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Authors:

[1]Charlotte Sau Lan TSANG, PT, PhD, [1,2]Huixi OUYANG, PT, PhD, [1,3,4]Tiev MILLER, PhD, and [1]Marco Yiu Chung PANG, PT, PhD

Affiliations:

1. Department of Rehabilitation Sciences, The Hong Kong Polytechnic University, Hong Kong.
2. School of Biomedical Engineering, Guangzhou Medical University, China.
3. International Collaboration on Repair Discoveries, Faculty of Medicine, University of British Columbia, Vancouver, British Columbia, Canada.
4. Department of Medicine, Division of Physical Medicine and Rehabilitation, University of British Columbia, Vancouver, British Columbia, Canada.

Contact details of corresponding author: Professor Marco Yiu Chung PANG

Address: QT510a, Yuk Choi Road, Hung Hom, Kowloon, Hong Kong

Email: marco.pang@polyu.edu.hk

Phone: (852) 2766-7156

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Effects of cognitive task type and complexity on dual-task interference during level-ground walking and obstacle negotiation in individuals with stroke

ABSTRACT

Background: Compromised dual-task walking ability reduces functional independence in community-dwelling individuals after stroke.

Objective: To examine the influence of the type and complexity of mobility and cognitive tasks, and their interaction on dual-task level-ground walking and obstacle-crossing after stroke.

Methods: Ninety-three individuals with chronic stroke [mean (SD) age=62.4 (6.7) years, stroke duration=67.7 (53.5) months] participated in this observational study with repeated measures. For each dual-task testing condition, a mobility task (level-ground walking or obstacle-crossing) was performed concurrently with one of five cognitive tasks (serial-subtractions, category naming, clock test, auditory discrimination, shopping-list recall). Each cognitive task involved low and high complexity levels, yielding a total of 20 dual-task conditions. Dual-task effect [DTE= (single-task - dual-task) / single-task] on walking distance (mobility-DTE) and number of correct responses (cognitive-DTE) were calculated for each dual-task condition.

Results: Medium to large interaction effects were observed between cognitive task type and complexity on cognitive (F=12.0-15.8, p<0.001, η_p^2=0.12-0.15) and mobility performance (F=3.2-5.5, p<0.05, η_p^2=0.03-0.06) during dual-task level-ground walking and obstacle-crossing. Among the cognitive tasks, serial-subtraction had the greatest interference effect on both cognitive (Mean DTE=-9.2 to -21.5%) and mobility performance (Mean DTE=-18.7 to -19.1%). Overall, "mobility interference" (decrement in walking distance without a decrement in cognitive performance) was the most common dual-task effect pattern observed.

Conclusion: The type and complexity level of the mobility and cognitive tasks interact to influence the degree and pattern of dual-task effects, with the serial-subtraction task inducing the greatest effect. Standardized assessments involving distinct cognitive domains are necessary for profiling dual-task interference during walking among individuals with chronic stroke.

Keywords (MeSH): Task Performance and Analysis, Multi-Tasking Behavior, Cognition, Mobility Limitation, Stroke Rehabilitation, Walking

INTRODUCTION

The ability to engage in another task while walking (i.e., dual-task walking) is essential for performing many activities of daily living after stroke.[1] Dual-task interference (DTI) refers to a decrement in either cognition, locomotion, or both when attempting to perform two tasks simultaneously. This phenomenon has been associated with reduced community participation,[2] loss of functional independence,[3] and greater fall proclivity among older adults with and without a history of stroke.[4]

DTI is likely affected by the type and complexity of the tasks involved.[5-7] According to the bottleneck delay or task-switching model of attention theory, competition for cognitive resources during dual-tasking is influenced by the manner in which responses are generated (i.e., internally vs externally driven).[8] It has been suggested that cognitive tasks involving internally driven responses (e.g., serial-subtractions which involve consecutive internally driven responses) may hinder *walking* performance to a greater extent than tasks involving externally driven responses (e.g., auditory discrimination tasks involving externally prompted responses) in adults with and without neurological conditions.[7] However, the way in which dual-task combinations influence *cognitive task* performance under dual-task conditions remains largely unknown.

Within the context of dual-task testing, Plummer et al (2013) proposed nine possible dual-task effect (DTE) patterns (i.e., no interference, mobility interference, cognitive interference, mutual interference, mobility facilitation, cognitive facilitation, mobility priority trade-off, cognitive priority trade-off and mutual facilitation).[9] Although a number of studies have examined how different cognitive tasks affect DTE patterns, reported findings are often conflicting.[1, 10-22] For example, mental tracking tasks have been shown to induce a mutual interference pattern in several studies,[1, 10, 11, 13, 19] while others reported either a mobility interference (i.e., maintenance of cognitive performance and decrement in walking performance) or a cognitive interference pattern (i.e., maintenance of walking performance and decrement in cognitive performance).[15, 19, 22] This disparity may be attributed to differences in the complexity of the walking and cognitive tasks involved. Previous systematic reviews indicated that “mutual interference” was among the most common DTE patterns and was often observed during more challenging locomotor tasks in individuals with stroke.[7, 23] Understanding how various task combinations influence DTE may help identify key characteristics governing dual-task walking performance after stroke. These underlining characteristics provide important insights for designing interventions to improve dual-task walking post-stroke and inform future research.

Although obstacles are frequently encountered while ambulating in community settings, previous studies have largely focused on investigating DTE during level-ground walking conditions.[7] The ability to dual-task while negotiating obstacles may be an important factor associated with future fall risk in people with stroke, and is likely to be of greater importance than level-ground walking for improving functional recovery and independence.[5] Previous research has shown a strong association between gait during obstacle-course walking and cognitive function.[24] However, the effect of cognitive task type and complexity on DTE experienced during obstacle negotiation in people with chronic stroke remains relatively understudied. Potential differences in the DTE experienced between different mobility tasks (e.g., level-ground walking and obstacle negotiation) also remain unexplored.

The objectives of this study were to investigate the effects of mobility tasks, cognitive task type and complexity and their interaction on the degree and pattern of DTE among individuals with stroke. In our testing protocol, two mobility tasks (level-ground walking and obstacle negotiation) and five cognitive domains were incorporated. Within each cognitive domain, there were two complexity levels, yielding a total of 20 distinct cognitive tasks. We hypothesized that (1) cognitive task types involving internally driven responses would induce the greatest degree of interference on mobility and cognitive performance during both mobility tasks, (2) the complexity of the imposed cognitive task would interact with the cognitive task type in influencing the degree of interference on mobility and cognitive performance under dual-task conditions during both mobility tasks, and (3) obstacle negotiation would impose greater degree of interference on both mobility and cognitive performance.

METHODS

Study design and ethical approval

This was an observational study conducted in a university laboratory. All procedures followed the Declaration of Helsinki.[25] University ethics approval and written informed consent were obtained prior to data collection.

Participants

Community-dwelling individuals with chronic stroke were recruited through convenience sampling from self-help groups between May 2017 and August 2018. The inclusion criteria were (1) ≥50 years old, (2) ≥6 months post-stroke, (3) Montreal

Cognitive Assessment (MoCA) score ≥22 (i.e., cognition intact),[26] (4) Modified Rankin Scale score 2-3 (i.e., slight to moderate disability),[27] (5) ability to walk ≥1 min with or without walking-aids and/or orthoses, and (6) able to follow and respond to instructions. The exclusion criteria were having (1) any form of aphasia, (2) neurologic conditions other than stroke or (3) serious illness that precluded study participation (e.g., cancer).

Sample size calculation

The sample size estimation was conducted using G*Power software (version 3.1.9.2, Universität Düsseldorf, Germany).[28] A previous study by Yang et al. reported medium to large interaction effects for mobility (η_p^2=0.205) and cognitive performance (η_p^2=0.117) during dual-task walking with serial-subtraction tasks of progressive complexity in individuals with stroke.[29] To allow sufficient power for the investigation of hypotheses one and two, which focused on the interaction between cognitive task type and complexity during separate mobility tasks, we used a more conservative approach by assuming a smaller effect size of η_p^2=0.117 (equivalent to f=0.36) using two-way repeated measures ANOVA. With an alpha of 0.05, power of 0.8, and an attrition rate of 10%, a minimum sample size of 84 individuals with stroke was required to detect a significant interaction between cognitive task complexity (2 levels) and cognitive task type (5 levels).

Procedures

Demographic information was obtained through interviews. Clinical characteristics were assessed using the Geriatric Depression Scale–Short Form for depressive symptoms,[30] MoCA score for generic cognition,[26] Activities-Specific Balance Confidence scale for balance confidence,[31] the 10-meter walk test (10MWT) for walking speed,[32] Mini-Balance Evaluation Systems Test for balance performance,[33] and the Fugl-Meyer Assessment for lower extremity motor impairment.[34]

The testing paradigm involved five types of cognitive tasks, and two mobility tasks (level-ground walking and obstacle-crossing) (Table 1). Each cognitive task type involved two complexity levels, yielding a total of 10 different cognitive tests. Each of the cognitive and mobility tasks was tested in single-task condition (i.e., 12 single-task tests). The different combinations of cognitive and mobility tasks performed in conjunction (i.e., 20 dual-task walking conditions) were also tested, giving a total of 32 tests. Participants were instructed to complete the component tasks with equal effort during dual-task conditions (i.e., covering as much distance as one could without hitting the obstacles, if any, while generating verbal responses as accurately and quickly as one could). Each testing condition was one minute in duration. If there were signs of fatigue or technical issues affecting the accuracy of the results, data were discarded, and assessments were repeated. Each session lasted approximately 2 hours in total.

The same researchers performed all interviews and assessments. Participants were familiarized with all testing conditions during practice trials prior to data collection to minimize learning effects. To minimize order and learning effects, testing sequence for the 32 tests, i.e., all the mobility and cognitive tasks at both the single-task and dual-task conditions, was randomized. A one-minute rest period was provided after each task to minimize mental and exertional fatigue. To minimize confounding effects associated with the side of paresis, participants walked along the rectangular track in a direction such that all turns were made toward the hemiplegic side.

Mobility tasks

The level-ground walking task required participants to walk along a 4×6m rectangular track. In the obstacle-crossing task, participants were asked to cross five identical obstacles (9cm height × 4cm thickness × 1m length) placed every four meters apart along the same track. Mobility performance was measured as the amount of distance (in meters) covered for both tasks. For the obstacle-crossing task, the number of foot-obstacle contact and total number of obstacles encountered during the walk were also recorded. The obstacle-crossing accuracy rate (%) was then calculated as follows:

$$\frac{(Total\ number\ of\ obstacles\ crossed\ without\ foot-obstacle\ contact) \times 100}{Total\ number\ of\ obstacle\ encountered\ during\ the\ walk}$$

The 10MWT was not used in the dual-task testing protocol. Although the 10MWT does not involve any turns, previous dual-task assessment protocols using the 10MWT have demonstrated substantially lower reliability than the current testing protocol.[6] A longer walk test (e.g., 2-minute walk test) was also not used due to potentially confounding effects associated with greater physical or mental fatigue.

Cognitive tasks

Five distinct cognitive domains (i.e., types) were included: (1) an auditory discrimination task for testing discrimination and decision making,[35] (2) a category naming task for semantic verbal ability,[36] (3) a shopping-list recall task for short-term memory,[16] (4) a serial-subtraction task for mental tracking,[37] and (5) an auditory clock test for visuospatial cognition.[11, 38] Cognitive performance was determined by the number of correct responses recorded.

Among the five cognitive task types, serial-subtraction and category naming involved internally driven responses.[39] Participant responses were consecutively self-generated after receiving a one-off question given at the beginning of the task (i.e., the starting number for the serial-subtraction task, and the name of the category for the category naming task). These tasks were self-paced. For the auditory discrimination task and auditory clock test, responses were externally driven. Participants generated each response consecutively after receiving each auditory stimulus. Once participants provided their response, the next stimulus was given to prompt the subsequent response. These tasks were paced externally. Finally, for the shopping-list recall task, participants were asked to memorize items given before walking (dual-task) or sitting (single-task) and recall them upon completing the walking or sitting tasks. Responses were not internally or externally driven.

Data analysis

SPSS software (version 29, IBM, Armonk, NY, USA) was used for all data analyses. To compare DTE across each cognitive task type using a standardized score, the dual-task effect (DTE, %) of the walking distance (mobility-DTE), and number of correct responses (cognitive-DTE) were calculated using the following formula:[40]

$$\frac{(Dual - task\ performance - Single - task\ performance) \times 100}{Single - task\ performance}$$

More negative DTE values represent greater DTI. Conversely, more positive DTE values represent greater dual-task facilitation (i.e., improvement in performance under the dual-task condition relative to that under the single-task condition).

The mobility and cognitive-DTEs were compared across dual-task conditions by separate three-way repeated-measures ANOVA (within-subject factors: two mobility tasks × five cognitive types × two cognitive task complexity levels). Effects of cognitive type and complexity on DTE of the obstacle-crossing accuracy rate and walking distance on level-ground walking and obstacle-crossing were investigated by separate repeated-measures ANOVA (within-subject factors: five cognitive types × two cognitive task complexity levels). Greenhouse-Geisser adjustment was used when the sphericity assumption was not fulfilled. If the above ANOVA models were significant, post-hoc pairwise comparisons using paired samples tests with Bonferroni adjustment were conducted. Effect sizes from the ANOVA were represented by partial-eta squared (η_p^2), with values of ≤0.01, 0.06, and 0.14 denoting small, medium, and large effect sizes, respectively.[41] A *p*-value ≤0.05 was considered statistically significant. The alpha value was adjusted to 0.01 for multiple post-hoc pairwise comparisons.

For each participant, the DTE pattern was identified for each dual-task condition according to the mobility and cognitive-DTEs observed. No previous research has determined the minimally important difference of the DTEs. In this study, a cutoff point of 0.5 standard deviation (SD) of the corresponding mean DTE was used (i.e., <-0.5SD: interference; >0.5SD: facilitation; -0.5SD to 0.5SD: no interference or facilitation), it has been associated with the minimally important difference for other health-related quality of life measures.[42] To compare the characteristics of participants between the most observed DTE patterns, independent t-tests was used.

RESULTS

Participant characteristics

After screening 157 people post-stroke, 93 were deemed eligible and completed all assessments (Figure 1). Most participants had mild disability, as indicated by the Modified Rankin Scale scores (Table 2).

Single-task and dual-task test performances

Single-task and dual-task test performances are shown in Table 3. Table 4 shows the dual-task effect on the cognitive and mobility performances. Those task combinations that resulted in a dual-task effect of clinical importance (>0.5 SD) are indicated in the same table. Figure 2 shows the interaction between cognitive task type and complexity on the cognitive and mobility performance during level-ground walking and obstacle-crossing.

Dual-task effect: Cognitive performance

Effects of mobility task

Three-way repeated measures ANOVA showed significant interaction effects of mobility task × cognitive task type × cognitive task complexity ($F_{(3.2,\ 3402.3)}$ =5.2, p=0.001, ηp^2=0.05), mobility task × cognitive task type ($F_{(3.3,\ 4438.5)}$ =5.6, p<0.001, ηp^2=0.06), *but not* mobility task × cognitive task complexity ($F_{(1,\ 1050.7)}$ =1.6, p=0.216, ηp^2=0.02) were found for the cognitive performance. (Figure 2A)

Post-hoc paired samples tests with Bonferroni adjustments showed that with the same cognitive task type and at the same cognitive complexity level, the cognitive-DTI during obstacle-crossing was lower (i.e., DTE became less negative) than that during level-ground walking by an average of 15% (95%CI=7.3-22.7%, $p<0.001$) when the high-complexity category naming task was used. On the other hand, cognitive-DTI during obstacle-crossing was higher than that during level-ground walking by 10.2% (95%CI=3.4-17.1%, $p=0.004$) and 7.6% (95%CI=1.8-13.3%, $p=0.10$) when the 10-item shopping list recall and serial-3-subtraction task was used, respectively. (Table 4)

Effects of cognitive task type and complexity

Three-way repeated measures ANOVA showed significant cognitive task type × cognitive task complexity interaction effect and main effect of cognitive task type for both level-ground walking (interaction: $F_{(3.1,\ 35386.6)}=15.8$, $p<0.001$, $\eta p^2=0.15$; cognitive task type: $F_{(3.2,\ 13836.2)}=5.7$, $p<0.001$, $\eta p^2=0.06$) and obstacle-crossing (interaction: $F_{(2.8,\ 31672.5)}=12.0$, $p<0.001$, $\eta p^2=0.12$; cognitive task type: $F_{(3.1,\ 41239.2)}=17.8$, $p<0.001$, $\eta p^2=0.16$). A significant main effect of cognitive task complexity ($F_{(1.0,\ 14693.3)}= 7.0$, $p=0.010$, $\eta p^2=0.07$) was observed only during obstacle-crossing, but not during level-ground walking ($F_{(1,\ 4895.1)}=2.4$, $p=0.125$, $\eta p^2=0.025$).

Post-hoc paired samples tests with Bonferroni adjustments showed that as complexity of the category naming task increased, cognitive-DTI increased (i.e., cognitive-DTE became less positive) by an average of 36.4% for the level-ground walking task (95%CI=22.6-50.1%, $p<0.001$) and 20.0% for the obstacle-crossing task (95%CI=4.8-35.2%, $p=0.011$). On the other hand, increasing the complexity of the auditory discrimination task resulted in a reduction of cognitive-DTI (i.e., cognitive-DTE changed from negative to positive) by 10.0% (95%CI=3.8-16.2%, $p=0.002$) and 8.9% (95%CI=2.1-15.8%, $p=0.011$) for the level-ground walking and obstacle-crossing tasks respectively. Similarly, increasing the complexity of the auditory clock test also resulted in a reduction of DTI (level-ground walking: 28.2%, 95%CI=13.5-42.8%, p<0.001; obstacle-crossing: 39.9%, 95%CI=22.8-57.8%, p<0.001) (Figure 2A and Table 4).

Among all dual-task combinations, the greatest DTI (i.e., the most negative cognitive-DTE) occurred during serial-3-subtraction (mental tracking category with low complexity level) while walking (Mean cognitive-DTE=-14.0 to -21.5%). Conversely, the high-complexity auditory clock test showed the least DTI and the greatest dual-task facilitation (i.e., the most positive DTE) during walking than virtually all other cognitive tasks (Mean DTE=28.8 to 38.7%) (Figure 2A and Table 4).

Dual-task effect - Mobility performance (walking distance)

Effects of mobility task

Three-way repeated measures ANOVA showed significant interaction effects of mobility task × cognitive task type ($F_{(4.0,\ 223.6)}$=3.3, p=0.012, η_p^2=0.03) and mobility task × cognitive task complexity ($F_{(1.0,\ 301.6)}$=6.0, p=0.016, η_p^2=0.06), but not mobility task × cognitive task type × cognitive task complexity ($F_{(2.7,\ 170.8)}$ =1.65, p=0. 183, η_p^2=0.02) for the mobility performance, i.e., walking distance. (Figure 2B)

The mobility-DTEs were compared between level-ground walking and obstacle-crossing conditions for each cognitive task used using post-hoc paired samples tests with Bonferroni adjustments. The only significant differences were found when the high-complexity category naming (MD=5.3%, 95%CI=2.5-8.2%, p<0.001) and high-complexity serial-subtraction (MD=3.4%, 95%CI=0.9-5.8%, p=0.008) tasks were used. In both tasks, the mobility-DTI was lower (i.e., mobility-

DTE was less negative) during obstacle-crossing than level-ground walking. (Table 4)

Effects of cognitive task type and complexity

Separate two-way repeated measures ANOVA were performed for the mobility performance (i.e., walking distance) on level-ground walking and obstacle-crossing. Significant interaction effects between cognitive task type and cognitive task complexity was observed in both the level-ground walking ($F_{(4, 169.3)}$=3.2, p=0.013, ηp2=0.03) and obstacle-crossing tasks ($F_{(1.9, 1245.7)}$=5.5, p=0.005, ηp^2=0.06). Significant main effects of cognitive task type (level-ground walking: $F_{(3.5, 11180.0)}$=99.2, p<0.001, ηp2=0.52; obstacle-crossing: $F_{(3.3, 9254.9)}$=74.3, p<0.001, ηp^2=0.45) and cognitive task complexity (level-ground walking: $F_{(1.0, 2342.5)}$=31.0, p<0.001, ηp2=0.25; obstacle-crossing: $F_{(1, 568.2)}$=10.9, p=0.001, ηp^2=0.11;) were also evident.

Post-hoc paired samples tests with Bonferroni adjustments showed that during both the level-ground waking and obstacle-crossing conditions, DTI became significantly greater (i.e., more negative DTE) with increasing complexity level of the auditory clock test (level-ground walking: MD=4.5%, 95%CI=2.6-6.4%, p<0.001; obstacle-crossing: MD=2.3%, 95%CI=0.6-4.1%, p=0.007) and shopping list recall test (level-ground walking: MD=5.3%, 95%CI=3.0-7.7%, p<0.001; obstacle-crossing: MD=7.4%, 95%CI=3.5-11.4%, p=0.007). (Figure 2B and Table 4).

The greatest interference effect occurred during the category naming (Mean DTE=-21.9 to -16.6%) and serial-subtraction tasks (Mean DTE=-18.7 to -22.5%). No dual-task combinations facilitated walking performance (Figure 2B and Table 4).

Dual-task effect - Obstacle-crossing accuracy rate

Two-way repeated measures ANOVA only showed significant main effect of cognitive task type ($F_{(3.0,\ 461.9)}$=3.0, p=0.031, ηp2=0.03). Post-hoc pairwise comparisons showed that the obstacle-crossing accuracy rate was higher with the category naming task compared to the auditory clock test [Mean difference (MD)=3.1%, 95%CI=0.1-6.1%, p=0.043] (Figure 2Bii). No other significant differences were shown. The mobility-DTEs of obstacle-crossing accuracy rate found in all dual-task combinations had small mean values (-0.5% to 3.8%) and large SDs (26.1-35.3%). No clinically meaningful differences were identified.

DTE patterns

A summary of the nine DTE patterns identified for each dual-task combination among individual participants is provided in Supplementary Table 1. “Mobility interference” (i.e., degradation of mobility performance without change in cognitive performance) was consistently the most common DTE pattern identified across virtually all cognitive task types and complexity levels, regardless of the mobility task used (20-53%). The only exceptions were the shopping list recall and serial-subtractions. In the 10-item shopping list recall, while “mobility interference” remained the most common DTE pattern observed during level-ground walking (24%), “mutual interference” was the most common pattern identified during obstacle-crossing (26%). It was also the most common pattern observed in the serial-7-subtractions during level-ground walking (100%), and serial-3-subtractions during both level-ground walking (48%) and obstacle-crossing (55%). “No interference” was the most common pattern identified for 3-item shopping list recall during both level-ground walking (40%) and obstacle-crossing (50%). On the other hand, “mobility-priority trade-off” and “Mutual facilitation” were consistently the least observed patterns in general, regardless of the mobility task used (0-3%).

Characteristics of participants who demonstrated different DTE patterns were compared (Supplementary Table 2). Participants who showed mobility interference were younger (MD=4.6-5.2 years, 95%CI=0.04-10.2 years, $p<0.05$), had higher MoCA score (MD=1.4-1.9, 95%CI=0.4-2.9, $p<0.005$) and less severe depressive symptoms (MD=2.6-2.9, 95%CI=0.8-4.6, $p<0.005$) than people who showed mutual interference or cognitive priority trade-off in different dual-task combinations. The observed difference in MoCA scores exceeded the minimal clinically important difference.[43] The mean differences in age and depressive symptoms also exceeded the cutoff point of 0.5 SD of the corresponding measures, suggesting a clinically important difference.[42]

DISCUSSION

Evidence summary

Both cognitive task type and complexity, and their interactions were found to have significant impact on both mobility and cognition performance under dual-task conditions on both level-ground walking and obstacle-crossing.

Influence of cognitive task type on dual-task mobility and cognitive performance

Our first hypothesis was partially supported, in that the degree of *mobility performance* interference was greatest during cognitive task types involving internally driven responses during both level-ground walking and obstacle-crossing conditions (i.e., serial-subtraction and category naming tasks) (Figure 2B and Table 4). This finding is consonant with those of previous systematic reviews on dual-task performance among adults with and without neurological disorders.[7, 39] In fact, these were the only two cognitive task types that induced a reduction in walking distance (MD: 6.5-10.2m) that was considered clinically important (>6m) (Table 3).[44]

For the *cognitive performance*, only the serial-3-subtraction task induced a substantial interference (i.e., mean DTE <-0.5SD) during obstacle-crossing. During level-ground walking, serial-3-subtraction and the high-complexity category naming tasks induced a clinically important interference effect. (Table 4).[42] The task-related factors may explain the observed phenomena, as discussed below.

Task-specific factors

First, performance of both the serial-subtraction and category naming tasks may share more neural substrates with walking (e.g., prefrontal cortex) than other cognitive tasks tested in the current study.[45] According to the bottleneck delay model of attention theory, if tasks are processed by the same neural substrates, each task will be completed sequentially, thereby resulting in a bottleneck delay and subsequent performance decrement in either or both tasks (i.e., DTI).[46]

Second, both the serial-subtraction and category naming tasks demand more working memory and executive function than the other cognitive tasks performed.[45, 47] In people with stroke, deficits in processing speed and working memory are often greater than those of the other cognitive domains.[48] These task-specific factors make the serial-subtraction and category naming tasks relatively more challenging to them, thereby inducing a greater degree of interference during dual-task walking in this population.

Influence of cognitive task complexity on dual-task mobility and cognitive performance

Our second hypothesis was only partially supported. There were significant interaction effects between the cognitive type and complexity on dual-task cognitive and mobility performances during both level-ground walking and obstacle-crossing conditions. However, as cognitive task complexity increased, DTI increased for certain task types but not in others. In some cases, increasing cognitive task complexity may result in facilitation of dual-task performance (Figure 2). For example, when the cognitive task complexity increased, cognitive-DTI significantly increased in the category naming task only (involving internal driven responses) during both obstacle-crossing and level-ground walking. On the other hand, increasing the complexity of the auditory discrimination and auditory clock tests (both involving externally driven responses) resulted in dual-task cognitive facilitation during both obstacle-crossing and level-ground walking. Besides the task-specific factors, changes in individual arousal levels while performing tasks of different complexity levels may also be the contributing factors.

Individual arousal level

According to the capacity sharing model of attention theories, interference occurs when cognitive demands exceed a finite attention capacity. However, the allocation of finite attention is malleable and is highly dependent on individual arousal level and momentary intention.[46] Therefore, the prevailing DTE pattern would be influenced by individual arousal level during the single cognitive task condition as well as the resource allocation strategy employed during the dual-task condition. This is accordant with the parabolic (i.e., a reversed u-shaped) relationship observed between the efficacy of postural control and concurrent cognitive demands reported in previous literature.[49] When a simple cognitive task was added to standing, postural control improved. However, the beneficial effect of adding a cognitive task component diminished as cognitive task-related demand increased.[49] Among people with similar cognition and mobility, individuals who are more focused may perform better during single cognitive task conditions. However, during the dual-task conditions, cognitive performance may decline when attention capacity is limited by a concomitant mobility task, irrespective of the focus and dedication to the task.

Among individuals who were less focused during single cognitive tasks, performing the low-complexity category naming task while walking might have enabled them to focus more on this particular cognitive task. The previously “idled” attention capacity might be subsequently recruited to maintain the cognitive performance during dual-task conditions, rendering a deterioration in the dual-task mobility performance but not the dual-task cognitive performance. This phenomenon may also explain the improved cognitive performance during obstacle-crossing while performing the more complex auditory discrimination task (i.e., discriminating the pitch (high or low) of the words “High” and “Low”), or during level-ground walking combined with the more challenging shopping list recall task (i.e., memorizing 10 items).

During cognitively demanding tasks, such as serial-7-subtraction, participants might have already been fully aroused and attentive during the single-task condition.

Therefore, an improvement in cognitive task performance during dual-tasking scenarios was less likely to occur.

Influence of mobility task on dual-task mobility and cognitive performance

Our third hypothesis was partially supported in that obstacle negotiation not necessarily imposed greater degree of interference on the mobility and cognitive performance. The effects of cognitive type and complexity on DTE during level-ground walking and obstacle-crossing were generally similar. However, when compared between the level-ground walking and obstacle-crossing conditions, significant differences in the mobility- and cognitive-DTEs were found in tasks mostly involving internal driven responses (i.e., serial subtraction, category naming).

The task-specific factors, individual arousal level and subliminal cognitive task prioritization discussed above for the influence of cognitive task type and complexity may explain the phenomenon.

Influence of cognitive task type and complexity on DTE pattern

Subliminal cognitive task prioritization

Overall, “mobility interference” was the most common interference pattern observed. This may suggest a subliminal cognitive task prioritization when the testing paradigm did not require, nor explicitly specify, any task prioritization. These findings are similar to those reported in previous research involving people with or without stroke. In a study by Plummer-D’Amato et al. (2008) involving 13 individuals with stroke, while the participants were instructed not to prioritize either task during dual-task walking, interference on *mobility performance occurred in all tested task combinations* (i.e., walking with a visuospatial task, working memory task and spontaneous speech task). *However, interference on cognitive performance was not observed for most dual-task conditions*.[15] In another study involving 40 young and 14 older adults, Yogev-Seligmann et al. (2010) compared dual-task verbal fluency and walking performance between conditions with and without explicit prioritization for either task. Under the condition without prioritization, walking speed decreased in both groups, resembling the results in conditions where the participants were instructed to prioritize the verbal fluency (i.e., cognitive) task.[50]

People tend to reduce their walking speed during challenging dual-task situations. This may be an adaptive strategy to safeguard gait stability. A recent study showed a decreased risk of falling with an increased mobility interference during dual-task walking (i.e., greater reduction in dual-task walking speed).[51] Although participants were instructed to perform both tasks with equal effort, it is likely that tasks were prioritized differently, either covertly or overtly, according to individual differences in hazard estimation.

Apart from the influence of task-specific factors, individual differences in arousal level and subliminal task prioritization, the DTE patterns observed in the current study may also reflect individual differences in baseline characteristics such as age, generic cognition and depressive symptoms that may affect cognitive and locomotor ability. Future neuroimaging and behavioral studies are needed to enhance our understanding of these interference patterns in people with stroke.

Clinical implications

The results clearly demonstrate an interaction between cognitive task type and complexity relative to the degree and pattern of DTE observed. To generate a more comprehensive DTE profile for mobility testing after stroke, it is important to test various dual-task conditions on an individual basis. Dual-task exercise training has been shown to be effective in reducing DTI during walking as well as reducing fall incidence and injury.[52] Another study found relatively limited translation of the dual-task gait training effect from one trained cognitive domain to another untrained domain among individuals with stroke.[53] Obtaining a comprehensive dual-task walking profile would provide useful information for developing dual-task training interventions. Based on these findings, training could be allocated according to the domains with the greatest observable deficits.

Scenarios in which the cognitive or mobility performance was facilitated without a change in the counterpart performance during the dual-task condition were also observed. This suggests that dual-task training could be an effective strategy for improving cognition and mobility. In addition to investigating the effect of training on dual-task performance, further research exploring the effect of dual-task training on single-task cognition and mobility is warranted.

Limitations and future directions

The generalizability of these findings may be limited to ambulatory, community-dwelling, cognitively intact individuals with mild to moderate chronic stroke. Perceived challenges in performing mobility tasks may vary based on participant leg length, balance and motor impairment, whereas perceived challenges in performing cognitive tasks may vary based on education level, pre-stroke occupation and general cognitive status. Differences in stroke duration, location and severity that affect the integrity of neural networks, total brain capacity and/or cognitive functioning may also influence the degree of difficulty posed by each task. Although the effects of these factors on DTI might have been “normalized” through

DTE calculations, additional studies involving a larger participant sample would facilitate adequately powered subgroup analyses based on stroke type, location, duration and severity. This study and most previous studies only used walking speed/distance and obstacle-crossing accuracy/obstacle-foot contact as measures of mobility performance. For a fuller picture of the effects of dual tasking on mobility performance, future studies may investigate the effect of DTI on other gait parameters (e.g., gait variability and symmetry).

Virtually all participants were able to successfully recall the 3-item shopping list. Studies aiming to decrease the ceiling effect associated with the low-complexity shopping-list recall task by increasing the number of items to be memorized are needed moving forward. Although the study participants were all cognitively intact (MoCA score=26.8±2.2), processing speed, working memory and other specific cognitive domains were not independently assessed. Future studies may consider the inclusion of these specific assessments to elucidate the effect of distinct cognitive domains on various dual-task outcomes. The inclusion of a healthy control group would also help in determining whether the DTE observed is reflective of stroke-related deficits.

Although regular intermittent rests were provided to minimize the effect of mental fatigue, future studies assessing cognitive performance during dual-task conditions should consider including an objective means of monitoring mental status to further minimize the potential effect of fatigue. Subjective measures of self-perceived challenges and objective measures of attentiveness for a given task (e.g., electroencephalography and skin conductance) may be instrumental in identifying discrepancies between subjective perception and objective physiological reactions.[54]

Randomized control trials are needed to explore domain-specific cognitive training effects on dual-task and component task performance.

CONCLUSIONS

Cognitive task type and complexity level interact to influence the degree and pattern of dual-task interference. Individual differences in cognition and mobility, arousal level and subliminal task prioritization may also affect dual-task interference patterns. Standardized assessments involving distinct cognitive domains and complexities are necessary for profiling dual-task interference during walking and obstacle negotiation among individuals with chronic stroke.

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Declaration of conflicting interests

The authors have no conflicts of interest to declare.

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FIGURES

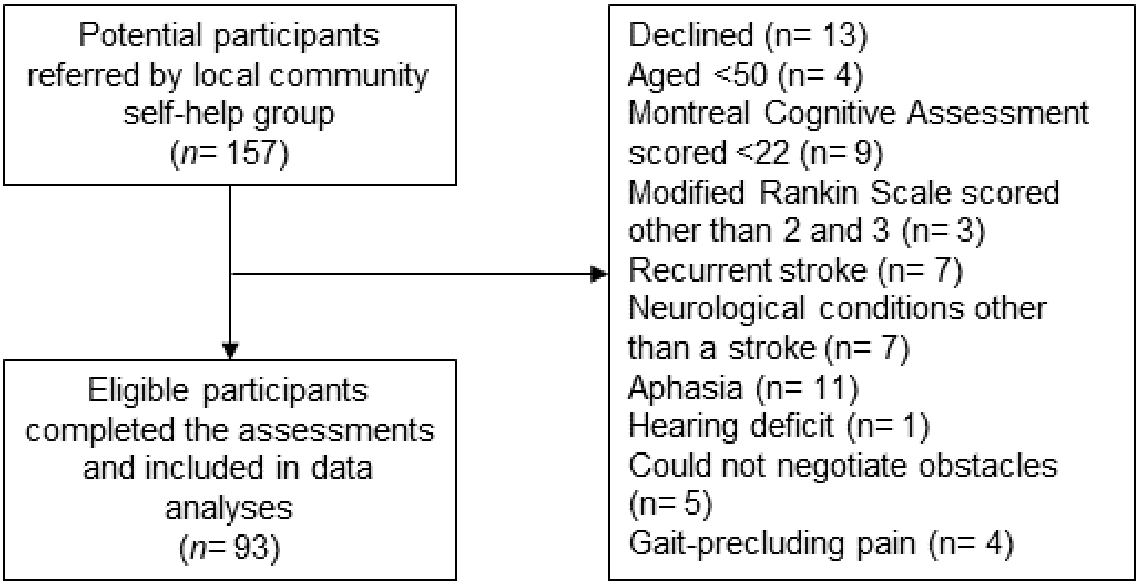

Figure 1. Flow of participants in the study.

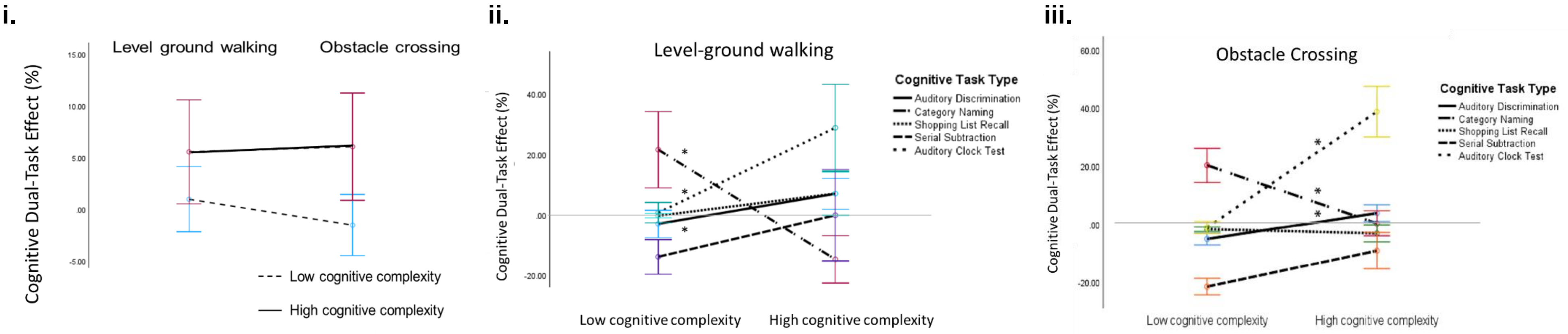

Figure 2A. Interaction effect between cognitive task type and complexity on cognitive dual-task effect (DTE) during dual-task walking. i. Interactions on mobility-DTE between mobility task and cognitive complexity; ii-iii. Interactions on mobility-DTE between cognitive type and complexity during level-ground walking and obstacle-crossing. DTE was calculated as *(Dual-task performance - Single-task performance) x 100% ÷ Single-task performance.* The error bar represents one standard error of the mean.

* Indicates a significant difference with Bonferroni adjustment for multiple comparisons.

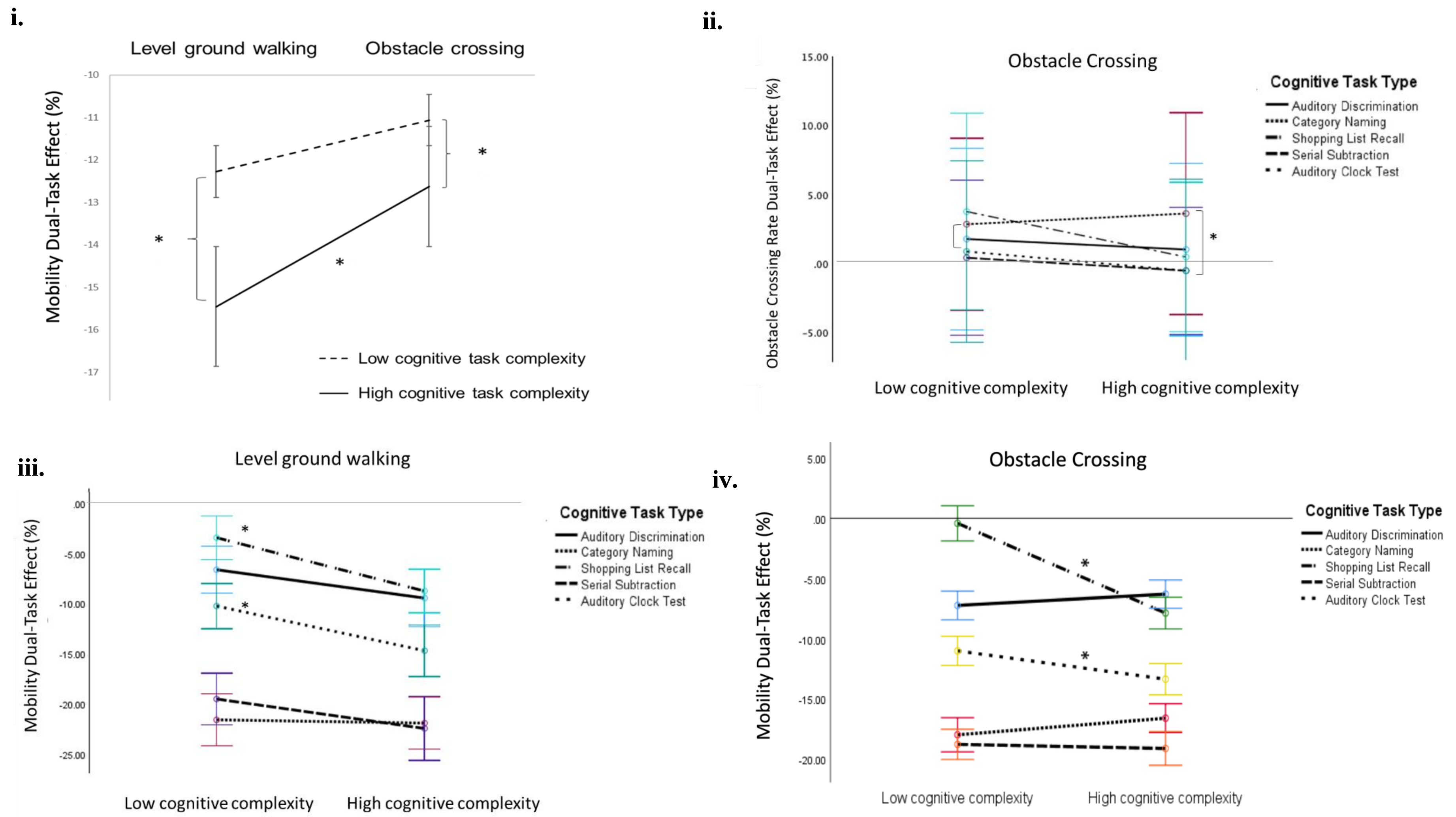

Figure 2B. Interaction between cognitive task type and task complexity levels on mobility dual-task effect (DTE) during dual-task walking. i. Interactions on mobility-DTE between mobility task and cognitive complexity; ii. Interactions on DTE of obstacle-crossing accuracy rate between cognitive type and complexity; iii-iv. Interactions on mobility-DTE between cognitive type and complexity during level-ground walking and obstacle-crossing. DTE was calculated as *(Dual-task performance - Single-task performance)* × *100%* ÷ *Single-task performance.* The error bar represents one standard error of the mean.

* Indicates a significant difference with Bonferroni adjustment for multiple comparisons.

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Table 1. Protocol for dual-task walking assessments and corresponding single-task tests

Description of task type and complexity		Outcome
Walking task: Each for one minute. The tasks were performed in isolation in the single-task conditions and in conjunction with each cognitive task in the dual-task conditions.		
1. Level-ground walking: Participants were asked to cover as much distance as possible along a 6x4 meter rectangular level-ground course.		Distance (meters)
2. Obstacle-crossing: Participants were asked to cover as much distance as possible along the same rectangular course with five identical obstacles (9cm high × 4cm thick × 1m long) placed at every four-meter interval while avoid hitting the obstacles.		1. Distance (meters) 2. Obstacle-crossing accuracy rate*
Cognitive task: Each for one minute. The tasks were performed in isolation in sitting in the single-task conditions and in conjunction with *each walking task* in the dual-task conditions.		
Task 1: Auditory discrimination (Domain: Discrimination and decision making)		
Low	Participants were asked to discriminate the pitch (high or low) of a word “Ba”.	Number of correct responses
High	Participants were asked to discriminate the pitch (high or low) of words “High” and “Low”.	
Task 2: Category naming (Domain: Semantic verbal fluency)		
Low	Participants were given a less confined category name, e.g., “food”, and were asked to give as many exemplars as possible.	Number of correct responses
High	Participants were given a more confined category name, e.g., “fruits”, and were asked to give as many exemplars as possible.	
Task 3: Shopping list recall (Domain: Short-term memory)		
Low	Participants were asked to listen to and memorize a 3-item shopping list that was repeated three times.	(Number of correct responses/items to be recalled) x 100
High	Participants were asked to listen to and memorize a 10-item shopping list that was repeated three times.	
Task 4: Serial-subtraction (Domain: Mental tracking)		
Low	Participants were asked to repeatedly subtract three from a random number between 390 and 399.	Number of correct responses
High	Participants were asked to repeatedly subtract seven from a random number between 390 and 399.	
Task 5: Auditory clock test (Domain: Visuospatial cognition)		
Low	Participants were asked to discriminate the location (upper half or lower half) of the minute-hand on a clock at a specific time point, e.g., 10:12.	Number of correct responses
High	Participants were asked to discriminate the location (upper-left, lower-left, upper-right or the lower-right quarter) of the minute-hand on a clock at a specific time point, e.g., 10:12.	

*Obstacle-crossing accuracy rate was calculated as :

$$\frac{(Total\ number\ of\ obstacles\ crossed\ without\ foot{-}obstacle\ contact)\times 100}{Total\ number\ of\ obstacle\ crossed\ during\ the\ walk}$$

Table 2. Participant demographics (N=93)

Participant characteristics	Mean (SD)	Minimum-Maximum (Range)
Age (years)	62.4 (6.7)	50-81 (31)
Sex - female, n (%)	37 (40)	
Weight (kg)	62.4 (9.6)	41.5-85.7 (44.2)
Height (m)	1.6 (0.1)	1.4-1.8 (0.4)
Body Mass Index (kg/m^2)	23.9 (3.0)	16.8-32.5 (15.7)
Education (years)	9.7 (3.7)	1-21 (20)
Pre-stroke occupation, category 0-10*	8/ 6/ 15/ 22/ 4/ 15/ 23/ 0/ 0/ 0/ 0	
Post-stroke duration (months)	67.7 (53.5)	9-254 (245)
Hemiplegic side – left, n (%)	52 (56)	
Location of stroke, n (%):		
Cortical region	10 (11)	
Subcortical region	57 (61)	
Both cortical and subcortical regions	18 (19)	
Unknown	8 (9)	
Montreal Cognitive Assessment score (0-30)	26.8 (2.2)	22-30 (8)
Geriatric Depression Scale- Short Form score (0-15)	5.2 (3.9)	0-14 (14)
Activities-specific Balance Confidence score (0-100)	70.3 (16.6)	21.3-96.9 (75.6)
Gait speed derived from 10-Meter Walk Test (m/s)	0.9 (0.4)	0.2-1.9 (1.7)
Mini-Balance Evaluation Systems Test score (0-28)	19.7 (4.2)	7-28 (21)
Fugl-Meyer Assessment for lower extremity score (0-34)	24.8 (4.6)	15-34 (19)
Modified Rankin Scale - ranked 2/3, n (%)	80 (86) / 13 (14)	
Use of walking aids during test – none, n (%)	75 (81)	
Use of orthosis during test - none, n (%)	84 (90)	

***** Categorized with reference to the International Standard Classification of Occupations (ISCO-08)[55]: 0. Retired/ Housewife 1. Managers 2. Professional 3. Technicians and associate professionals 4. Clerical support workers 5. Service and sales workers 6. Skilled agricultural, forestry and fishery workers 7. Craft and related trades workers 8. Plant and machine operators, and assemblers 9. Elementary occupations 10. Armed forces occupations.

Table 3. Cognitive and mobility performance during single- and dual-task conditions (N=93)

Task	Complexity	Measure	Mean	95% CI Lower	95% CI Upper	Cognitive task complexity	Measure	Mean	95% CI Lower	95% CI Upper	Cognitive task complexity	Measure	Mean	95% CI Lower	95% CI Upper
Single-tasks						**Obstacle-crossing**					**Level-ground walking**				
Walking	Low	D (m)	42.7	39.1	46.3	-	-	-	-	-	-	-	-	-	-
	High	D (m)	37.6	34.5	40.7	-	-	-	-	-	-	-	-	-	-
		OCR	95.5	92.6	98.5	-	-	-	-	-	-	-	-	-	-
Auditory Discrimination	Low	D (m)	-	-	-	Low	D (m)	35.1	32.0	38.1	Low	D (m)	39.4	32.0	38.1
		OCR	-	-	-		OCR	95.5	92.5	98.4		OCR	-	-	-
		NCR	19.3	18.6	20.0		NCR	18.1	17.3	19.0		NCR	18.5	17.3	19.0
	High	D (m)	-	-	-	High	D (m)	35.0	32.0	38.0	High	D (m)	38.4	32.0	38.0
		OCR	-	-	-		OCR	94.5	91.4	97.6		OCR	-	-	-
		NCR	17.2	16.3	18.1		NCR	17.3	16.4	18.2		NCR	17.8	16.4	18.2
Category Naming	Low	D (m)	-	-	-	Low	D (m)	30.8	28.1	33.5	Low	D (m)	32.9	28.1	33.5
		OCR	-	-	-		OCR	96.0	93.1	98.9		OCR	-	-	-
		NCR	13.6	12.6	14.7		NCR	14.9	13.8	16.0		NCR	14.6	13.8	16.0
	High	D (m)	-	-	-	High	D (m)	31.2	28.4	33.9	High	D (m)	32.7	28.4	33.9
		OCR	-	-	-		OCR	96.0	92.7	99.3		OCR	-	-	-
		NCR	14.2	13.3	15.0		NCR	13.2	12.5	13.8		NCR	11.3	12.5	13.8
Shopping List Recall*	Low	D (m)	-	-	-	Low	D (m)	37.0	33.8	40.2	Low	D (m)	41.0	33.8	40.2
		OCR	-	-	-		OCR	96.6	93.7	99.4		OCR	-	-	-
		NCR	100.0	100.0	100.0		NCR	98.2	96.7	99.8		NCR	99.6	96.7	99.8
	High	D (m)	-	-	-	High	D (m)	34.8	31.7	37.9	High	D (m)	38.5	31.7	37.9
		OCR	-	-	-		OCR	94.1	90.6	97.7		OCR	-	-	-
		NCR	57.0	49.9	56.5		NCR	53.2	49.9	56.5		NCR	58.3	49.9	56.5
Serial-Subtraction	Low	D (m)	-	-	-	Low	D (m)	30.4	27.8	33.0	Low	D (m)	33.8	27.8	33.0
		OCR	-	-	-		OCR	94.3	91.0	97.5		OCR	-	-	-
		NCR	17.4	15.8	19.0		NCR	13.1	11.7	14.4		NCR	14.4	11.7	14.4
	High	D (m)	-	-	-	High	D (m)	29.9	27.4	32.3	High	D (m)	32.5	27.4	32.3
		OCR	-	-	-		OCR	93.4	89.9	96.8		OCR	-	-	-
		NCR	9.3	8.2	10.4		NCR	7.6	6.6	8.5		NCR	8.3	6.6	8.5
Auditory Clock Test	Low	D (m)	-	-	-	Low	D (m)	33.8	30.8	36.8	Low	D (m)	38.1	30.8	36.8
		OCR	-	-	-		OCR	93.7	90.4	97.1		OCR	-	-	-
		NCR	14.2	13.6	14.9		NCR	14.0	13.2	14.7		NCR	14.0	13.2	14.7
	High	D (m)	-	-	-	High	D (m)	32.8	29.9	35.6	High	D (m)	36.0	29.9	35.6
		OCR	-	-	-		OCR	92.9	89.0	96.8		OCR	-	-	-
		NCR	9.1	8.3	9.9		NCR	10.8	10.0	11.5		NCR	10.3	10.0	11.5

* NCR for shopping-list recall= Number of items correctly recalled ÷ Number of items to be recalled × 100. Abbreviations: 95% CI = 95% Confidence intervals, D = Distance; MD = Mean difference; NCR = Number of correct responses; SE = Standard error; OCR = Obstacle-crossing accuracy rate (i.e., Number of obstacles crossed without touching the obstacles ÷ Number of obstacles encountered during the walk × 100).

Table 4. Dual-task effect on cognitive and mobility task performance (N=93)

			Mobility Task Performance				Cognitive Task Performance			
	Cognitive task	Complexity	Mean mobility-DTE, walking distance (%)	SD	95% CI Lower	95% CI Upper	Mean cognitive-DTE (%)	SD	95% CI Lower	95% CI Upper
Level-ground walking	Auditory discrimination	Low	-6.6	20.5	-9.0	-4.3	-3.1	8.1	-7.6	1.5
		High	-9.4	31.0	-12.3	-6.6	6.9*‡	10.3	1.9	12.0
	Category naming	Low	-21.6	34.7	-24.2	-19.0	21.5‡	13.0	8.9	34.2
		High	-21.9	23.2	-24.5	-19.3	-14.8*‡	12.7	-22.7	-7.0
	Shopping list recall	Low	-3.4	11.1	-5.6	-1.2	-0.4	7.2	-1.1	0.4
		High	-8.7*	25.8	-10.9	-6.6	7.0‡	11.9	-0.2	14.2
	Serial-subtraction	Low	-19.5	40.8	-22.1	-16.9	-14.0‡	12.2	-19.7	-8.2
		High	-22.5	48.0	-25.7	-19.3	-0.2	14.3	-15.3	15.0
	Auditory clock test	Low	-10.2‡	14.2	-12.5	-8.0	0.6	8.5	-2.8	4.0
		High	-14.7*‡	25.7	-17.3	-12.1	28.8*‡	12.9	14.4	43.2
Obstacle-crossing	Auditory discrimination	Low	-7.2‡	11.5	-9.6	-4.9	-5.2	19.7	-9.2	-1.1
		High	-6.3‡	11.3	-8.6	-4.0	3.7*	27.5	-1.9	9.4
	Category naming	Low	-18.0‡	13.7	-20.8	-15.1	20.2	56.5	8.6	31.9
		High	-16.6†‡	11.6	-19.0	-14.2	0.2*†	41.6	-8.3	8.8
	Shopping-list recall	Low	-0.4	14.1	-3.3	2.5	-1.8	7.6	-3.3	-0.2
		High	-7.9*‡	12.6	-10.5	-5.3	-3.2†	28.5	-9.1	2.6
	Serial-subtraction	Low	-18.7‡	12.0	-21.2	-16.3	-21.5†‡	27.3	-27.2	-15.9
		High	-19.1†‡	13.5	-21.9	-16.3	-9.2	60.1	-21.6	3.2
	Auditory clock test	Low	-11.0‡	11.7	-13.4	-8.6	-1.2	20.1	-5.3	2.9
		High	-13.3*‡	12.5	-15.9	-10.8	38.7*	83.8	21.4	55.9

Data are presented as estimated marginal mean difference and standard deviation with 95% confidence intervals.
* Significant difference in DTE between low and high cognitive task complexities with Bonferroni adjustment at $p \leq 0.05$.
† Significant difference in DTE between level-ground walking and obstacle-crossing with Bonferroni adjustment at $p \leq 0.05$.
‡ DTE Exceeded a prior defined level of clinically meaningful difference at mean changes <-0.5 SD or >0.5 SD.
Abbreviations: SD = Standard Deviation, 95% CI = 95% Confidence intervals, DTE = Dual-task effect [(Dual-task performance - Single-task performance) × 100 ÷ Single-task performance].