditions such as dementia, fall risk[3], age-related declines in executive function and loss of mobility[4]. Dual task walking is the dominant paradigm used to study the interplay between attentional cognition and gait, and has been used to draw conclusions about the neural mechanisms subserving attentional cognition and gait[5]. Results from these methodologies have contributed to the development of theories, such as attentional capacity and divided attention capacity sharing[6,7], bottleneck [8]and multiple resource theory [9].

Inherent within the dual task paradigm is a requirement to prioritize tasks. It is assumed that participants may deploy different strategies to prioritize gait or the cognitive task. Prioritizing, for example, posture first or posture second is dependent on motor and cognitive capabilities, hazard estimation, postural reserve and intrinsic factors [1]. When there is capacity, young adults flexibly prioritize walking or talking dependent on the task constraints[10]. Changes in stride-to-stride variability of stride time (STV), is often measured to indicate the effect of the dual task on gait. Increases in STV are often interpreted as evidence for the increased involvement of attentional cognition in the control of gait and loss of gait stability[11]. The effect of the DT on either the cognitive task performance or STV is used to understand how tasks are prioritized and processed by the walker. However, these processes do not draw on resources consistently across individuals [7] and operate on timescales that could potentially change dynamically over the course of a trial resulting in, for example, serial processing of the motor and cognitive task[8]. Despite this potential to change, measurement methods do not take into account this flux. Therefore, it is possible that there is a change in prioritization over each stride that allows the dual task to be achieved.

It is possible to account for the fluctuations and complexity of the human movement system[12,13]. Specifically, in the area of gait analysis, tools have been developed from a dynamical systems theory (DST) perspective to account for the fluctuations and complexity of gait[14]. Coordination between the movements of, for example, body segments have been examined in terms of the phase relation and frequency locking behaviour[15,16]. Furthermore, locomotor-respiratory coupling has been observed in humans, where breathing and stepping frequency become entrained with each other’s rhythms[17,18]. A proposed explanation for this coupling is that the breathing cycle is coupled to phases of the gait cycle to exploit mechanical efficiency. Inspiration is coupled to a point immediately following heel strike and expiration to peak propulsion in order to minimize the antagonistic loading on the respiratory muscles and thereby improving energetic efficiency of breathing[19]. In dual-task gait, it may be the case that verbalization of the response is coupled to, or coordinated with the mechanical constraints of gait such that verbalization is coordinated with the phase of the gait cycle where expiration is most mechanically efficient (mid-swing to heel strike) and decoupled from the phase at which inspiration occurs (heel strike to mid stance) [19].

The coordination of gait with the dual task may alternatively reflect the coordination of neural activations in brain networks involved in walking and the cognitive task[20]. The prefrontal cortex is involved in exerting top-down control on task performance by biasing cognitive processing[21]. The dorsolateral prefrontal cortex has been identified as an important brain region implicated in task switching in DT gait[22,23]. Coordinating the cognitive task and a phase of the gait may result from coordinated switching of the neural networks activated during tasks[24]. However, little is known about how and when this switching occurs and what drives switching in DT gait. Therefore, the aim of this study was to examine the mechanism of coordination between gait and attentional cognition within the phases of the gait cycle. It was predicted that participants would coordinate verbalization of the cognitive task within six phases of the gait cycle [19]. If found, support for mechanical coordination would be seen if verbalizations occur in the phases when expiration is most mechanically efficient and not found when inspiration is least mechanically efficient. However, if coordination also occurred at other points of the gait cycle, then this would indicate coordinated switching of attentional resources during DT gait [22,23].

Method

Participants

A convenience sample of nineteen healthy young adults (15 females, mean ± SD: age, 22 ± 2 years; body mass, 67.1 ± 11.1 kg; height, 168 ± 10 cm) were recruited for this study.

Exclusion criteria for the study included known gait dysfunction, contraindications to walking exercise, neurological conditions or dyscalculia. Inclusion criteria included aged 18-60 years old, able to walk on a treadmill, able to understand instructions given in English and able to count for 120 s using English words for numbers. The University of Brighton Ethics committee approved this study. All methods were performed in accordance with the relevant guidelines. All participants gave written informed consent prior to participation in the study.

Procedure

Participants walked on a motorized treadmill (Life fitness CLST, Life Fitness, Cambridge, UK) for 120 s. Participants were instructed to walk as comfortably and as naturally as they could at their preferred walking speed whilst performing the cognitive task (dual task) and to prioritize neither task. The verbal instructions for these tasks were as follows: “walk as comfortably and as naturally as you can” and “perform as many subtractions as accurately as you can”. Preferred treadmill walking speed was determined using an established technique[25] where participants started walking at 2.0 $km.h^{-1}$, whilst speed was increased in 0.1 $km.h^{-1}$ increments until the participant reported that the speed equaled their preferred walking speed. The treadmill speed was then increased to 6.5 $km.h^{-1}$ and lowered in 0.1 $km.h^{-1}$ increments until the participant again identified their preferred speed. This process was repeated four times and the mean of the identified preferred walking speeds was used as the preferred walking speed. Participants walked at their preferred treadmill walking speed for 15-20 s before recording began.

Measures

Gait analysis

Gait variables were recorded using a wireless gait analysis system which consisted of three body worn sensors, each containing a gyroscope (OPAL, APDM, Portland, USA, for details see[26,27]). Two sensors were placed on the left and right shank, 4 cm superior and anterior to the malleolus. The third was placed on the lumbar trunk at the L5 spinous process. The sensors transmitted their data online to a wireless receiver linked to the Mobility Lab software package (Version 1, APDM, Portland, USA). Three separate temporal events, heel strike, toe off and mid-swing were identified through changes in shank angular velocity around the lateral-medio axis using a custom-built MATLAB (The MathWorks, Natick, MA, USA) script[28]. For both left and right leg data, midswing events were found from the peak shank angular velocity by finding the peaks that were greater than 0.3 radians.s^{-1} and at least 100 samples apart to make sure faster walkers' midswings were also detected. Heel strike and toe off events were identified by first applying a 3Hz low pass Butterworth filter then the inverse peaks before and after the midwing were identified. Next, using these inverse peaks as a starting location, a 10Hz low pass Butterworth filter was applied to the raw data and then inverse peaks found within the 10Hz data searching backwards in an empirically determined number of samples. The inverse peaks in the 10 Hz data was then used to identify heel strike and toe off events in the raw data. Heel strike in the raw data was identified by searching for the first inverse peak from midswing to the 10 Hz heel strike inverse peak. Toe off in the raw data was identified by searching for the first inverse peak from midswing to the 10 Hz toe off inverse peak (for further details of the method see [29]). For Left and right leg toe off, midswing and heel strike events were used to define the six phases of the gait cycle (see Figure 1). Left Double Stance (LDS) was defined as the time between left heel strike and right toe off. Right Initial Swing (RIS) was defined as the time between right toe off and right midswing. Right Terminal Swing (RTS) was defined as the time between right midswing and right heel strike. Right Double Stance (RDS) was defined as the time between right heel strike and left toe off. Left Initial Swing (LIS) was defined as the time between Left toe off and left midswing. Left Terminal Swing (LTS) was defined as the time between left midswing and left heel strike.

INSERT FIGURE 1 ABOUT HERE

Relative reliability was chosen as a measure of stride variability because this measure allows comparison between groups and walking conditions where mean values may differ, but variation may (or may not be) similar.

Verbalization times

Cognitive task performance and Verbalization times

Participants performed serial subtractions in sevens starting from a number between 590-599 which was recorded using a portable digital dictaphone (UX200, Sony, Tokyo, Japan) and analyzed off-line. The starting number for each trial was selected using the pseudo-randomization function in Microsoft Excel (Version 2013, Microsoft Corporation, Redmond, USA). The numbers of correct responses and errors were recorded (see Ellmers et al. [30]). Participants were instructed to make as many correct subtractions as possible in 120 s.

Verbalizations from the cognitive task were analyzed using QuickTime Media Player (Apple, Cupertino, California, USA) audio file playback to identify the time points that they occurred at. Audio files were analyzed at a temporal resolution of .01 ms. An audio tone signaled the start of the trial, at which point a marker was inserted into wireless accelerometry time series and the participant began counting backwards. Time points for every verbalization were recorded for the following two points: first, mid verbalization time (VER_{Mid}), which was defined as the start of the participant verbalizing the word 'and'. This point was selected as a point during the cognitive processing of the secondary task. Second, end verbalization time (VER_{End}), which was defined as the end of the verbalization of the last word for each three-digit number. This point was chosen as a marker of verbalization after completing secondary task cognitive processing. Verbalization Response Duration (VRD) was calculated as the difference in time (s) between the VER_{Mid} and VER_{End} and used as a marker of cognitive processing of the secondary task with longer VRD indicating longer cognitive processing times. It has been shown that calculation response times increase with increases in calculation difficulty and number of calculation subprocesses performed [31,32]. VRDs for one-digit, two-digit and three-digit transformations in the cognitive task for all participants were compared using paired samples *t*-tests. One-digit VRDs were significantly shorter than two-digit VRDs ($t(18)=5.267$, $p=0.00005$, $d=1.2$), but two-digit VRDs were not significantly shorter than three-digit VRDs ($t(18)=0.207$, $p=0.839$, $d=0.05$). Inter-rater reliability of the VRDs between two independent assessors was $r=0.973$.

Coordination of gait and verbalization

The frequency that both VER_{Mid} and VER_{End} verbalization times occurred in each of the six phases of the gait cycle were calculated using a bespoke algorithm in MATLAB

(The MathWorks, Natick, MA, USA). To locate the gait cycle that the VER $_{Mid}$ occurred in, first the start and end point of the gait data was identified by finding the first and last heel strike of the right foot in the 120 s trial. Then the absolute difference between the VER$_{Mid}$ and the right heel strike with the shortest duration away from the verbalization time for each VER$_{Mid}$ was calculated. If the nearest right heel strike that occurred was after the VER$_{Mid}$ then the first right heel strike before the VER$_{Mid}$ was used to define the start point of the gait cycle that the verbalization occurred in. If the nearest right heel strike occurred before the VER$_{Mid}$ then the next right heel strike after the verbalization was used to define the end of the gait cycle. The time of these events within the gait cycle was used to identify the phase that VER$_{Mid}$ occurred in for each verbalization for each participant. This process was repeated to find the phases of gait that VER$_{End}$ occurred at. To control for bias in the frequency counts resulting from differences in the gait phase durations, count density distributions were calculated for each participant's VER$_{Mid}$ and VER$_{End}$ based on the mean gait phase duration for each cycle analyzed.

After performing the dual task, participants reported their perceived effort on the task using a visual analogue scale with 1 being lowest effort and 10 being highest effort rating.

Data Analysis

All statistical analyses were performed in SPSS and MATLAB software packages. Data were checked for normality using the Shapiro-Wilk's test, non-parametric statistical tests were used if data violated normality assumptions.

To examine systematic effects in the coordination of gait and verbalization across all participants, One-way between-subjects ANOVAs were used to calculate differences in normalized density distributions between the six gait phases (LDS, RIS, RTS, RDS, LIS, RTS) for VER_{Mid} and VER_{End} times. To examine individual differences in the coordination of gait and verbalization, distributions of the VER_{Mid} and VER_{End} times across the gait phases were compared to chance level distributions using a chi-squared goodness of fit test (χ^2). To examine subgroup differences in those that coordinated gait and VER_{mid} and VER_{End} times and those that did not, two groups were created *post-hoc* using a median split of the Index of Coordination (Coordinators, Non-coordinators). Index of Coordination was calculated by dividing the individual χ^2 value of the normalized proportion of verbalizations in each phase by the sum of the absolute adjacent differences in the normalized proportion of verbalizations in phases. Coordination group was then used as a between subjects factor in a Two-way mixed design ANOVAs with Gait Phase as the within-subjects factor. To examine differences in cognitive processing time in Coordinators and Non-coordinators, independent samples *t*-test were used. Calculation of Verbalization Response Durations (VRD) were measured from the first verbalization of the 3-digit number to the final verbalization of the last digit but only when ones or ones and tens digits needed to be transformed in the cognitive task. Effect sizes were calculated using partial eta squared (ηp^2) for ANOVA effects and Cohen's *d* pairwise comparisons. The threshold for rejecting the null hypothesis was set at $p<0.05$.

Results

Group level analysis

Proportions of Normalized VER_{Mid}

No significant effect of Gait Phase was found in the normalized count density distributions of VER_{Mid} ($F_{(3.341,66.812)}=.702$, $p=0.569$, $\eta p^2=0.034$). Furthermore, no normalized proportion was significantly different to chance (all $p>0.05$). Proportions have been plotted for each condition in Figure 2.

INSERT FIGURE 2 ABOUT HERE

Proportions of Normalized VER$_{\text{End}}$

No significant effect of Gait Phase was found in the normalized count densities proportions ($F_{(2.819,56.358)}=.956$, $p=0.449$, $\eta p^2=.046$ Furthermore, no normalized proportion was significantly different to chance (all $p>0.05$). Proportions have been plotted for each condition in Figure 3.

INSERT FIGURE 3 ABOUT HERE

Proportions of Normalized VER$_{\text{End}}$

Individual analysis

To further investigate the coordination between gait and verbalization, post hoc analysis of individual data was conducted. An analysis of individual trends in verbalization patterns was carried out using χ^2 goodness of fit analysis for each participant. The VER$_{Mid}$ times revealed 10/19 participant's distributions of verbalizations were significantly different ($p<0.01$). A similar number of significant differences ($p<0.01$) was also found for the VER$_{End}$ times (9/19).

Subgroups analysis

To analyze subgroups, data was separated using a median split of the Index of Coordination into Coordinators and Non-coordinators. This created group sizes of 10/19 for the VER$_{\text{Mid}}$ subgroup classification and 10/19 for the VER$_{\text{End}}$ data. Table 1 contains summary statistics of the subgroups. Next, VRD as markers of cognitive processing were compared between the groups. Significant differences between VRDs for VER$_{\mathrm{Mid}}$ Coordinators and Non-coordinators were found (t(17)=2.365, p=0.03, d=1.10). Mean VRD for Coordinators was 1.40 s (SD=0.18), and 1.11 s (SD=0.32) for Non-coordinators. No significant differences between VRDs for VER$_{End}$ Coordinators and Non-coordinators were found (t(17)=1.361, p=0.18, d=0.59). Mean VRD for Coordinators was 1.37 s (SD=0.34), and 1.19 s (SD=0.29) for Non-coordinators.

INSET TABLE 1 ABOUT HERE

Normalized proportions of VER$_{Mid}$ across the gait phases for VER$_{Mid.}$ Coordinators and Non-coordinators showed no significant main effect of Phase ($F_{(5,\,95)}$=0.650, p=0.662, ηp^2=.033), nor an VER$_{Mid}$ Coordination by Phase interaction ($F_{(5,\,95)}$=0.467, p=0.800, ηp^2=.024). Additionally, no significant effects were found for the VER$_{End}$ Coordination Phase, $F_{(3.024,57.464)}$=.997, p=0.401, ηp^2=.050, nor an VER$_{Mid}$ Coordination by Phase interaction, $F_{(3.024,57.464)}$=1.976, p=0.127, ηp^2=.094.

No significant differences in the STV CoV were found between VER$_{Mid}$ Coordinators and Non-coordinators (t(17)=1.464, p=0.161 d=0.43, VER $_{Mid}$ Coordinators STV CoV mean=0.96, SD=0.12, VER $_{Mid}$ Non-Coordinators mean=1.08, SD=0.68).

No significant difference in the STV CoV were found for VER$_{End}$ between Coordinators and Non-coordinators t(17)=0.249, p=0.806, d=0.11, Coordinators mean=1.01, SD=0.22, Non-coordinators mean=1.03, SD=0.18).

Discussion

The aim of this study was to investigate coordination between gait and attentional cognition within the phases of the gait cycle. Group comparisons of the proportion of VER_{Mid} and VER_{End} during the six phases of the gait cycles did not differ significantly between gait phases they occurred at. However, individual analysis of this coordination between verbalization and gait phase showed significant differences in the distribution of VER_{Mid} and VER_{End} verbalization points across the gait cycle for fourteen of the nineteen participants ($p<0.05$) respectively. This does not support the prediction that mechanical coordination was responsible for this effect because verbalization was not linked to the phase of gait where the mechanical load on the diaphragm is known to be at its lowest[19]. The distribution of VER_{Mid} and VER_{End} proportions across the gait phases was not random for most participants and patterns were specific to individuals. Additionally, cognitive processing time of the cognitive task was significantly longer in those who showed evidence for coordinating VER_{Mid} with particular gait phases. VER_{Mid} are points in the cognitive task where processing is higher than VER_{End}. These findings support the prediction that there is dynamic switching of attentional resources during the dual task because verbalizations are not independent of gait phase and are not equally distributed across it. The coordination between gait and attentional cognition resulted from both motor and cognitive tasks using shared resources because those that required greater cognitive resources, indicated by longer VRDs, showed greater coordination between gait and the SERIAL 7 task.

No systematic group coordination between VER_{Mid} or VER_{End} and gait phase indicates that neither mechanical nor neural mechanism constrained the coordination of gait and the cognitive task to specific phases of the gait. By hypothesis, the lack of a mechanical mechanism constraining motor and cognitive coordination may have resulted from the load of the diaphragm not being great enough during the heel strike phase of the walking task. The invasive nature of measuring forces in the diaphragm prevented this measurement from being included in this study. However, this lack of a constraint would allow verbalization to be distributed across all phases of the gait cycle rather than coupled to the initial swing phase as seen in expiration during running (e.g. [19]). Additionally, the performance of the gait and cognitive tasks did not result in a systematic coordination pattern between the two tasks at the level of the group. But, coordination of gait and the cognitive task was seen at an individual level, suggesting there is no common neural processing constraints that drives this coordination. The exact mechanisms that causes dual-task interference remain controversial. It is widely assumed that dual-task effects arise when simultaneously performed tasks are controlled by a shared central resource[6,8,33]. Two competing theories have been proposed to explain the nature of this resource: the bottleneck and central capacity theories. The bottleneck theories posit that there is one central, limited, cognitive resource which operates serially. During dual-task performance, concurrent demands on this resource leads to a bottleneck in processing. Importantly, there is an assumption that tasks cannot be processed concurrently[8]. Central capacity theories posits that task performance is dependent on capacity-limited pools of cognitive resources which allows for the parallel processing of tasks[6]. Dual-task interference arises if one of the tasks places demands on a shared resource which exceeds its limited capacity[6,7]. The present data shows that healthy adults can dynamically switch the locus of control between walking and cognitive task performance indicating that the dual-tasks may be processed serially. This switching may reflect the coordination of neural activations during walking and the cognitive task[20]. The dorsolateral prefrontal cortex has been identified as an important brain region implicated in task switching in DT gait[22,23].

Individual differences in the coordination between tasks is consistent with the deployment of different strategies used by the participants. Here we provide evidence to support the view of Watanabe and Funahashi[24] that coordinating the cognitive task and a phase of the gait may result from coordinated switching of the neural networks activated during tasks. Herein the present study, we show that the shared motor and cognitive mechanism across participants do not constrain performance towards a similar spatio-temporal pattern across the gait cycle, and may result from differences in strategy or individual motor and cognitive constraints on DT gait. When there is capacity, young adults flexibly prioritize walking or talking depending on the available resources to act within the task constraints[10]. Additionally, we also show that prioritization of gait or the cognitive task is not necessarily an "either-or" process throughout the dual task. A cognitive task prioritization would result in verbalizations that were not evenly distributed across the phases of the gait cycle and presumably superior cognitive task performance, which was not seen in the data. Prioritization can change during DT gait.

What is driving the coordination between gait and the cognitive task in participants? The findings from our subgroup analysis support the view that cognitive processing during DT gait drives the coordination between gait and the cognitive task. Individuals that have higher indexes of coordination between VER_{Mid} and gait phase show longer VRD indicative of greater cognitive processing. However, those that have lower index of coordination between VER_{Mid} and gait phase have shorter VRD indicative of less cognitive, more automatic processing which has long been associated with less attentional capacity demands[34] and skillful task performance[35]. No differences were found between these comparisons when subgroups were separated by those that showed higher indexes of coordination between gait phase and VER_{End} and those that showed lower indexes. This finding is consistent with the literature showing dual task gait disrupts both gait and cognition[5], it is also consistent with researchers who have shown coordination between digit verbalization and gaze behavior during dual task gait[30]. However, the present study shows for the first time that when demands on cognitive processes are high enough, the walkers respond by coordinating motor and cognitive processes.

The lack of coordination of gait and cognition in those with shorter VRD reflects more automatic processing of the serial subtraction task and gait, indicating these processes may be performed using independent systems in these individuals. Furthermore, we did not find any evidence that high or low cognitive processing in the serial subtraction task interfered with STV, the most frequent marker of gait control in the literature[36]. It may be the case that coordination between gait and the cognitive task is a more sensitive marker of gait stability in the DT task walking paradigm. Somewhat contrary to the literature that argues cognitive task interferes with gait[5], we found that greater cognitive processing was indicative of greater coordination between gait and cognition. It may be that when cognitive resources are limited but not exhausted, participants deal with the cognitive processing demands of the dual task by coordinating motor and cognitive processes. However, by hypothesis, if cognitive processing requirements are greater than the resources available then there may be a breakdown in this coordination. In support of this proposal, it has been shown by Ellmers et al. [30] that the coordination between gaze behavior and gait breaks down under conditions of high cognitive load (serial subtraction secondary task), but coordination between serial subtraction verbalizations emerges. It may also be the case that those with personality traits to consciously ‘reinvest’ motor processes or have higher trait anxiety and alert attention to these processes in consciousness, are more likely to coordinate cognitive and motor processes. Thus, in turn they may have a greater propensity for dual tasks to break down under conditions of high cognitive load[30], which has been observed in older and clinical populations[37] or during more complex motor tasks, such as obstacle avoidance[38].

It has been argued that both low and high STV reflect gait stability[36], suggesting there is an ‘optimal’ gait speed that is less variable. These authors argue that functional adaptation to the walking environment is indicative of higher STV. Furthermore, it has been shown that greater STV is seen in over-ground compared with treadmill walking and that a dual-task increases this effect[39]. However, STV can be interpreted differently. To our knowledge, this is the first study to examine how gait and attentional cognition are coordinated during the gait cycle. This approach adds to the methods of analysis in the dual-task gait literature and may allow for a deeper understanding of the mechanisms of this coordination. Measuring the change in STV may not capture important within-stride effects. In addition, the argument that changes in STV indicate changes in cognitive control may be more nuanced. According to the DST approach, variability in gait may represent noise in the motor system or it may reflect functional adaptation to the task[40]. For example, long-range correlations with power law scaling of gait stride times show that the order of stride times are important as well as the size of the interval itself[41]. As such, variability can contribute positively towards achieving the movement goal, work against it or make no contribution, depending on the constraints which the individual is moving within[42]. Importantly, our approach allows us to capture individual differences in task performance, which may not be seen when STV and the effect of DT on STV is measured across groups to indicate gait stability.

We argue that our method of examining the coordination of gait and verbalization adds to the DST approaches to measuring of stability in gait alone[43]. It may provide a new measure to study conditions such as dementia, fall risk and age-related decline in executive function and loss of mobility where the breakdown of coordination between neuromotor and neurocognitive systems may be important, perhaps through dysfunctional frontal cortex activity and limited attentional resources[20].

In conclusion, for the first time, we have found within stride coordination between gait and verbalization, and that prioritization in DT gait is dynamic. This effect does not occur at a consistent phase in the gait cycle across participants and is not solely a result of biomechanical constraints. Individual differences in the coordination between verbalization and gait phase exist, reflecting strategic approaches adopted by the participants. Furthermore, there was evidence that longer cognitive processing time during the cognitive task is found in those that coordinate cognitive processing with gait phase, indicating that there may be shared cognitive and motor resources in some but not all participants during DT gait and that efficient task processing in the cognitive task may reduce demand on shared resources.

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Author Contributions

The conceptual design was conceived by NS, JW and MV. All authors contributed to the acquisition and analysis of the data. NS, JW and MV contributed to the interpretation of the data and the drafting of the manuscript. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Figure titles

Figure 1. Example angular velocity of the left (green line) and right shank (red line) during the six phases of a gait cycle for one participant. Grey bars represent the Count Density of articulation (arbitrary units) of all mid articulation times (VER_{mid}) across the Left Double Stance (LDS), Right Initial Swing (RIS), Right Terminal Stance (RTS), Right Double Stance (RDS), Left Initial Swing (LIS) and Left Terminal Stance (LTS) gait phases. Count Density normalizes the proportion of articulations to control for different gait phase durations. The width of the Grey bars represents the duration of the gait phase as a percentage of the gait cycle. For this participant, the highest count density of articulations occurred in the LTS phase.

Figure 2. Percentage of VER_{Mid} within each gait phase for all participants. Black line represents the condition mean and each grey dot represents one participant's data. LDS is Left Double Stance, RIS is Right Initial Swing, RTS is Right Terminal Swing, RDS is Right Double Stance, LIS is Left Initial Swing, LTS is Left Terminal Swing.

Figure 3. Percentage of VER_{End} within each gait phase for all participants. Black line represents the condition mean and grey dots represent the participants' data. LDS is Left Double Stance, RIS is Right Initial Swing, RTS is Right Terminal Swing, RDS is Right Double Stance, LIS is Left Initial Swing, LTS is Left Terminal Swing

Tables

Table 1. VER_{Mid} *and* VER_{End} Coordinators and Non-coordinators participant characteristic, gait and articulation measures.