Gait Performance is not Influenced by Working Memory When Walking at a Self-selected Pace

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Grubaugh, J. & Rhea, C.K. (2014). Gait performance is not influenced by working memory when walking at a self-selected pace. *Experimental Brain Research, 232(2),* 515-525.doi: 10.1007/s00221-013-3759-y

The final publication is available at Springer via http://dx.doi.org/10.1007/s00221-013-3759-y

Abstract:

Gait performance exhibits patterns within the stride-to-stride variability that can be indexed using detrended fluctuation analysis (DFA). Previous work employing DFA has shown that gait patterns can be influenced by constraints, such as natural aging or disease, and they are informative regarding a person's functional ability. Many activities of daily living require concurrent performance in the cognitive and gait domains; specifically working memory is commonly engaged while walking, which is considered dual-tasking. It is unknown if taxing working memory while walking influences gait performance as assessed by DFA. This study used a dual-tasking paradigm to determine if performance decrements are observed in gait or working memory when performed concurrently. Healthy young participants (N = 16) performed a working memory task (automated operation span task) and a gait task (walking at a self-selected speed on a treadmill) in single- and dual-task conditions. A second dual-task condition (reading while walking) was included to control for visual attention, but also introduced a task that taxed working memory over the long term. All trials involving gait lasted at least 10 min. Performance in the working memory task was indexed using five dependent variables (absolute score, partial score, speed error, accuracy error, and math error), while gait performance was indexed by quantifying the mean, standard deviation, and DFA α of the stride interval time series. Two multivariate analyses of variance (one for gait and one for working memory) were used to examine performance in the single- and dual-task conditions. No differences were observed in any of the gait or working memory dependent variables as a function of task condition. The results suggest the locomotor system is adaptive enough to complete a working memory task without compromising gait performance when walking at a self-selected pace.

Keywords: Dual-tasking | Gait | Working memory | Variability

Article:

Introduction

Human gait is a complex task that involves input from the cerebellum, basal ganglia, motor cortex, and other proprioceptive sensors to carefully control locomotor behavior (Hausdorff *2007*). Further, increasing the complexity of gait control is the fact that it must be altered in the context of environmental challenges such as static obstacles (e.g., a tree or lamp post) or moving obstacles (e.g., pedestrians or vehicles). For successful navigation in one's environment, it is important for a human to be able to change his/her stride (i.e., to exhibit gait variability) to meet these challenges—a concept termed functional mobility (Hausdorff *2007*; Stergiou and Decker *2011*; Rhea and Kiefer *2013*). Thus, functional (or dysfunctional) gait behavior is tied to an actor's ability to adapt his/her gait in a specified manner. This is best tested by examining the overground gait response while the task complexity is manipulated. Alternatively, a common proxy for examining adaptive gait ability is to quantify different gait variables—such as gait variability—that emerge during steady state locomotion, which is a conventional method in the clinical gait literature to examine functional ability (von Porat et al. *2006*; Stolze et al. *1997*; Olmo and Cudeiro *2005*).

Stride-to-stride variability has been reported for over 100 years (Vierordt *1881*), and it is commonly expressed as the standard deviation around the mean of the time between strides. Theories examining functional gait control have typically focused on the *magnitude of variability* via the standard deviation or coefficient of variation in gait behavior. For example, it is posited that functional behavior may be reduced when rigid behavior (low variability magnitude) emerges because it may be difficult for the actor to transition to a new behavior (Stergiou and Decker *2011*; Hausdorff *2007*). It should also be noted that very skilled actors exhibit low variability magnitude in their movement patterns, which makes them accurate for a particular task, but may make them less adaptive if asked to suddenly switch to a new task. Functional behavior may also be reduced when a large range (high variability magnitude) in the behavior emerges because it may be difficult for the actor to specify a particular response to a perturbation (Vaillancourt and Newell *2002*). Research over the past 20 years has begun to not only examine the magnitude of variability in the behavior, but also how the variability is structured (Hausdorff et al. *1995*, *1996*; West and Griffin *1999*; Scafetta et al. *2009*; Dingwell and Cusumano *2000*; Jordan et al. *2009*; Buzzi et al. *2003*). Studies focusing on the *structure of variability* have revealed that variability in gait is necessary in order to adapt to external and internal factors (see Rhea and Kiefer (*2013*) for a review). Thus, stride-to-stride variability can be described on a continuum between adaptive to maladaptive variability. Adaptive variability describes when individuals' skeletal, muscular, and neurological systems productively work together in order to allow for functional mobility (Rhea and Kiefer *2013*). On the contrary, maladaptive variability refers to difficulty in coordinating these systems, leading to suboptimal or limited mobility.

There are a number of factors that may influence an actor's ability to exhibit functional mobility. Constraints to the nervous system via natural aging or pathology have been shown to alter the structure of variability in gait, indicating reduced functional capacity (Hausdorff et al. *1997*, *2000*; Buzzi et al. *2003*). Likewise, constraints to the task, such as walking slower or faster than the preferred walking speed, have also been shown to alter the structure of variability in gait (Jordan et al. *2006*, *2007a*, *b*; Buzzi and Ulrich *2004*). Task constraints can be further increased by adding an additional task—commonly termed dual-tasking. The dual-task paradigm has been used in the psychometrics and motor behavior literature as a method to determine which task has priority when they are performed concurrently (Hausdorff et al. *2008*; Mitra and Fraizer *2004*; Woollacott and Shumway-Cook *2002*; Ebersbach et al. *1995*). The interest in cognitive and motor dual-tasking likely stems from the commonality in which these two tasks are performed in activities of daily living (ADLs). It is not uncommon to be actively recalling information while walking. However, the secondary cognitive task may interfere with the control of gait, potentially increasing the likelihood of a fall. Previous work has examined compensatory behavior when walking and memorizing tasks are performed concurrently, and it has been shown that there is an interaction between gait and cognitive tasks, especially as task complexity increases and when age is taken into consideration (Li et al. *2001*; Lindenberger et al. *2000*). This has led many researchers to use the dual-task approach as a means of identifying injury risk when examining gait behavior in aging and clinical populations (Springer et al. *2006*; McCulloch *2007*; Camicioli et al. *1997*; Haggard et al.*2000*; Plummer-D'Amato et al. *2008*).

The influence of the cognitive task on gait may depend on the nature of the task. Many ADLs require the need to engage working memory while walking. Working memory is described as the ability to hold information in order to perform either verbal or nonverbal tasks, and it requires an active awareness and management of information despite interfering distractions (Becker and Morris *1999*). It is involved in one's ability to reason, solve problem, comprehend language, and establish long-term learning (Engle *2002*). Working memory should be distinguished from earlier models of short-term memory, which simply focused on storage (Baddeley and Hitch *1974*). Working memory performance is limited by the amount of resources an individual has to allocate to the task or multiple tasks, which is referred to as working memory span (Baddeley *1986*; Cowan *2001*). Therefore, when one is required to perform concurrent tasks, an individual draws from the same resources resulting in a competition of resources between tasks (Beilock *2007*; Wickens *2002*). One or both tasks could require working memory or simply draw from a similar resource pool (e.g., attention). Two alternatives to the resource-competition model have been proposed—the facilitatory control hypothesis and the adaptive-resource-sharing model. The facilitatory control hypothesis posits that a primary task may enable performance on a secondary task, so increased variability in the primary task should not be interpreted as dysfunctional behavior (Riccio and Stoffregen *1988*; Stoffregen et al. *1999*). For example, when examining postural control during a standing and reaching task, increased variability in postural control should not be interpreted as dysfunctional because it may have facilitated increased performance in the reaching task. The adaptive-resource-sharing model suggests that behavior in the primary and secondary tasks is dependent on task difficultly (Mitra and Fraizer *2004*). If the primary task is perceived as more difficult, then resources may be shifted to that task to enable performance, while performance on the secondary task suffers. Conversely, performance on the primary task may decline if the secondary task is perceived as more difficult.

Two our knowledge, only one study in the dual-tasking literature has examined the structure of variability in the performance of a concurrently performed cognitive and gait task. Kiefer et al. (*2009*) had participants to perform three tasks: (1) walking only (gait task), (2) tapping a button to estimate one-second intervals (cognitive task), and (3) walking while tapping a button to estimate one-second intervals (gait and cognitive task performed concurrently). The researchers found that the structure of variability in gait was preserved in the dual-task condition, but the structure of variability in the timing estimate was compromised. This finding provides support for the "posture first principle" introduced by Woollacott and Shumway-Cook (*2002*), which suggests that posture tasks take priority over cognitive tasks when they are performed concurrently due to the inherent physical risk of reduced motor performance (e.g., a trip or fall).

Since memory recall is commonly performed during gait, the current project was designed to further this line of research by specifically examining the influence of working memory on gait performance. Thus, the purpose of this study was to examine gait performance [stride interval mean and variability (magnitude and structure)] when performed in isolation and concurrently with a working memory task. Based on previous literature, it was hypothesized that gait performance would be preserved in the dual-tasking condition, while a decrement in working memory performance would be observed when performed concurrently with gait.

Methods

Subjects

Twenty-one participants were recruited from the undergraduate population at the University of North Carolina at Greensboro (UNCG). Five of the 21 original participants' data were dropped from this sample due to technical difficulties with the data collection. Data from three males and 13 females (age: 20.3 ± 1.7 years; height: 1.67 ± 0 .08 m; weight: 68.7 ± 13.5 kg) were used in the study. The UNCG Institutional Review Board approved all procedures, and all participants signed an informed consent. The participants self-reported no history of lower extremity injury or neuromuscular disorders that inhibited normal walking and had normal or corrected-to-normal vision.

Materials

Working memory task

The automated operation span task (Aospan) was used as the working memory task (Unsworth et al. *2005*). The Aospan is a computer-administered task written in E-Prime version 2.0 that is presented visually and scores itself to prevent administrator error. The Aospan task has good internal consistency (α = .78) and test–retest reliability (r = .83) (Unsworth et al., *2005*). Unlike previous research that allowed the participants to control a mouse to indicate their answers (Unsworth et al., *2005*), the current project used an experimenter to control the mouse and the answers were indicated verbally by the participants. This allowed for a similar response style when performing the Aospan at the computer terminal and when walking.

The Aospan task consisted of three separate practice sections (with each section lasting about 2–4 min). The first section was intended for remembering letters, and one letter at a time was presented visually on the screen for 800 ms. After a set size was complete (practice set sizes ranged from two to three letters presented in a row), participants were prompted to verbally recall the letters in the order they appeared (this portion was untimed). In the second section, participants were visually presented with individual math problems (e.g., $(5 \times 3) - 7$) on the screen. They were asked to mentally solve them as quick as possible and then indicate when they were ready to move on to the next screen, which contained a potential solution (e.g., 8) and boxes indicating “true” or “false.”. The participants verbally indicated whether the answer was true or false and the experimenter clicked on the box chosen by the participants. This practice session consisted of 15 math problems and the mean time to complete each math problem (time interval from initial presentation to the indication to move to the answer screen) was calculated. The mean time plus 2.5 standard deviations was used to prescribe the time limit for the math problems in the actual test.

The third practice section combined the first two sections. First, a math problem was visually displayed on the screen and the participant was asked to mentally solve it. Next, the participants were asked if a solution was true or false, and then a letter was presented visually on the screen for later recall. These math-word pairings occurred in set sizes ranging from two to three in the practice phase, and participants were asked to recall the letters at the end of each set in the order they were presented. After each math problem, participants were provided with a red number in the upper-right-hand corner of the screen that represented the percentage of math problems they were completing correctly. They were expected to keep that number above 85 %, an accuracy criterion set by Unsworth et al. (*2005*) to ensure that the participants were doing the task as accurately as possible. The actual testing trial used to test cognitive performance in single- and dual-tasking was the same format as the third practice section (i.e., math problem → true/false response → letter presentation). The math-word pairings occurred in set sizes of three to seven in the actual testing trial and a total of 75 math problems and 75 letters were presented.

Cognitive performance in the working memory domain was indexed using five dependent variables provided by the Aospan: (1) absolute score, (2) partial score, (3) speed errors, (4) math errors, and (5) accuracy errors. The absolute score was calculated as the sum of scores for all perfectly recalled sets. The partial score was the number of letters recalled in the correct serial position. Math errors were the total number of recorded task errors, which was then broken down into speed and accuracy errors. A speed error occured when a participant was unable to respond to the mathematical operation within the time allowed. An accuracy error described when a participant answered a math problem incorrectly.

Gait task

All walking trials (single- and dual-tasking) occurred on a treadmill (Simbex, Lebanon, NH) at each participant's preferred walking speed (1.15 ± 0.32 m/s). The front of the treadmill was located 1.5 m from a wall containing a 1.65 m tall × 2.95 m wide projection screen. The Aospan task was projected onto the screen in the dual-tasking condition, and participants were asked to verbally respond to the experimenter commanding the Aospan task. Reflective markers were placed on the lateral aspect of the mid-thigh, the knee, and the mid-shank and recorded at 200 Hz with a motion capture system (Qualysis, Gothenburg, Sweden). Gait data were reduced to sagittal plane knee angles, which were further reduced to stride interval times by determining the time between peak knee flexion of the right limb for each stride. This peak-to-peak method has been used previously to create a time series that indexes stride-to-stride behavior (Kiefer et al.*2009*; Rhea et al. under review; Jordan et al. *2009*).

Gait performance was indexed computing the stride interval mean, magnitude of the stride interval variability (standard deviation), and structure of the stride interval variability. The latter was quantified by submitting the stride interval time series to detrended fluctuation analysis (DFA) to examine patterns in the knee angle time series in each of the conditions. The details of DFA have been published extensively elsewhere (Peng et al.*1994*; Hausdorff et al. *1995*; Rhea and Kiefer *2013*), but they are briefly outlined here. First, the time series is integrated by subtracting the mean from each data point using the equation:

$$y(k) = \sum_{i=1}^{k} [S(i) - S_{ave}]$$, (1)

where $y(k)$ = the integrated time series, $S(i)$ = the original time series, and S_{ave} = the mean of the original time series. Next, this time series is separated into boxes that consist of an equal number of data points. The box size ranged from $n = 4$ to $n = N/4$, with n representing the number of data points in each box and Nrepresenting the total number of data points in the time series. A trend line is fit to the data in each box and the remaining fluctuations ($F(n)$) are then quantified using the root-mean-square method:

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - y_n(k)]^2}$$,(2)

Lastly, the root-mean-square value is plotted with the log of F(n) on the y axis and the log of the box size on the x axis. A least squares line is used to measure the slope of the data and corresponds to the DFA α value, which describes the long-range correlations and indicates the strength of those values (Fig. 1). In human gait, DFA α is typically around 0.75, whereas a constraint from natural aging, pathology, or injury can drive DFA αtoward 0.5 or 1.0, depending on the context. DFA α values tending toward 0.5 indicate weaker long-range correlations, potentially reflecting reduced fine-tuned motor control. Conversely, DFA α values tending toward 1.0 indicate stronger long-range correlations, possibly reflecting more rigid control.

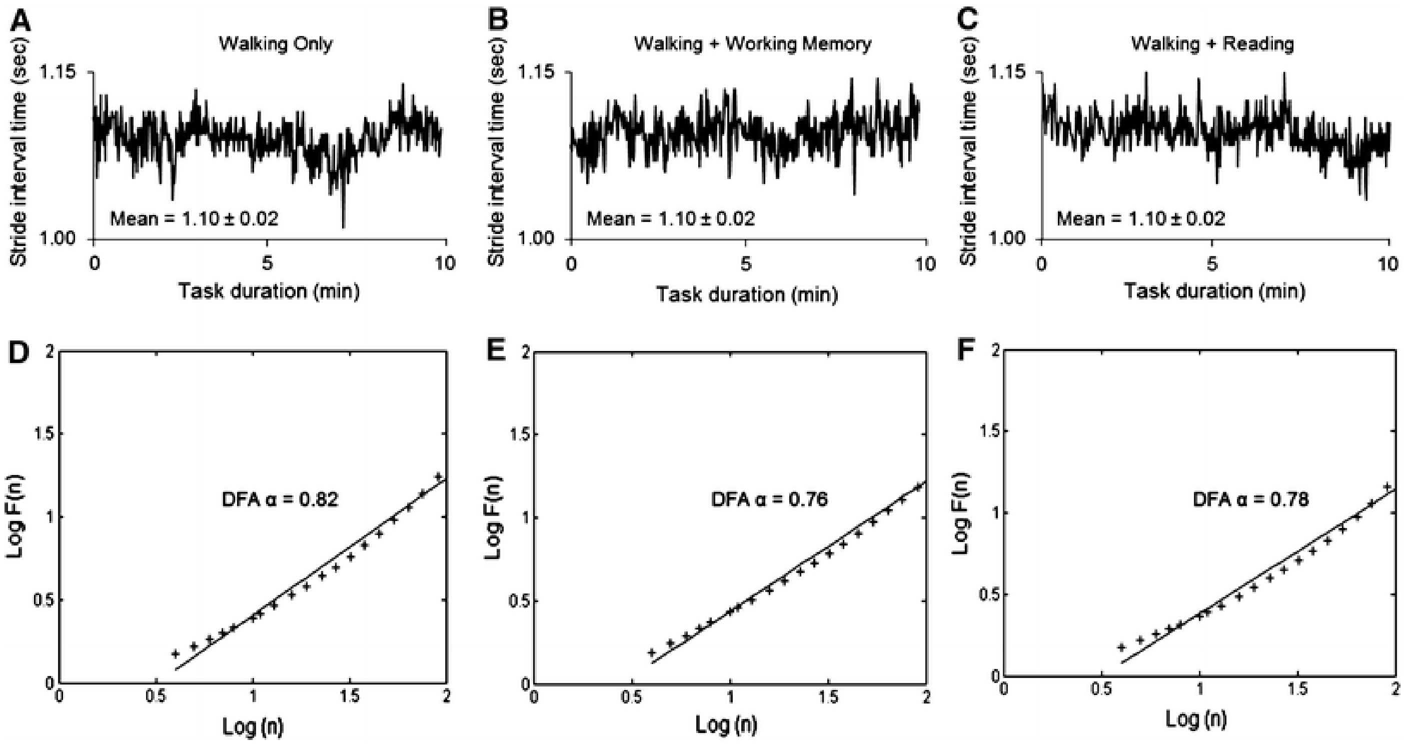

Fig. 1 Stride interval time series for one participant in each of the three conditions (**a**, **b**, **c**) and the corresponding DFA plots for each time series (**d**, **e**, **f**)

Experimental procedure

Participants were tested individually within a single session (~2 h). Prior to starting any tasks, the participants completed an informed consent form and a short questionnaire about their demographics and history of physical activity and injuries.

Next, the participants walked on the treadmill for a 1-min familiarization period prior to beginning the experiment. Participants self-selected a comfortable speed similar to one they would use while walking across campus. After the speed was chosen, this speed was held constant throughout the three conditions that included walking: (1) walking only (single-task), (2) walking while performing the working memory task (dual-task), and (3) walking while reading (dual-task). A fourth condition of testing working memory only (single task) was also included and a 5-min break was provided after each condition. The walking alone condition was always presented first, and the order of all other conditions was randomized. The walking only condition was presented first because past studies have shown that gait can have a trial carryover effect when gait patterns are purposely altered (Rhea et al. *2013*; Hove et al. *2012*). Thus, in order to get a baseline of gait performance, the walking only task needed to be performed first. In the walking only condition, the participants walked at their self-selected pace for 10 min.

The working memory only condition consisted of completing the Aospan task while sitting at a computer terminal that lasted 10–15 min depending on the participants' speed in answering the questions. Participants were asked to sit in this trial in order to keep the procedure similar to the one used in Unsworth et al. (*2005*). Rather than requiring participants to respond to the Aospan task with a mouse, participants were asked to verbally respond to the Aospan task while the experimenter drove the mouse. This process was implemented to keep it similar to the procedure in the dual-task condition (walking while performing Aospan task). The participants completed three practice sections and then the actual testing trial. In the first practice section where participants were asked to remember the letters presented to them on the screen, participants remained silent until they were prompted to recall the letters in proper order. Once prompted, they would announce verbally to the experimenter the order of the letters. In the second practice section where participants solved math problems, they mentally solved the math problems and then verbally told the researcher whether the solution provided was true or false. In the third practice section and the actual testing trial where memorizing letters and solving math problems were combined, the participants responded verbally to the researcher whether the individual math solutions were true or false, and then at the end of each set size they verbally recalled the letters in the order they remembered them.

In the walking while performing the working memory task condition, participants responded the same as they were in the working memory only task. However, rather than being seated, participants walked at their self-selected speed on the treadmill while completing the Aospan task for approximately 10–15 min (duration of task was dependent on the speed of the participant). Participants were asked to verbally respond to the Aospan task so the experimenter could drive the mouse.

Lastly, a second dual-task condition of walking while reading a textbook chapter on the projection screen was used. The walking while reading task was included to test if gait dynamics changed simply due to performing a different visual task (one that does not relate to short-term working memory) while walking. If a change in gait dynamics from the single-task condition (walking only) to the second dual-task condition (walking while reading) were to be observed, then changes in gait may be attributed to the visual processing and long-term working memory rather than the influence of taxing short-term working memory. In the walking while reading task, participants were asked to walk on the treadmill at the previously self-selected pace while silently reading the article up on the projection screen (the same screen used in the walking plus working memory task). The participants were told to read the article for understanding, and they would be asked questions after the 10 min trial to check for understanding. Once the participants were on the treadmill, the researcher sat at the computer driving the mouse, and the participants verbally told the researcher when to scroll down within the document. After 10 min of reading while walking, participants were asked questions to confirm they were actually doing the reading task. These questions came from the first few pages of the article to make sure that each participant would have advanced that far in the reading and would be able to sufficiently answer the questions after reading those pages. The book chapter was *On the Interplay of Emotion and Cognitive Control: Implications for Enhancing Academic Achievement* (Beilock and Ramirez *2011*).

Data analysis

Prior to testing our hypotheses, a number of preliminary analyses were conducted on the data. First, the homogeneity of the data was examined using Levene's test of equality of error variances. Next, since the number of data points in a stride interval time series can influence the structure of variability (Damouras et al.*2010*), the number of strides taken in each gait condition (walking only, walking with short-term working memory, and walking while reading) was compared using a repeated measures ANOVA. Lastly, the influence of task order was examined by dividing the participants into two groups. Group one performed the working memory only condition first and the working memory while walking condition second and group two performed the opposite order. Each gait performance and working memory performance metric was compared between groups using an independent samples *t* test.

To test our hypotheses, a MANOVA was used to determine whether task condition influenced gait performance (stride interval mean, standard deviation, or DFA α) or working memory performance (absolute score, partial score, speed error, accuracy error, or math error). Alpha was set at .05. Follow-up tests were used as appropriate.

Results

Preliminary analyses

Homogeneity of data

Levene's test of equality of error variances showed there were no differences in the variances of each metric across conditions (all $p > .05$). Thus, parametric tests were used for the main analyses.

Number of strides in each condition

A repeated measures ANOVA showed that the number of strides differed by condition, $F(2, 30) = 24.54$, $p < .01$. Follow-up Bonferroni corrected paired-sample *t* tests showed that the number of strides were not significantly different between the walking only (440.6 ± 43.6) and walking while reading conditions (427.2 ± 46.9), $t(15) = 1.42$, $p = .18$. However, the working memory task while walking condition (536.6 ± 95.3) contained significantly more strides than the walking only condition, $t(15) = -4.82$, $p < .01$ and the walking while reading condition, $t(15) = -5.57$, $p < .01$, presumably because the working memory condition lasted longer than the other two conditions. To determine whether the number of strides influenced the structure of variability in the gait data sets, all data sets were truncated to the fewest strides taken by any participant in any condition ($n = 353$), and DFA was run on both the original and truncated data sets. A 2 × 3 repeated measures ANOVA was used to determine whether the two types of data sets (original or truncated) influenced DFA α in any of the three conditions (walking only, walking while reading, or walking while performing the working memory task). The data type by condition interaction was not significant, $F(2,30) = 1.78$, $p = .19$, nor was the main effect for condition, $F(2,30) = 1.01$, $p = .38$. However, a main effect of data type was observed, $F(1,15) = 10.16$, $p < .01$, signifying that the means of each data type were different. This suggests that truncating data to an equal number of data points did influence the DFA alpha values and should warrant future examination. However, since the main question in this paper concerns gait performance across conditions, and the data type by condition interaction was not significant, we elected to use the full data set (nontruncated) in doing the main analyses.

Effect of task order

No differences were observed in any of the gait or working memory metrics between groups ($-.14 < t < .31$ and $.09 < p < .93$), indicating that there was no effect of task order. Thus, the order of tasks was removed from the subsequent analyses.

Main analyses

No differences across conditions were observed in gait performance, $F(6,86) = 0.31$, $p = .93$ or cognitive performance $F(4,27) = 0.82$, $p = .52$. A summary of gait performance for each participant is shown in Table 1, and a summary of cognitive performance is shown in Table 2. A stride interval time series and corresponding DFA plot is shown in Fig. 1 for each condition for participant 8.

Table 1 Mean, standard deviation, and DFA α of the stride interval time series for each participant

Participant	**Single task**			**Dual task**					
	Walking only			**Walking + reading**			**Walking + working memory**		
	M	**SD**	**DFAα**	**M**	**SD**	**DFAα**	**M**	**SD**	**DFAα**
1	1.50	0.05	0.60	1.57	0.05	0.61	1.56	0.04	0.66
2	1.23	0.02	0.73	1.27	0.03	0.66	1.24	0.04	0.66
3	1.28	0.04	0.76	1.44	0.06	0.82	1.40	0.07	0.69
4	1.38	0.03	0.67	1.34	0.03	0.71	1.30	0.04	0.77
5	1.55	0.07	0.87	1.59	0.05	0.68	1.58	0.07	0.82
6	1.46	0.04	0.70	1.46	0.05	0.70	1.39	0.05	0.80

7	1.63	0.08	0.82	1.59	0.09	0.72	1.45	0.07	0.81
8	1.10	0.02	0.82	1.10	0.02	0.76	1.10	0.02	0.78
9	1.34	0.04	0.86	1.32	0.05	1.11	1.34	0.03	0.76
10	1.33	0.03	0.71	1.34	0.03	0.75	1.34	0.03	0.83
11	1.36	0.03	0.83	1.36	0.03	0.81	1.34	0.04	0.84
12	1.41	0.06	0.77	1.42	0.06	0.77	1.43	0.04	0.67
13	1.28	0.03	0.58	1.29	0.03	0.61	1.26	0.03	0.65
14	1.39	0.04	0.84	1.36	0.03	0.75	1.36	0.04	0.61
15	1.29	0.03	0.81	1.30	0.02	0.71	1.28	0.07	0.71
16	1.45	0.04	0.68	1.54	0.05	0.59	1.51	0.05	0.62
Mean	1.37	0.04	0.75	1.39	0.04	0.74	1.36	0.05	0.73
SD	0.13	0.02	0.09	0.13	0.02	0.12	0.12	0.02	0.08

No differences were observed in any of the metrics across tasks (all $p > .05$)

Table 2 Scores for all components of the AOSPAN task for each participant

Participant	**Single task**					**Dual task**				
	Working memory only					**Walking + working memory**				
	Absolute	**Partial**	**Speed error**	**Accuracy error**	**Math error**	**Absolute**	**Partial**	**Speed error**	**Accuracy error**	**Math error**
1	31	44	0	1	1	22	45	1	1	2
2	32	59	5	0	5	44	61	0	3	3
3	10	33	0	5	5	11	25	0	2	2
4	35	61	0	3	3	44	62	0	0	0
5	9	20	0	0	0	57	65	0	0	0

6	14	35	0	0	0	32	48	0	3	3
7	0	19	0	2	2	32	50	1	2	3
8	26	47	1	0	1	18	44	0	0	0
9	44	60	1	0	1	25	54	0	0	0
10	0	23	0	1	1	29	51	0	0	0
11	9	33	1	2	3	22	37	1	1	2
12	57	67	0	0	0	49	60	0	1	1
13	7	29	0	3	3	8	23	0	1	1
14	21	38	0	3	3	13	43	0	1	1
15	10	30	0	2	2	14	37	1	1	2
16	7	43	0	3	3	8	36	0	2	2
Mean	19.5	40.1	0.5	1.6	2.1	26.8	46.3	0.3	1.1	1.4
SD	16.5	15.2	1.3	1.5	1.6	15.3	12.6	0.4	1.0	1.1

No differences were observed in any of the metrics across tasks (all $p > .05$)

Discussion

The goal of this study was to determine whether gait performance was influenced by a working memory task when both tasks were performed concurrently. We hypothesized that gait performance would be preserved in dual-tasking, but working memory performance would show a decrement. The results showed that neither gait performance nor working memory performance declined in the dual-tasking condition, suggesting that both tasks could be performed equally well when performed alone or while walking at a preferred speed. The findings are discussed in the context of constraints on the locomotor system and models of dual-task performance.

Our results support the findings of Kiefer et al. (*2009*), who adopted a dynamics framework to investigate dual-task performance. Their research investigated performance in gait and cognitive tasks completed in isolation and concurrently by examining the mean, magnitude of variability (standard deviation), and structure of variability (DFA α and fractal dimension) of the performance in each domain. Treadmill walking at a preferred speed was used as the gait task and a timing estimation task was used as the cognitive task, and the participants had to estimate one-second intervals by pressing a button over the 16-min trials. Similar to our findings, Kiefer et al. (*2009*) showed no changes in mean, standard deviation, or DFA α in the gait task when performed in the dual-task condition. They also showed no differences in the mean cognitive performance in the dual-task condition; a finding also observed in our current study. However, Kiefer et al. (*2009*) also examined the magnitude and structure of variability in the cognitive performance task. While magnitude (standard deviation) did not differ, the structure of variability (DFA α and fractal dimension) was altered in the dual-tasking performance. Taken together, the authors suggested that gait may be granted priority when performed concurrently with a cognitive task, since a decrement in gait may lead to a fall and potential injury. This postulate supports the posture first principle, which suggests that tasks involving balance can take priority in a dual-task situation (Woollacott and Shumway-Cook *2002*). No hierarchy in task performance was identified in our study, indicating that task competition was not at a level where one task needed to take priority.

Gait performance while concurrently performing a working memory task has been examined previously (Lövdén et al. *2008*; Verrel et al. *2009*; Schaefer et al. *2010*). While these previous studies used age as an independent variable, parallels between this previous work and our current work can be drawn when comparing the data between the young adult groups in each paper. For example, Lövdén et al. (*2008*) showed that cognitive performance is preserved when dual tasking; a finding that is supported by our data. However, we did not find any changes in gait performance when performed with the working memory task, which is inconsistent with the previous research (Lövdén et al. *2008*; Verrel et al. *2009*; Schaefer et al. *2010*). This difference is most likely due to the nature of the question posed in our current work compared with previous research. We were primarily interested in examining the structure of variability in gait in single- and dual-tasking situations. This research question emerged from the plethora of research that has examined the structure of variability in gait using DFA, and it has been shown that long-range correlations are influenced when a variety of neurological or task constraints are imposed (see Hausdorff (*2007*) for a review). A logical question to pursue was whether long-range correlations in gait are also influenced when a working memory task is performed while walking. Our results showed that DFA α in gait was unaffected by a concurrent working memory or reading task, supporting the findings of Kiefer et al. (*2009*). While previous work has shown that changes to the magnitude or structure of gait variability in dual-tasking exist (Lövdén et al. *2008*; Verrel et al. *2009*; Schaefer et al. *2010*), these findings are limited to smaller data collection times (20 s) compared with the current study (10 min). Thus, our finding that performance is preserved in gait (as assessed by DFA) and working memory (as assessed by the working memory Aospan task) in a 10 min dual-tasking trial is a novel contribution to the literature.

While performing an initial task, the addition of a second task can be conceptualized as an added constraint on the control system. Constraints to the nervous system have been shown to influence gait performance (Hausdorff et al. *1997*, *2000*; Buzzi and Ulrich *2004*). However, constraints via a secondary task may not automatically influence performance on the initial task. Several models have been proposed to describe whether and how a second task would influence the initial task. In the case of the resource-competition model (see Wickens (*2002*) for a review), a limited number of resources are available to be shared between tasks. Thus, if optimal performance in both tasks requires more than the allotted availability of resources, either (1) one task takes priority and the second task suffers or (2) performance in both tasks decreases. Alternatively, the facilitatory control hypothesis suggests that one task may act to enable performance on the other task (Riccio and Stoffregen *1988*; Stoffregen et al. *1999*). Lastly, the adaptive-resource-sharing model posits that task difficulty dictates how the resources are allotted to drive performance (Mitra and Fraizer *2004*). While our experiment was not designed to test competing dual-tasking theories, it appears that performance in the working memory and gait domains does not interact in a manner that leads to a decrement in performance when walking at a preferred speed. This could be due to an abundance of resources available to complete both tasks (resource-competition model), or gait is not reliant on working memory for optimal performance (facilitatory control hypothesis), or the combined task difficulty between the two tasks was not high enough to require a sharing of resources (adaptive-resource-sharing model). Future research should design experiments to systematically test each dual-tasking hypothesis.

In Kiefer et al. (*2009*), it is plausible that the gait task interfered with the timing estimation task because both tasks shared a common timing requirement. In our study, we elected to use a working memory task as our secondary task because of its ties with ADLs. However, this also allowed us to use a secondary task that did not contain a timing component, positioning us to examine dual-tasking with two tasks that potentially did not share a common mechanism. Previous research has shown that seemingly unrelated secondary tasks can lead to impaired cognitive performance (Lajoie et al. *1996*) and reduced walking speed (Springer et al. *2006*) in dual-tasking performance. In sum, these findings led us to hypothesize that we would observe a decrement in the working memory task when performed with walking, while no decrement in gait performance would be observed. Our hypotheses were partially supported in that walking performance was preserved while performing the working memory task. Contrary to our hypothesis, working memory performance was not influenced in the dual-tasking condition. Our data supports the findings of Hausdorff (*2005*) showing that walking was not impacted by memory or cognitive function in general. Our data supports previous research showing that gait at a preferred walking speed in healthy adults is uninfluenced by a secondary task (Kiefer et al. *2009*; Bloem et al. *2001*).

One could argue that the consistent gait performance across conditions may be due to participants not performing the working memory task while walking. To ensure that the participants in the current study were performing the working memory task while walking, an accuracy criterion was included in the design of the working memory task to confirm participants were correctly answering 85 % of the math problems. Since all subjects answered with at least 85 % accuracy on the cognitive task in both the single- and dual-task conditions, it is safe to assume that the subjects were performing the working memory task in isolation and while dual tasking. An additional way we controlled for extraneous variables across conditions was to include a second dual-task condition that did not engage short-term working memory (reading while walking). After participants completed this condition, they were asked several questions from the reading to confirm they were doing the task. These questions were based off the first few pages of reading to assure that every participant would be able to answer the questions if they did the reading (regardless of his/her reading pace). Subjects were consistent in accurately answering the questions. Again, no differences were observed in the mean, standard deviation, or dynamics of gait performance, suggesting that reading required long-term working memory, just like short-term working memory, has no influence on the control of gait.

It should be noted that two participants in the current study scored a zero on their absolute score and relatively low on their partial scores (19 and 23). To determine whether these two participants were affecting the data set, their data were removed and the analyses were rerun. However, the mean absolute and partial scores were only slightly raised (from 19.5 to 22.3 and from 40.1 to 42.8, respectively) and no differences in the statistical analyses were observed when compared with the entire data set. It should also be noted that eight of the 16 participants increased their absolute score when dual tasking. This data provides support for the finding that walking at a preferred speed can increase working memory performance (Schaefer et al.*2010*), at least in some individuals. Given the relatively lower cognitive scores of the participants in the current study compared with normative data, it is plausible that the participants did not have the working memory ability to do the task at a high level, or they performed at a subpar level in both tasks. This is conceivable considering UNCG undergraduate students tend to perform relatively lower than other schools on operation span tasks (Redick et al. *2012*).

One possible limitation of this study was that individuals completed all tasks in one 2-h session. This may have influenced the second scores (i.e., retest) on the Aospan task since the first working memory test would have been recently completed. The test–retest sample used in Unsworth et al. (*2005*) had a mean lag time of 13 days (ranging from 1 to 173 days). However, this is an unlikely limitation because (1) the retest scores were not inflated and (2) condition order was randomized, likely washing out any inflation across conditions. Another limitation was that subjects walked on a motorized treadmill. Even though subjects were able to self-select their pace, treadmill walking could impose different task constraints compared with overground walking because it allows for fewer options in altering one’s speed. Nevertheless, similar values in the structure (DFAα) and magnitude (coefficient of variation) of variability have been observed in the stride interval time series in 15-min trials when comparing treadmill and overground walking characteristics (Chang et al. *2009*). While the stride interval characteristics may be similar, the different task constraints should be taken into account when interpreting the current findings. The most plausible limitation of our study is that the subjects performed the Aospan task sitting down as opposed to standing in the single-task condition. Had the subjects been asked to stand on the treadmill while completing the task, the single-task condition would have been more similar to the dual-task condition (walking while performing the Aospan task). We elected to keep the procedure of this Aospan task as similar to the original one performed in Unsworth et al. (*2005*) in the single-task condition, so it was decided that the participants should perform that task while seated. Nevertheless, the sitting versus standing difference in our working memory task was a confounding factor. Lastly, it should be noted that the Aospan task is a relatively difficult task compared with other working memory tasks, which may have influenced the results. Other researchers examining gait and working memory performance when performed in isolation and concurrently have used the N-back working memory task (Lövdén et al. *2008*; Verrel et al.*2009*; Schaefer et al. *2010*), which may be a more appropriate cognitive task than the Aospan task to use in dual-tasking paradigms due to its relatively lower difficulty.

The results in this study raise a number of relevant questions for future research. What is the effect of dual-task interference on gait and cognitive performance during more attention-demanding gait tasks? Would gait patterns fluctuate in overground walking due to having a more complex surrounding environment? Such questions will need to be addressed in future studies in order to further understand the relationship between working memory and gait. Research regarding these questions may help to clarify which model of dual-task performance is the most plausible or help to create new models. Future research should continue to study the relationship between dynamic patterns in gait and cognition to help clinicians and researchers provide better rehabilitation to those with impairments (either in gait or cognition). This advancement in research is dependent on identifying whether gait and cognition share the same resource pools, as well as what factors influence impairment in walking and cognitive patterns. The challenge for researchers pursuing answers to these questions is that there may not be a way to quantify or identify shared resource pools.

In sum, research examining the relationship between working memory and gait is a relatively new area. Studies involving young and older adults are increasing our understanding of the role cognitive factors play in the control of stability while walking. Using dual-task paradigms to examine the effect of attentional requirements of balance control while performing a secondary task can be useful to better understand stability in both healthy and impaired older adults. The results from this study did not show a difference in gait performance in the single- or dual-task conditions. It is possible that no differences were found in gait performance because the cognitive task and gait task were not drawing from the same resources. Since neither cognitive nor gait dynamics changed from single- to dual-task conditions, and these results shared consistencies and inconsistencies with past research, it is apparent that more research needs to be done regarding motor and cognitive dual tasks.

Acknowledgments

The authors would like to thank Dr. Jennifer Etnier and Dr. Michael Kane for their guidance in this project.

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