Cognitive Load and Dual-Task Performance During Locomotion Poststroke: A Feasibility Study Using a Functional Virtual Environment

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Background. Gait and cognitive functions can deteriorate during dual tasking, especially in people with neurological deficits. Most studies examining the simultaneous effects of dual tasking on motor and cognitive aspects were not performed in ecological environments. Using virtual reality technology, functional environments can be simulated to study dual tasking.

Objectives. The aims of this study were to test the feasibility of using a virtual functional environment for the examination of dual tasking and to determine the effects of dual tasking on gait parameters in people with stroke and age-matched controls who were healthy.

Design. This was a cross-sectional observational study.

Methods. Twelve community-dwelling older adults with stroke and 10 age-matched older adults who were healthy participated in the study. Participants walked on a self-paced treadmill while viewing a virtual grocery aisle projected onto a screen placed in front of them. They were asked to walk through the aisle (single task) or to walk and select (“shop for”) items according to instructions delivered before or during walking (dual tasking).

Results. Overall, the stroke group walked slower than the control group in both conditions, whereas both groups walked faster overground than on the treadmill. The stroke group also showed larger variability in gait speed and shorter stride length than the control group. There was a general tendency to increase gait speed and stride length during dual-task conditions; however, a significant effect of dual tasking was found only in one dual-task condition for gait speed and stride duration variability. All participants were able to complete the task with minimal mistakes.

Limitations. The small size and heterogeneity of the sample were limitations of the study.

Conclusions. It is feasible to use a functional virtual environment for investigation of dual tasking. Different gait strategies, including an increase or decrease in gait speed, can be used to cope with the increase in cognitive demands required for dual tasking.
Achiving an optimal level of participation in community activities is a main goal of rehabilitation. A common daily activity such as shopping requires the ability to perform 2 or more cognitive and motor activities simultaneously (ie, dual tasking) and to adapt the performance even when unexpected events occur. The paradigm of dual tasking and the effect of a secondary task on balance, gait, and cognitive performance have been examined in healthy and clinical populations in order to understand the role of attention on the maintenance of postural stability and walking. In this issue, for example, Yogev-Seligmann et al explore the influence on walking performance of manipulating attentional demands under dual-task conditions.1 In particular, studies have investigated the “cost” of dual-task performance, usually measured by performance changes in one or both tasks when carried out simultaneously.2

Gait and cognitive performance can deteriorate during dual-task performance, especially in people with neurological deficits. Several studies have examined the change in gait or balance parameters while performing a secondary cognitive task3–5 or the reaction to postural perturbations during performance of another task.6–7 Dual tasking was found to increase the risk of falling among frail elderly people8 and, thus, can be used to predict future falls in older adults.9

Dual tasking decreases gait speed and stride length during overground walking in people who are survivors of stroke.5,10 Plummer-D’Amato et al11 found that in community-dwelling adults who were survivors of stroke, the largest decrease in gait speed occurred during a spontaneous speech task compared with auditory one-back (working memory) and auditory clock (visuospatial) tasks. Canning et al12 also found that walking performance in survivors of stroke can deteriorate (reduced gait speed, stride length, step length, and cadence) under dual- and triple-task conditions, similar to that observed in elderly people.

Lord et al13 examined the effect of constraints in the physical environment (clinic, shopping mall, suburban street) and task (no task, stepping over an obstacle, and identifying even and odd numbers) on gait parameters in a cohort of patients with chronic stroke. A significant effect due to environmental context was found on gait speed (eg, patients walked slower within the shopping mall), but there were no significant main effects due to task or interaction effects between task and environment on gait parameters. Although the approach used in that study was novel, the observations should be interpreted with caution because results were reported for only 3 subjects in each of 9 conditions. Controlled studies are needed to determine how the environmental context affects dual tasking, and virtual reality (VR) technology can be used to create simulated functional environments that can be manipulated by the researcher.

Virtual reality refers to the use of interactive simulations created with computer hardware and software to introduce users to opportunities to interact in environments that seem and feel similar to the real world. Users interact, move, and manipulate virtual objects in a way that attempts to “immerse” them within the virtual environment (VE), thereby producing a feeling of “presence” in the virtual world.14 The rationale for using VR for rehabilitation is based on a number of unique features of this technology.15,16 One important feature is the ability to manipulate and grade stimulus delivery while measuring changes in performance within the VE. In addition, behavioral changes can be measured by adding other types of technologies such as motion analysis systems. Virtual reality hardware, composed of several types of technologies, facilitates the input and output of information and, when used in combination with programmed VEs, can provide the necessary tools for designing a variety of environments and complex tasks. These tools can enable researchers to analyze task performance in ecologically valid situations similar to real life, yet under experimentally controlled conditions.16 In the past decade, studies have demonstrated the potential of using VR of various levels of complexity and ecologically valid VEs to study a range of motor and cognitive behaviors following stroke or brain injury.17–22 Virtual reality also has been used to assess multitasking in people who were healthy23 and in people with brain injury24 and stroke.25

Most studies that examined dual-task performance have limited ecological validity because the tasks (eg, walking within the laboratory and memorizing a shopping list, walking and counting backward) were not performed within a functional environment or context. Those studies...
that were done within functional physical environments or VEs focused mainly on cognitive performance and did not examine the performance of an accompanying motor activity. Therefore, the objectives of this study were to test the feasibility of using a virtual functional environment for the examination of dual tasking and to determine the effect of dual tasking within a functional context on gait parameters in people with stroke in comparison with age-matched controls who were healthy. We hypothesized that gait parameters (ie, speed, stride length, and duration and variability of these parameters) would change during dual tasking performed in a functional context. Moreover, we hypothesized that these changes would be greater in people with stroke compared with age-matched controls.

Method
Participants
A convenience sample of 7 men and 5 women who had had a stroke (mean [±SD] age = 68.7 ± 6.9 years) were recruited for the study. Five individuals had a left hemispheric stroke, and 7 individuals had a right hemispheric stroke. Participants were included if they were community dwelling, at least 3 months post-stroke, able to walk on a self-paced treadmill, and scored at least 25 on the Mini Mental State Examination.26 Their mean (±SD) overground gait speed during performance of the 10-m walk test was 0.74 ± 0.42 m/s. Slow walkers were defined as those individuals in the lower quartile, with an overground gait speed of less than 0.54 m/s. In addition, 4 men and 6 women who were healthy (mean [±SD] age = 69.7 ± 7.1 years) were recruited as a control group. Their mean (±SD) overground gait speed during performance of the 10-m walk test was 1.26 ± 0.20 m/s (available for only 8 participants in whom subsequent analyses were done). All participants signed an informed consent form prior to the study.

Instrumentation and Measurement
Virtual reality instrumentation. The instrumentation has been documented previously, where VR technology was used in combination with a self-paced treadmill mounted on a motion platform and a real-time motion tracking system. In that study, the feasibility of using the combined technologies was demonstrated for gait training poststroke, as 2 individuals with chronic stroke were able to adapt and control their gait speed to overcome physical changes in the terrain and in the VE while walking on the treadmill.

In the current study, participants stood or walked on a self-paced, motorized treadmill mounted on a 6-degree-of-freedom motion platform. The VE was rear projected on a 2.44 × 3.05-m screen mounted 1.5 m in front of the end of the treadmill. The treadmill (0.6 × 1.5 m) was custom-built and incorporated a PID servo-controlled motor driven by an algorithm that included the real-time distance acquired by a potentiometer attached to the walking individual, as well as the instantaneous velocity. Thus, the speed of the treadmill was adjusted at will by the moving individual. The participant held with both hands on to a bar that was mounted with linear-bearing sliders on 2 handrails over the treadmill. The handle bar could be pushed up to a predefined point to simulate walking while pushing a shopping cart. A functional VE of a grocery aisle, 16-m long, was created and controlled within the CAREN (Computer Assisted Rehabilitation Environment) system.28 (Fig. 1). This system synchronized the instantaneous treadmill speed and scene progression such that the participant had control of his movement within the VE. In addition, motion of the body was captured in real-time with a 6-camera Vicon motion analysis system at 100 Hz. Participants walked through the grocery store aisle and selected or “shopped for” items that were placed at the rear of the aisle in front of them, according to the auditory instructions (with different levels of complexity) delivered prior to or after gait initiation. “Shopping for” an item consisted of deciding which object to select and then touching it with the hand. There were 4 experimental dual-task conditions: (1) condition 1—shop for one item only (instruction was delivered after gait initiation); (2) condition 2—shop for one item, which was changed to another item after 6 seconds; (3) condition 3—shop for 2 items (instruction was delivered after gait initiation); and (4) condition 4—memorize and shop for a list of 5 items provided prior to gait initiation.

The combination of items for which the participants were asked to shop was randomly changed between repetitions. Two baseline walking and standing conditions (single tasks) were included in which the participant walked through the grocery aisle without instructions (repeated 4–5 times) or shopped for items while standing (repeated 4 times with a different number of items), respectively. Experimental conditions (dual tasks) were grouped into blocks of 4 trials containing one trial of each condition, randomly ordered within each block. Data from 2 to 5 blocks were collected. Data analysis focused on the third walking baseline trial and the second experimental block in order to control for fatigue and learning effects, as well as for adapting to the dual task. Data analysis also focused on "steady-state lo-
comotion" in the middle (60%) of each trial based on the number of strides. The number of strides for analysis varied among the participants depending on their stride length and gait speed and ranged between 6 and 32.

Measurement of gait parameters. For the analysis of gait parameters, a special algorithm (written in MATLAB) was used to detect critical gait cycle events, based on the foot trajectory in the sagittal plane (using 2 markers on each foot). The algorithm took into account different foot-fall patterns (heel-strike or toe contact) in accurately detecting initial contact (beginning of stance) or toe-off (beginning of swing). The following gait parameters were measured: stride length, stride duration, and cadence. Gait speed was derived from the treadmill motor output acquired by the CAREN system. In addition, the variability of each parameter across multiple strides was measured by the coefficient of variation (CV), defined as a percentage of the standard deviation over the mean. Task completion was measured as the number and type of mistakes that occurred. Mistakes were defined as forgetting an item, selecting the wrong item, or selecting extra items.

Data Analysis
Descriptive statistics were used to describe the performance of the participants for each of the gait parameters. In order to examine how well the self-paced treadmill simulated natural walking, a mixed-model, 2-way, repeated-measures analysis of variance (ANOVA) was used to compare overground and baseline treadmill gait speed. The independent variables were group (between-subject factor: control versus stroke) and condition (within-subject factor: overground versus baseline).

To compare gait parameters between baseline and experimental (dual-task) conditions, taking into account the different locomotor abilities of the participants, mixed-model, repeated-measures analyses of covariance (ANCOVA) were used for each gait outcome measure with the same independent variables (the conditions here were single and dual tasks), but using overground gait speed as a covariate. If there was an interaction between the covariate and group, further analyses were done to compare the different outcomes based on different locomotor abilities (gait speed). Post hoc comparisons were used to investigate differences between conditions and groups (Bonferroni correction −.005 for condition). Statistical analyses were performed using SPSS version 15 and SAS version 9.1.3 software.

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Figure 1.
(A) The virtual reality setup viewed from behind the participant. (B) The virtual grocery aisle.
Results
Participants from both groups were able to walk on the self-paced treadmill and interact within the VE. For 3 participants (2 in the stroke group and 1 in the control group), data from one condition were lost for current analysis due to technical problems, such as a marker falling off while walking. Descriptive statistics for gait parameters at baseline for both groups are presented in the Table.

Gait Speed
In both groups, participants walked significantly faster overground (0.74±0.42 m/s for the stroke group versus 1.26±0.20 m/s for the control group) than on the treadmill (0.51±0.23 for the stroke group versus 0.87±0.13 m/s for the control group; \(F_{1,18}=35.25, P=.0001\)). The control group walked significantly faster than the stroke group in both conditions (\(F_{1,18}=13.47, P=.002\)).

Analyzing the differences in gait speed between baseline (single task) and experimental conditions (dual tasks) revealed that the direction of change was not consistent, although an overall tendency to increase gait speed during the dual-task conditions was seen. For gait speed, a main effect due to task conditions was found (\(F_{4,70}=3.83, P=.007\)). Post hoc comparisons showed that participants walked slower at baseline than in condition 1 (\(t=3.64, P=.0005, 95\% \text{ CI}=0.05 \text{ to } 0.18\)). A similar but nonsignificant change in gait speed was observed between baseline and condition 2 (\(t=2.57, P=.012, 95\% \text{ CI}=0.02 \text{ to } 0.15\)) and between baseline and condition 3 (\(t=2.76, P=.007, 95\% \text{ CI}=0.03 \text{ to } 0.15\)).

The stroke group showed greater variability in gait speed compared
with the control group \((F_{1,16}=7.61, P=.014)\). The group difference was due mainly to the lower functioning of the participants in the stroke group, who were slow walkers over-ground \((t=-2.63, P=.018, 95\% \text{ CI} = -32.8 \text{ to } -3.5)\). Gait speed variability ranged from 20.7\% at baseline to 24.3\% in condition 2 for the stroke group, and from 10.1\% in condition 1 to 14.7\% in condition 1).

**Stride Length and Duration**
Overall, there was large variability within each group for stride length and duration during single or dual tasking. For stride length (paretic leg of the stroke group and left leg of the control group), a main effect due to group was found (Fig. 3; \(F_{1,17}=5.74, P=.028\)). The same was found for stride length of the other leg (nonparetic leg of the study group and right leg of the control group) \((F_{1,17}=5.59, P=.03)\). The control group had significantly longer stride lengths across all conditions.

There was an overall tendency to decrease stride duration during dual-task conditions; however, there was a main effect only for stride duration variability in the nonparetic leg of the stroke group and right leg of the control group \((F_{1,70}=2.57, P=.045)\). Post hoc comparisons almost reached significance, showing that stride duration variability tended to be smaller at baseline (4.72\%±2.12) compared with condition 1 (6.79\%±5.23) \((t=2.61, P=.011, 95\% \text{ CI}=0.49 \text{ to } 3.67)\). In addition, stride duration variability tended to be greater in condition 1 than in conditions 2, 3, and 4 \((t=2.42, P=.018; 95\% \text{ CI}=0.34 \text{ to } 3.55; t=2.76, P=.007, 95\% \text{ CI}=0.61 \text{ to } 3.79; \text{ and } t=1.99, P=.05, 95\% \text{ CI}=0.0001 \text{ to } 3.21, \text{ respectively})\).

**Cadence**
An overall tendency to increase cadence during dual-task conditions was seen; however, none of the differences reached significance in either group. In addition, no significant differences were found between groups.

**Additional Analysis**
In order to better understand the participants’ performance during the various dual-task conditions, an ANCOVA was done with performance at baseline as the covariate. An interaction effect between group and stride length at baseline was found for the bilateral stride lengths (left/paretic leg: \(F_{1,50}=8.66, P=.005\); right/nonparetic leg: \(F_{1,55}=8.66, P=.005\)), with greater differences in stride length during dual-task conditions occurring in participants who had shorter strides at baseline (left/paretic leg: \(t=2.92, P=.005, 95\% \text{ CI}=93.86 \text{ to } 575.01\)). A main effect due to group was found for the left/paretic leg stride length variability \((F_{1,19}=4.73, P=.042)\). An interaction effect between group and stride duration at baseline was found for the bilateral stride durations (left/paretic leg: \(F_{1,50}=9.99, P=.003\); right/nonparetic leg: \(F_{1,57}=10.30, P=.002\)). However, post hoc analyses revealed no differences based on short or long stride duration.

In addition, for the purpose of explaining the increase in gait speed, Spearman correlations were performed between stride length and duration, cadence, and gait speed. In the stroke group, high correlations \((r=.85-.96)\) were found only be-
Cognitive Load and Dual-Task Performance During Locomotion Poststroke

between gait speed and stride length of both legs. The correlations did not change between baseline and dual-task conditions. In contrast, as expected in the control group, moderate to high correlations were found between all gait parameters and gait speed. Interestingly, the correlation coefficients between stride length and gait speed decreased from baseline ($r = .86$ for left leg and .83 for right leg) to dual-task conditions (range between $r = .57$ to $r = .71$ in both legs) (Fig. 4).

Completion of Task
The ability to complete the task was determined in comparison with baseline performance (where participants were asked to shop without walking). Overall, the participants in both groups were able to complete the task with only minor mistakes. In the stroke group, 3 participants selected the wrong item once, 1 participant selected an extra item, and 1 participant forgot to select an item. In the control group, 3 participants selected the wrong item once, 1 participant selected an extra item, and 1 participant forgot to select an item.

Discussion and Conclusions
This study showed the potential of using a functional VE to examine dual-task performance during locomotion. The use of the VR setup involving tasks that were context-dependent made it possible to examine performance of dual tasking in an ecologically valid setting. The participants, even those who were lower functioning or slow walkers, were able to walk on the self-paced treadmill and interact with the VE. However, it is important to note that the participants’ overground gait speed measured in the physical environment was significantly faster than in the baseline (single-task) condition measured in the VE, in both groups. The decrease in gait speed may have been partly due to having to walk on the treadmill while holding on to the handle of a simulated shopping cart or due to the visual processing required to see the virtual aisle. In addition, the overground and VE conditions may not be strictly comparable because we did not test participants walking overground in a similar aisle pushing a shopping cart. Mean overground gait speed of the stroke group in the current study was similar to that reported for single tasks in previous studies.

There are a number of potential reasons why there were no significant differences in most gait variables between single- and dual-task conditions in the current study. The results of this study showed large between- and within-subjects’ variability in direction and amount of change of gait parameters between single- and dual-task conditions. Although the differences between the conditions in either direction were not always statistically significant, when we examined the relative percentage of change between baseline and experimental conditions, we found that some participants had decreased gait speed during dual-task conditions, whereas other participants had increased gait speed. Thus, the same individual could cope with the increased cognitive load by decreasing gait speed in one condition while increasing it in another. However, despite the large variability, a significant increase in gait speed was found between the single task and one of the dual-task conditions (condition 1—shopping for one item), and a similar trend was found in other dual-task conditions except one (condition 4—memorizing and shopping for a list of 5 items).

These results are in contrast to the findings of other studies that examined the performance of dual tasking in people who had a stroke or in elderly individuals. Those studies showed consistent directions of change in all participants that mostly resulted in decreased gait speed and stride length during dual tasking. In addition, a decrease in gait speed was found in other populations, such as in people with Parkinson disease, in young subjects who were healthy, and in older individuals. The differences may be explained by the fact that the task in the current study was different from that used in other studies; participants were asked to perform a functional task of shopping within the relevant VE of a grocery aisle, while walking on a self-paced treadmill. On one hand, this task was a familiar everyday activity for all of the participants, who probably have developed their own habits and routines. On the other hand, walking on a self-paced treadmill could be perceived by most participants as a novel task in itself, which was reflected by a decrease in gait speed compared with overground walking. These characteristics of the task might have led the participants to use different strategies during dual-task performance, which might explain the inconsistent changes found within- and between-subjects. Within-subject variability was reported by Bock, who examined different dual-task conditions and showed that young and older individuals who were healthy decreased gait speed in a task that required visual processing while walking but not in another task that required memorizing details from a picture. Bock suggested that the visual demand of the secondary task might have affected the cost of dual tasking. In the current study, the visual demands of the secondary task during walking were small, which might explain the lack of a main effect for condition in most of the variables tested.

Two explanations can be found for the strategy of increasing gait speed and stride length during dual-task conditions. Canning found that...
when subjects with PD were given the instruction to focus on walking and not on a secondary motor task (carrying a tray with glasses), they walked at a speed similar to the single-task condition, and this had no impact on the secondary task. It might be that the participants in the current study, although they were not asked to, prioritized the more novel walking task over the routine shopping task, with the latter task being perceived as easier. Prioritization of gait, especially in novel situations, is considered to be an appropriate strategy.2

An alternative explanation can be derived from the motor learning literature. As mentioned previously, the VE treadmill walking task in the current study was new to the majority of the participants. Despite the practice and habituation that were done prior to the beginning of the study and the fact that analysis was performed on the second block of trials, it might be that the participants were in the process of learning this new walking task. One of the principles of motor learning stipulates that an external focus of attention (ie, focusing on the result of the action or on the object) enhances motor learning and performance more than an internal focus of attention (ie, focusing on the movement itself) in adults who are healthy36 as well as in people with PD.57 It is possible that some of the participants focused on the shopping task, trying not to forget the items (which were projected on the screen in front of them) they needed to “buy,” knowing that at the end of the aisle, they would need to select the requested items. Therefore, they paid less attention to walking, which became more automatic and thus faster and closer to their overground speed.

Verghese et al38 reported that when older adults were asked to prioritize a secondary talking task while walking, they decreased their gait speed. Because the paradigm of the current study did not address either of these proposed explanations, future studies should examine the effect of task prioritization as well as the role of motor learning theories in dual tasking. In addition, future studies should investigate whether the increase in gait speed and stride length is an efficient and safe strategy, especially for people who have had a stroke. It might be that, in the event of an unexpected external perturbation, the person who speeds up will not be able to maintain balance, resulting in a fall. As suggested by Kelly et al,59 the usual finding of a decrease in gait speed during dual tasking might be a mechanism that helps to maintain stability during walking and not necessarily a sign of impaired locomotor control. These authors found that adding a cognitive load to narrow-based walking in elderly people who were healthy resulted in decreased gait speed but did not affect frontal-plane stability. Overall gait variability did not worsen during dual-task conditions in either group, which may suggest that the participants generally were able to maintain gait stability during dual tasking. Changes in gait parameters and stability often are seen when the walking task and the secondary task are complex and challenging.2 In the current study, because the feasibility of the setup was being explored, there were no perturbations of the surface or manipulation of the VE, which could add to the complexity of the tasks. This might explain the lack of interference with the cognitive task or absence of interaction effects. The absence of an interaction effect on gait is consistent with previous findings in survivors of stroke who were asked to memorize a shopping list as a secondary task,5 as well as with similar outcomes when comparing elderly people who were healthy with people with stroke using dual and triple tasks.12 Our findings, however, were different from those reported by Yang et al,10 who found greater changes in gait during dual-task conditions that involved a motor task in survivors of stroke, especially those who were least-limited community ambulators, than in elderly individuals who were healthy. Moreover, the interaction found between groups and performance at baseline in our study suggests that the differences were mainly between those participants with stroke who had poorer locomotor abilities at baseline and the control participants.

Finally, all analyses were done using overground gait speed as a covariate. Simple analyses that were done without this variable as covariate did show more significant results. The heterogeneity of this variable in our sample may have underpowered the study, leading to nonsignificant findings. It should be noted that many of the comparisons were significant at a level of $P<.05$, although not significant after applying the strict criterion of $P<.005$ with Bonferroni correction.

In conclusion, the results of the current study showed the potential of using a functional VE for investigating dual-task performance. In addition, the different coping strategies adopted by each individual should be investigated further. However, the results of this study should be interpreted with caution due to the small size and heterogeneity of the study sample, as well as the lack of a more-complex secondary task.

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Cognitive Load and Dual-Task Performance During Locomotion Poststroke


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