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Cognitive-Motor Interference in Walking After Stroke: Test-Retest Reliability and Validity of Dual-Task Walking Assessments

INTRODUCTION

The effect of undertaking a cognitive task whilst walking, known as cognitive-motor interference, is thought to underlie options with mobility in people with brain damage. However the reliability and validity of the measures is currently poorly studied.

Mounting evidence showed significant impact of cognitive-motor interference on walking in people after stroke [1-5]. Decrements in both the cognitive performance and walking velocity in dual-task walking among stroke survivors were reported [2, 3]. Other studies reported a significant increase in braking double-support time [1] and gait variability [6] during dual-task walking. Dual-task walking performance was also correlated with falls [7], functional independence [8] and community participation [9]. Thus, assessing dual-task walking performance in people with stroke is essential.

The reliability and validity of cognitive-motor walking tests has been established among older adults [10]. However, dual-task walking and cognitive performance was reported to vary with different central neural lesions [11], and the type and complexity of cognitive and walking tasks performed [5]. Therefore, a battery of reliable and valid dual-task assessments involving different cognitive task domains and difficulty levels would be crucial for directing treatment in stroke rehabilitation.

To date, only three studies have assessed the reliability and validity of dual-task walking assessments in people after stroke [12-14]. Only serial subtraction and verbal fluency were assessed, and the walking distance was short (10 meters or less) [12-14]. Other cognitive task domains (e.g., working memory, discrimination and decision making) were not evaluated. Because of the short distance, the resulting walking time was often too brief to allow a sufficient delineation of dual-task cognitive performance across individuals.

Addressing the above limitations, the current study was undertaken to investigate the reliability and validity of various dual-task mobility assessments in individuals with chronic stroke. Different cognitive task domains were assessed. The difficulty levels of both the component mobility and cognitive tasks were also varied.

METHODS

This was an observational study with repeated measurements at a local university laboratory. Community-dwelling individuals with stroke were recruited by convenience sampling from community self-help groups between May and August 2016. Inclusion criteria included: (1) stroke onset for more than 6 months, (2) ability to walk independently for 1 minute with or without orthosis and/or walking aids, (3) Montreal Cognitive Assessment score ≥ 22, (4) ability to follow given instructions and (5) no active participation in any cognitive or mobility training. The exclusion criteria were: (1) gait-precluding pain or comorbidity, (2) neurological conditions other than stroke, and (3) changes in medication in-between assessments. Prior ethics approval was obtained. All participants provided written informed consent before participation. All procedures were conducted in accordance with the Declaration of Helsinki.

Apart from interviewing the participants in the first session for obtaining the demographic data, Montreal Cognitive Assessment score [15, 16] and Impairment Inventory of Chedoke-McMaster Stroke Assessment for leg and foot scores [17] were assessed in the same session. Dual-task walking assessments were administered to each participant twice within 7-14 days to establish the test-retest reliability. Prior practice trials were given to familiarize subjects with the tasks in both sessions. Testing sequence was randomized to minimize potential order effect. Participants were instructed to perform the cognitive and mobility tasks equally well in dual-task conditions. Intermittent rests were given to minimize any physical or mental fatigue. Each session, including the rest periods, usually lasted around 2 hours.

Table 1 summarizes the mobility and cognitive tasks involved in our testing paradigm. Basically, assessment protocol consisted of one mobility task and four cognitive tasks. Each of the mobility and cognitive tasks had two levels of difficulty (low and high difficulty), resulting in a total of 16 dual-task conditions. The mobility tasks included 1-minute level ground walking with obstabcle negotiation (high difficulty level) [18-21] and without obstacle negotiation (low difficulty level) [22]. The four cognitive tasks, covering five cognitive domains included: (1) Auditory Stroop Test [18, 24, 25], for testing both the reaction time and discrimination and decision making; (2) Serial Subtraction [26, 27], for assessing mental tracking; (3) Shopping List Recall [3], for assessing short-term memory; and (4) Category Naming [28], for testing semantic verbal fluency. The above mobility tasks and cognitive tasks were chosen because they are relevant to community living and are commonly used in research and clinical trials [23]All these also lasted for 1-min each. The number of correct responses, rather than the number of responses, was recorded for all cognitive tasks to minimize potential effect from random guessing. Reaction time in seconds was also recorded for the Auditory Stroop test with a LabVIEW 8.6 progarm (National Instruments, Austin, TX).

Test-retest reliability was analyzed by intraclass correlation coefficient ($ICC_{(2,1)}$) with 95% confidence intervals (CI). Values below 0.75 indicate poor to moderate reliability, and those above 0.75 are good[29]. A standard error of measurement (SEM), indicating the amount of change due to measurement error, was calculated as $\mathrm{SD} \times \sqrt{1 - \mathrm{ICC}}$ [30, 31], where SD is the pooled standard deviation from the first session. Minimal detectable change at 95% CI (MDC_{95}), indicating the amount of change that is not due to measurement variability, was calculated as $1.96 \times SEM \times \sqrt{2}$ [30-33]. In addition, the SEM% and MDC_{95}%, which are independent of the unit of measurement, were also calculated to facilitate comparison of results across different studies [31, 34]. Paired t-test analysis comparing performance between the test and retest sessions was conducted for detecting any learning effect.

Data taken at the first assessment was analyzed for the construct validity and sub-group analyses. First, the construct validity was assessed by examining the relationship between (1) dual-task mobility performance (distance) and the Impairment Inventory of Chedoke-McMaster Stroke Assessment for leg and foot scores, (2) dual-task cognitive performance (number of correct responses and reaction time) and the Montreal Cognitive Assessment score, (3) among the different dual-task mobility tests, and (4) among the various dual-task cognitive tests with Spearman's rank correlation coefficient. ~~Second, the relationship between the performance and age, living status, stroke duration, number of stroke, education years, pre-stroke occupation, highest education level received, number of falls in the past year and the degree of self-perceived recovery from stroke were also explored with the Spearman's rank correlation coefficient. A value of 0.0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0 represents a very weak, weak, moderate, strong and very strong relationship, respectively [35]. Mann-Whitney U tests were used to compare for differences in the dual-task performance between men and women. Difference in the dual-task performance among individuals with different education levels, side of paresis, type of stroke, and pre-stroke occupation were analyzed using Kruskal-Wallis tests. Any significant results were further analyzed by Mann-Whitney U test with Bonferroni adjustment.~~

The sample size was calculated using NCSS Trial and PASS 14 software (NCSS, LLC. Kaysville, Utah, USA). Alpha level of 0.05 and power of 0.8 were adopted. Previous studies on dual-task mobility assessment reported moderate to excellent test-retest reliability (ICC = 0.69-0.99) [12, 13, 36, 37]. The test-retest reliability of the current study was thus hypothesized to be excellent. Assuming a 5% attrition rate, a null reliability with ICC = 0.75 and expected reliability with ICC = 0.90, 29 participants would be required. For the construct validity, we hypothesized a moderate correlation of the dual-task walking performance with cognitive impairment and lower limb impairment ($r = 0.6$). Together with a 5% attrition rate, 24 participants would be required. Statistical Package for Social Sciences version 23 was used for all the data analysis (SPSS Inc., Chicago, IL, USA). A more stringent alpha value (2-tailed) of less than 0.01 was adopted to correct for any potential family-wise error rate across the multiple task comparisons [38].

RESULTS

Thirty-one people with stroke participated in this study. One of these individuals dropped out for medical reasons. Complete data sets were obtained from 30 participants with mild to moderate motor impairment. The characteristics are summarized in Table 2.

There were no significant differences in findings between the first and second testing sessions in all the 44 but five outcomes, indicating no substantial learning effect (Table 3). Table 4 and 5 provides details of the test-retest reliability findings, including the ICC, SEM and MDC_{95} values.

Excellent reliability ($ICC_{(2,1)} = 0.891–0.984$, $p < 0.05$) was found in both the walking distance and OHR in all dual-task conditions. Number of correct responses in serial subtraction and verbal fluency tests demonstrated moderate to excellent reliability ($ICC_{(2,1)} = 0.714–0.911$, $p < 0.05$)

(Table 5). A discrepancy in the reliability of number of correct responses at low and high difficulty levels was observed in the shopping list recall task.

Walking distance attained in various dual-task conditions were all found to have significant moderate relationship with the Impairment Inventory of Chedoke-McMaster Stroke Assessment for leg and foot scores (r_s = 0.466–0.561, $p < 0.01$), except during level-ground walking combined with high-level category naming and low-level shopping list recall (Table 6). No significant correlations were found between the Montreal Cognitive Assessment score and the number of correct responses or the reaction time in all dual-task conditions (Table 6).

The walking distance achieved in both walking tasks in different dual-task conditions were found to be strongly correlated with each other, regardless of the domain and difficulty level of the cognitive tasks (level-ground walking: r_s = 0.872–0.972, $p < 0.01$; obstacle negotiations: r_s = 0.840–0.985, $p < 0.01$) (Table 7).

For cognitive domains, moderate to excellent correlations were found in the number of correct responses (r_s= 0.515-0.793, $p < 0.01$) and the reaction time (r_s= 0.605-0.849, $p < 0.01$) between low- and high-level cognitive tasks of the same domain except for shopping list recall (Table 8). Except for the moderate correlation (r_s = 0.524-0.647, $p < 0.01$) found between the number of correct responses of verbal fluency tests and that of serial subtraction, the number of correct responses values showed no significant correlations among different dual-tasks (Table 8).

DISCUSSION

The main finding of this study is that the dual-task walking assessments tested here are reliable and valid when used among community-dwelling ambulatory individuals with stroke.

Excellent test-retest reliability of the dual-task walking distance measures (ICC=0.891-0.984) was found, regardless of the type of the cognitive tasks or difficulty levels of the tasks used. The reliability of the cognitive parameters tended to be lower, but still achieved moderate to excellent levels (ICC=0.556-0.911 for number of correct responses, ICC=0.499-0.800 for reaction time). These are consistent with findings from previous studies among older adults [31, 36, 39]. Our SEM% values of the distance measures under dual-task condition (4.6-11.3%) were comparable to those obtrained from community-dwelling older adults [31], but much lower than those reported in a previous stroke study (11.4-22.2%) [12]. The difference in results may be related to the difference in testing protocols. We measured the maximum distance covered within a fixed 1-minute time period for all conditions. In contrast, the previous study reported time (in seconds) required to cover a fixed walking distance of 10 meters. Their reported mean walking time ranged from 10.9s (3.5s) to 19.6s (8.0s) in level ground and obstacle course walking in single-task and dual-task conditions [35]. The time period involved in walking here was thus more than threefold, when compared with the previous study. With the longer walking time given, a better estimation of the true dual-task walking ability was allowed.

Despite the involvement of attention demands [40, 41], the walking task is more automated than the cognitive tasks. The higher reliability of the walking component compared with that of the cognitive component might be explained by the higher automaticity of walking. Although the neural pathway for gait automaticity might have once been interrupted by the incidence of stroke, our study participants probably had regained independent ambulatory function [42, 43]. The much lesser attention demand of walking task makes it less affected by the internal or external distraction and thus a higher reliability than the cognitive tasks. Albeit the participants were instructed to perform both the mobility and cognitive tasks equally well under the dual-task condition, they might have prioritized one task over the other, and varied the prioritization from trial to trial. As a higher cognitive demand is required in performing the less automatic cognitive tasks, reliability of the cognitive component is more susceptible to the changing prioritization between tasks. This agrees with the widely accepted attention theories such as the capacity sharing model, [44-46] which suggests that humans have a limited capacity in performing mental work and that the limited resources can be freely allocated among concurrent activities, and that attention allocation is highly flexible and responsive to the momentary intentions controlled by the autonomously operating pre-attentive mechanisums.

Among all the cognitive tasks, reliability of the auditory Stroop tests was lower, compared to the other three cognitive tasks. This might be explained by the distinct nature of the task in which both reaction time and discrimination/decision making domains are involved. The participants might have given priority to the generation of correct responses in one trial, and to the reaction time component in another, thus lowering the reliability. Moreover, with reference to the higher attention demand of Stroop test compared to other tasks [47], its reliability was more prone to changes in task prioritization, as mentioned earlier.

For the shopping list recall task at low difficulty level, all participants were able to consistently recall all three items in all dual-task conditions, leading to a zero variance. This indicated a ceiling effect of the 3-item shopping list recall as a short-term memory test for community-dwelling individuals with chronic stroke who have normal cognitive function.

In line with previous studies, there were moderate relationships between the lower limb motor function and walking distance covered at most of the different dual-task walking conditions, regardless of cognitive task domains or difficulty levels of the component tasks [12, 48].

There were no significant correlations between the number of correct responses in dual-task conditions and the Montreal Cognitive Assessment score. It might be explained by the homogeneity of our sample. We only included subjects scored ≥ 22 out of 30 in the Montreal Cognitive Assessment. Indeed, a high Montreal Cognitive Assessment mean score with small standard deviation (27.1 ± 1.6) was found in our sample. Another explanation of the lack of significant correlation may be related to the difference in the construct being measured. Montreal Cognitive Assessment consists of items that evaluate eight different cognitive domains [15]. In contrast, each of the cognitive tasks in our dual-task testing protocol mainly involved a single domain of cognitive function.

Given the same cognitive domain, the dual-task number of correct responses and distance values obtained when the difficulty level of the cognitive task was low showed moderate to excellent correlations with the corresponding values when the difficulty level of the cognitive task was high. This phenomenon applies to all cognitive domains except shopping list recall. This strong correlations indicated that for a given walking task, it may not be necessary to assess the same cognitive domain with two levels of difficulty. Similarly, the results were highly correlated between the level ground walking and obstacle crossing task. Assessment of one of the walking tasks may accurately predict that of the other. In contrast, the relatively low correlations among the different cognitive tasks, in turn, support the need to assess different cognitive domains during dual-task walking. The assessment would then provide a comprehensive picture of the dual-task walking ability of individual clients without being too lengthy. This is an important consideration because of the time cosntraints commonly encountered by physical therapists in daily clinical practice. The findings on different cognitive domains can also be used to identify specific areas of deficit, so as to direct treatment.

The results of the current study may only be generalized to community-dwelling individuals post-stroke with intact cognitive function and independent ambulation function. Furthermore, with the comprehensiveness of our series of assessments, time required to complete is rather long (1.5 to 2 hours). It might have caused physical and/or mental fatigue. However, intermittent rest period were provided and the results indicated no significant differences in findings between the first and second measurements. In our study, all the participants turned in the same direction irrespective of their side of paresis, and significant associations between the dual-task walking distance and the hemiplegic side were found. There may be a need to keep the direction of turns consistent (e.g., towards the hemilegic side) to allow for better within-subject and between-subject comparisons. As aforementioned, the self-perceived task difficulty may have covertly influenced the task prioritization. Future studies may address this issue by measuring the participants' self-perceived task difficulty or their arousal and stress levels physiologically [44] during the testing of single- and dual-task performance. A sample size of 30 is rather small It warrants futher larger scale studies with a larger sample size of 50 or more [53] to verify the findings and enable us to conduct sub-group analysis based on the demographic and clinical characteristics with more statistical power.

Clinical Messages

- The dual-task walking assessments tested are largely reliable and valid in measuring cognitive-motor interference during walking among community-dwelling individuals with chronic stroke.
- The set of assessments may help clinicians identify specific dual-task walking deficits and

thus direct treatment for their individual clients with stroke.

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Table 1 Dual-task mobility testing protocol

Complexity	Task Description	Outcome variable
Mobility task: Walked along a 7×3-meter rectangular walkway for one minute.		
Low	Level ground walking: Covered as much the distance as possible.	1. Distance (m), A longer distance covered indicates better performance. 2. OHR (%), if applicable. A smaller OHR indicates better performance.
High	Obstacle crossing: Covered as much the distance as possible while avoid hitting the obstacles with 9-cm height, 4-cm thickness and 1-m length [54, 55], at every four meters apart. Obstacle hitting rate (OHR) was calculated as $\frac{Total\ number\ of\ obstacles\ hit}{Total\ number\ of\ obstacles\ maneuvered} \times 100\%$.	
Cognitive task: Performed with mobility task for one minute for dual-task conditions Performed in sitting for one minute for single-task conditions		
Task 1: Serial Subtraction (Domain: Mental Tracking)		
Low	Serial 3 subtractions: Repeatedly subtracted 3 from a random number between 390 and 399.	Number of correct responses (NCR). More the NCR, better the performance.
High	Serial 7 subtractions: Repeatedly subtracted 7 from a random number between 390 and 339.	
Task 2: Auditory Stroop Test (Domain 1: Reaction time, and Domain 2: Discrimination and Decision Making):		
Low	Discriminated the pitch of words "High" and "Low" of a female voice.	1. NCR 2. Reaction time (s), Shorter time indicates better performance.
High	Discriminated the pitch of words "High" and "Low" and gender (male/female) of a male/female voice.	
Task 3: Shopping List Recall (Domain: Short-term memory):		
Low	Recalled a randomly generated 3-item shopping list that was repeated three times.	NCR recalled immediately and one minute afterwards.
High	Recalled a randomly generated 7-item shopping list that was repeated three times.	
Task 4: Category Naming (Domain: Sematic verbal fluency)		
Low	Named as many words as possible in a randomly selected category (e.g., Countries).	NCR
High	Named as many words as possible in a more confined randomly selected category (e.g., European countries).	

Abbreviations: NCR: Number of correct responses; OHR: Obstacles hitting rate.

Table 2 Characteristics of study participants (N=30)

Variables	**N or Mean ± SD**
Gender, Male/ Female	22/ 8
Age, years	62.4 ± 6.7
Number of falls in the past one year, 0/ 1/ 2/ 3/ 4/ 10	21/ 4/ 2/ 1/ 1/ 1
Hemiplegic Side, Left/ Right/ Both	13/ 16/ 1
Type of Stroke, Ischemic/ Hemorrhage/ Unknown	19/ 9/ 2
Time since onset of first stroke, years	9.2 ± 3.6
Number of stroke, 1/ 2/ 3	19/ 9/ 2
Pre-stroke occupation, categories 0-10**	2/ 4/ 1/ 8/ 1/ 8/ 0/ 0/ 4/ 0/ 1
Highest Education Level, Primary/ Secondary/ Tertiary	11/ 16/ 3
Years of education	9.3 ± 3.4
MoCA Score (0–30)	27.1 ± 1.7
Sum of CMSA Leg and Foot Score (2-14)	8.8 ± 2.0

* Living status categories: 1. living alone 2. living with family 3. living with maid 4. others

**Pre-stroke occupation categorized with reference to the International Standard Classification of Occupations (ISCO-08) [56]: 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

Abbreviations: N: Number; SD: Standard Deviation; MoCA: Montreal Cognitive Assessment; CMSA: Impairment Inventory of Chedoke-McMaster Stroke Assessment for leg and foot scores.

Table 3 Dual-task mobility and cognitive performance in test and retest sessions

Dual-Task	Difficulty Level	Measures	Test		Retest		*t*	*p* (2-tailed)
			Mean	SD	Mean	SD		
Without obstacles								
Auditory Stroop Test	Low	Distance (m)	39.3	14.6	39.7	14.6	-0.495	0.624
		NCR	15.0	5.5	15.1	5.5	-0.186	0.854
		RT (ms)	0.7	0.4	0.8	0.6	-0.921	0.365
	High	Distance (m)	38.5	13.0	38.5	13.8	-0.040	0.969
		NCR	13.1	4.8	13.7	3.9	-0.856	0.399
		RT (ms)	0.9	0.4	0.9	0.3	0.039	0.969
Verbal Fluency	Low	Distance (m)	33.6	11.1	34.2	10.8	-0.695	0.492
		NCR	12.8	5.2	14.2	6.4	-2.586	0.015*
	High	Distance (m)	33.1	10.5	33.3	10.8	-0.286	0.777
		NCR	8.3	4.7	9.4	5.2	-2.194	0.036*
Working Memory	Low	Distance (m)	42.8	16.6	42.9	16.6	-0.106	0.916
		NCR	2.9	0.1	2.9	0.1	-	-
	High	Distance (m)	40.3	14.9	39.7	14.2	0.812	0.424
		NCR	5.1	1.1	5.3	1.0	-1.270	0.214
Mental Tracking	Low	Distance (m)	34.2	10.6	34.4	11.1	-0.316	0.754
		NCR	15.2	8.4	16.3	8.3	-1.335	0.192
	High	Distance (m)	32.8	10.4	33.1	11.0	-0.497	0.623
		NCR	9.0	6.1	8.5	5.5	0.982	0.334
With obstacles								
Auditory Stroop Test	Low	Distance (m)	36.0	13.1	36.0	12.8	-0.113	0.911
		OHR	4.3	18.4	4.0	18.3	0.375	0.710
		NCR	15.8	4.4	15.9	4.2	-0.089	0.930
		RT (s)	0.7	0.3	0.7	0.3	0.484	0.632
	High	Distance (m)	35.0	12.1	35.4	12.4	-0.795	0.433
		OHR	4.3	18.4	3.6	18.2	0.897	0.377
		NCR	13.2	4.1	13.5	4.6	-0.464	0.646
		RT (s)	1.0	0.4	1.0	0.4	0.025	0.980
Verbal Fluency	Low	Distance (m)	31.4	10.	31.1	10.1	0.691	0.495
		OHR	4.29	18.	4.7	18.5	-0.641	0.526
		NCR	13.1	4.3	14.4	5.7	-2.017	0.053
	High	Distance (m)	29.7	9.8	30.5	10.2	-1.033	0.310
		OHR	4.6	18.7	6.0	18.6	-1.502	0.144
		NCR	8.0	3.1	8.9	3.9	-1.874	0.071
Working Memory	Low	Distance (m)	36.6	13.3	38.7	14.6	-3.754	0.001*
		OHR	4.3	18.4	4.0	18.5	0.363	0.719
		NCR	2.9	0.1	3.0	0.0	-1.000	0.326
	High	Distance (m)	35.3	13.0	35.8	12.0	-0.685	0.499
		OHR	4.5	18.4	5.1	18.8	-0.611	0.546
		NCR	5.0	1.3	5.3	1.32	-1.439	0.161
Mental Tracking	Low	Distance (m)	31.8	10.9	33.0	12.3	-1.159	0.256
		OHR	4.3	18.4	3.3	18.2	1.424	0.165
		NCR	15.7	9.3	16.6	8.4	-1.220	0.232
	High	Distance (m)	29.4	9.7	30.6	10.1	-2.410	0.023*
		OHR	4.7	18.5	4.4	18.5	0.235	0.816
		NCR	7.6	5.2	8.8	5.6	-2.482	0.019*

*: Statistically significant with $p<0.05$.

Abbreviations: SD: Standard deviation; NCR: Number of correct responses; RT: Reaction time; OHR: Obstacles hitting rate.

Table 4 Test-retest reliability for mobility-related parameters

Tasks	**Difficulty level**		**Distance, m (without obstacles)**	**Distance, m (with obstacles)**	**Obstacle hitting rate, %**
Single-task walking	NA	$ICC_{(2,1)}$	0.974*	0.969*	0.915*
		95% CI of $ICC_{(2,1)}$	0.946-0.987	0.935-0.985	0.830-0.959
		SEM (SEM%)	2.7 (6.1)	2.6 (6.8)	5.6 (117.6)
		MDC_{95} (MDC_{95}%)	7.6 (17.0)	7.3 (18.9)	15.4 (326.0)
Auditory Stroop Test	Low	$ICC_{(2,1)}$	0.956*	0.984*	0.965*
		95% CI of $ICC_{(2,1)}$	0.910-0.979	0.967-0.992	0.928-0.983
		SEM (SEM%)	3.1 (7.8)	1.7 (4.6)	3.5 (79.1)
		MDC_{95} (MDC_{95}%)	8.5 (21.6)	4.6 (12.8)	9.6 (219.4)
	High	$ICC_{(2,1)}$	0.955*	0.978*	0.974*
		95% CI of $ICC_{(2,1)}$	0.908-0.978	0.954-0.989	0.947-0.988
		SEM (SEM%)	2.8 (7.2)	1.8 (5.1)	3.0 (68.9)
		MDC_{95} (MDC_{95}%)	7.7 (19.9)	5.0 (14.2)	8.3 (191.0)
Category Naming	Low	$ICC_{(2,1)}$	0.917*	0.972*	0.975*
		95% CI of $ICC_{(2,1)}$	0.835-0.960	0.943-0.987	0.949-0.988
		SEM (SEM%)	3.2 (9.5)	1.7 (5.5)	3.0 (69.3)
		MDC_{95} (MDC_{95}%)	8.9 (26.4)	4.8 (15.2)	8.3 (192.2)
	High	$ICC_{(2,1)}$	0.946*	0.915*	0.962*
		95% CI of $ICC_{(2,1)}$	0.889-0.974	0.827-0.957	0.922-0.982
		SEM (SEM%)	2.5 (7.4)	2.9 (9.7)	3.7 (78.7)
		MDC_{95} (MDC_{95}%)	6.8 (20.5)	8.0 (26.9)	10.1 (218.2)
Shopping List Recall	Low	$ICC_{(2,1)}$	0.939*	0.966*	0.957*
		95% CI of $ICC_{(2,1)}$	0.875-0.970	0.880-0.987	0.912-0.979
		SEM (SEM%)	4.1 (9.6)	2.5 (6.7)	3.8 (87.7)
		MDC_{95} (MDC_{95}%)	11.4 (26.6)	6.8 (18.6)	10.6 (243.2)
	High	$ICC_{(2,1)}$	0.956*	0.955*	0.965*
		95% CI of $ICC_{(2,1)}$	0.911-0.979	0.908-0.978	0.928-0.983
		SEM (SEM%)	3.1 (7.8)	2.8 (7.9)	3.5 (75.4)
		MDC_{95} (MDC_{95}%)	8.7 (21.5)	7.7 (21.8)	9.6 (208.9)
Serial Subtraction	Low	$ICC_{(2,1)}$	0.928*	0.891*	0.979*
		95% CI of $ICC_{(2,1)}$	0.855-0.965	0.785-0.946	0.956-0.990
		SEM (SEM%)	2.9 (8.4)	3.6 (11.3)	2.7 (62.1)
		MDC_{95} (MDC_{95}%)	7.9 (23.2)	10.0 (31.3)	7.4 (172.0)
	High	$ICC_{(2,1)}$	0.952*	0.961*	0.962*
		95% CI of $ICC_{(2,1)}$	0.901-0.977	0.911-0.982	0.922-0.982
		SEM (SEM%)	2.3 (7.0)	1.9 (6.5)	3.6 (76.7)
		MDC_{95} (MDC_{95}%)	6.3 (19.3)	5.4 (18.1)	10.0 (212.6)

*: Statistically significant for Intraclass correlation coefficient (model 2, form 1) analysis (p<0.01).

Abbreviations: NA: Not applicable; $ICC_{(2,1)}$: Intraclass correlation coefficient (model 2, form 1); CI: Confidence interval; SEM: Standard error of measurement; SEM%: SEM percentage to mean; MDC_{95}: Minimal detectable change at the 95% confidence interval; MDC_{95}%: MDC_{95} percentage to mean.

Table 5 Test-retest reliability for cognitive-related parameters

Cognitive Tasks			Single-Task		Dual-Task (without obstacles)		Dual Task (with obstacles)	
			NCR (n)	RT (s)	NCR (n)	RT (s)	NCR (n)	RT (s)
Auditory Stroop Test	Low	$ICC_{(2,1)}$	0.619*	0.480*	0.756*	0.645*	0.556*	0.511*
		95% CI of $ICC_{(2,1)}$	0.337-0.799	0.049-0.715	0.546-0.876	0.380-0.813	0.245-0.762	0.188-0.734
		SEM (SEM%)	2.9 (17.4)	0.3 (41.8)	2.8 (18.3)	0.3 (31.5)	3.0 (18.6)	0.3 (35.8)
		MDC_{95} (MDC_{95}%)	8.0 (48.2)	1.0 (116.0)	7.6 (50.8)	0.7 (87.4)	8.2 (51.6)	0.8 (99.1)
	High	$ICC_{(2,1)}$	0.686*	0.550*	0.700*	0.800*	0.678*	0.499*
		95% CI of $ICC_{(2,1)}$	0.434-0.837	0.238-0.758	0.461-0.844	0.621-0.900	0.424-0.833	0.169-0.727
		SEM (SEM%)	2.3 (16.7)	0.3 (23.3)	2.6 (20.0)	0.2 (20.9)	2.3 (17.7)	0.3 (29.0)
		MDC_{95} (MDC_{95}%)	6.3 (46.2)	0.7 (64.7)	7.3 (55.5)	0.6 (58.0)	6.5 (49.0)	0.8 (80.3)
Category Naming	Low	$ICC_{(2,1)}$	0.768*	-	0.859*	-	0.766*	-
		95% CI of $ICC_{(2,1)}$	0.567-0.883	-	0.694-0.934	-	0.558-0.883	-
		SEM (SEM%)	2.0 (14.6)	-	2.0 (15.4)	-	2.1 (15.8)	-
		MDC_{95} (MDC_{95}%)	5.6 (40.4)	-	5.5 (42.6)	-	5.8 (43.8)	-
	High	$ICC_{(2,1)}$	0.804*	-	0.853*	-	0.714*	-
		95% CI of $ICC_{(2,1)}$	0.620-0.903	-	0.700-0.929	-	0.480-0.853	-
		SEM (SEM%)	1.5 (17.9)	-	1.8 (21.7)	-	1.7 (20.8)	-
		MDC_{95} (MDC_{95}%)	4.3 (49.5)	-	5.0 (60.2)	-	4.6 (57.7)	-
Shopping List Recall	Low	$ICC_{(2,1)}$	Bypassed with zero variance	-	Bypassed with zero variance	-	Bypassed with zero variance	-
		95% CI of $ICC_{(2,1)}$		-		-		-
		SEM (SEM%)	NA	-	NA	-	NA	-
		MDC_{95} (MDC_{95}%)	NA	-	NA	-	NA	-
	High	$ICC_{(2,1)}$	0.792*	-	0.595*	-	0.707*	-
		95% CI of $ICC_{(2,1)}$	0.607-0.895	-	0.310-0.783	-	0.474-0.848	-
		SEM (SEM%)	0.5 (8.9)	-	0.7 (14.4)	-	0.7 (14.6)	-
		MDC_{95} (MDC_{95}%)	1.4 (24.6)	-	2.0 (40.0)	-	2.0 (40.3)	-
Serial Subtraction	Low	$ICC_{(2,1)}$	0.911*	-	0.871*	-	0.910*	-
		95% CI of $ICC_{(2,1)}$	0.821-0.957	-	0.749-0.936	-	0.822-0.956	-
		SEM (SEM%)	2.7 (15.6)	-	3.1 (20.0)	-	2.8 (17.7)	-
		MDC_{95} (MDC_{95}%)	7.5 (43.2)	-	8.5 (55.4)	-	7.8 (49.2)	-
	High	$ICC_{(2,1)}$	0.869*	-	0.886*	-	0.872*	-
		95% CI of $ICC_{(2,1)}$	0.744-0.935	-	0.777-0.944	-	0.724-0.940	-
		SEM (SEM%)	2.0 (21.8)	-	2.1 (23.0)	-	1.9 (24.4)	-
		MDC_{95} (MDC_{95}%)	5.4 (60.5)	-	5.8 (63.9)	-	5.2 (67.7)	-

*: Statistically significant for Intraclass correlation coefficient (model 2, form 1) analysis (p<0.01).
Abbreviations: NRC: Number of correct responses; RT: Reaction time; $ICC_{(2,1)}$: Intraclass correlation coefficient (model 2, form 1); CI: Confidence interval; SEM: Standard error of measurement; SEM%: SEM percentage to mean; MDC_{95}: Minimal detectable change at the 95% confidence interval; MDC_{95}%: MDC_{95} percentage to mean: NA: Not applicable.

Table 6 Association of dual-task mobility and cognitive performance with motor impairment and cognitive function

Cognitive Tasks		**Distance and CMSA**		**Reaction Time and MoCA**		**NCR and MoCA**	
		Without obstacles	**With obstacles**	**Without obstacles**	**With obstacles**	**Without obstacles**	**With obstacles**
Auditory Stroop Test	Low	0.491*	0.542*	0.091	0.268	0.065	-0.127
	High	0.540*	0.496*	-0.067	0.038	-0.078	0.080
Category Naming	Low	0.509*	0.552*	-	-	0.215	0.232
	High	0.462	0.523*	-	-	0.190	0.039
Shopping list Recall	Low	0.438	0.522*	-	-	0.011	-0.296
	High	0.535*	0.466*	-	-	0.378	0.219
Serial Subtraction	Low	0.532*	0.512*	-	-	0.141	0.072
	High	0.539*	0.561*	-	-	0.110	0.190

*: Statistically significant for Spearman's rho analysis (p<0.01).

Abbreviations: CMSA: Chedoke McMaster Stroke Assessment (Leg and Foot); MoCA: Montreal Cognitive Assessment score.

Table 7 Correlations of dual-task mobility performance between different cognitive tasks

Mobility Parameters	**Cognitive Task**		**Auditory Stroop Test**		**Category Naming**		**Shopping list Recall**		**Serial Subtraction**	
			Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Distance (without obstacles)	Auditory Stroop Test	Low	-	-	-	-	-	-	-	-
		High	0.972*	-	-	-	-	-	-	-
	Category Naming	Low	0.895*	0.932*	-	-	-	-	-	-
		High	0.924*	0.959*	0.961*	-	-	-	-	-
	Shopping list Recall	Low	0.958*	0.966*	0.906*	0.952*	-	-	-	-
		High	0.940*	0.959*	0.872*	0.916*	0.957*	-	-	-
	Serial Subtraction	Low	0.935*	0.943*	0.909*	0.928*	0.886*	0.893*	-	-
		High	0.901*	0.933*	0.937*	0.938*	0.891*	0.889*	0.953*	-
Distance (with obstacles)	Auditory Stroop Test	Low	-	-	-	-	-	-	-	-
		High	0.948*	-	-	-	-	-	-	-
	Category Naming	Low	0.980*	0.985*	-	-	-	-	-	-
		High	0.933*	0.921*	0.952*	-	-	-	-	-
	Shopping list Recall	Low	0.957*	0.941*	0.943*	0.895*	-	-	-	-
		High	0.944*	0.923*	0.919*	0.875*	0.975*	-	-	-
	Serial Subtraction	Low	0.895*	0.913*	0.897*	0.840*	0.928*	0.941*	-	-
		High	0.927*	0.922*	0.951*	0.967*	0.902*	0.871*	0.870*	-
Obstacle Hitting Rate	Auditory Stroop Test	Low	-	-	-	-	-	-	-	-
		High	0.309	-	-	-	-	-	-	-
	Category Naming	Low	0.401	0.802*	-	-	-	-	-	-
		High	0.309	0.309	0.401	-	-	-	-	-
	Shopping list Recall	Low	0.309	0.309	0.401	0.309	-	-	-	-
		High	0.252	0.565*	0.732*	0.252	0.252	-	-	-
	Serial Subtraction	Low	0.309	0.309	0.401	0.309	0.678*	0.252	-	-
		High	0.252	0.252	0.341	0.545*	0.565*	0.194	0.252	-

*: Statistically significant for Spearman's rho analysis (*p*<0.01).

Table 8 Correlations of dual-task cognitive performance between different cognitive tasks

Cognitive Parameters	Cognitive Task		Auditory Stroop Test		Category Naming		Shopping list Recall		Serial Subtraction	
			Low	High	Low	High	Low	High	Low	High
No. of Correct Responses (without obstacles)	Auditory Stroop Test	Low	-	-	-	-	-	-	-	-
		High	0.515*	-	-	-	-	-	-	-
	Category Naming	Low	0.378	0.397	-	-	-	-	-	-
		High	0.331	0.402	0.902*	-	-	-	-	-
	Shopping list Recall	Low	0.097	0.313	0.280	0.258	-	-	-	-
		High	0.143	0.077	0.289	0.390	0.212	-	-	-
	Serial Subtraction	Low	0.341	0.296	0.647*	0.542*	0.312	0.262	-	-
		High	0.310	0.308	0.524*	0.430	0.280	0.257	0.793*	-
No. of Correct Responses (with obstacles)	Auditory Stroop Test	Low	-	-	-	-	-	-	-	-
		High	0.524*	-	-	-	-	-	-	-
	Category Naming	Low	0.492*	0.568*	-	-	-	-	-	-
		High	0.278	0.286	0.610*	-	-	-	-	-
	Shopping list Recall	Low	0.314	0.270	0.076	0.194	-	-	-	-
		High	0.224	0.359	0.150	0.318	0.189	-	-	-
	Serial Subtraction	Low	0.492*	0.093	0.244	0.078	0.075	0.286	-	-
		High	0.536*	0.311	0.227	0.064	0.130	0.240	0.776*	-
Auditory Stroop Test Reaction Time	Mobility Low	Low	-	0.605*						
		High	0.849*	-						
	Mobility High	Low	-	0.739*						
		High	0.696*	-						

*: Statistically significant for Spearman's rho analysis (p<0.01).

Table 9 Association between dual-task mobility performance and demographic and clinical characteristics (N=30)

Cognitive Task		Gender	Age (year)	Education years	Highest Education	Stroke Duaration	Stroke Type	Stroke Side	Number of Stroke	Falls in past year (N)	Pre-Stroke Occupation	Living Status	Recovery Percentage
Walking without Obstacles (Walking Distance)													
Auditory	Low	-0.174	-0.127	0.194	0.145	0.136	0.245	0.423*	-0.322	0.090	-0.009	-0.316	0.502**
Stroop Test	High	-0.170	-0.111	0.303	0.253	0.126	0.243	0.423*	-0.342	0.162	0.032	-0.316	0.459*
Category	Low	-0.174	-0.118	0.342	0.270	0.272	0.216	0.339	-0.308	0.232	0.145	-0.316	0.423*
Naming	High	-0.165	-0.193	0.348	0.265	0.146	0.186	0.331	-0.400*	0.148	0.127	-0.316	0.411*
Shopping list	Low	-0.200	-0.177	0.208	0.159	0.126	0.209	0.449*	-0.367*	0.111	0.046	-0.316	0.477*
Recall	High	-0.087	-0.041	0.201	0.138	0.131	0.105	0.419*	-0.289	0.160	0.032	-0.316	0.440*
Serial	Low	-0.131	-0.127	0.258	0.214	0.179	0.224	0.342	-0.400*	0.185	0.124	-0.316	0.422*
Subtraction	High	-0.226	-0.067	0.329	0.272	0.275	0.169	0.272	-0.364*	0.255	0.198	-0.316	0.332
Walking with Obstacles (Walking Distance)													
Auditory	Low	-0.218	-0.101	0.268	0.214	0.128	0.247	0.420*	-0.355	0.145	0.048	-0.316	0.468*
Stroop Test	High	-0.131	-0.050	0.229	0.176	0.208	0.167	0.372*	-0.388*	0.187	-0.004	-0.316	0.419*
Category	Low	-0.165	-0.095	0.278	0.210	0.181	0.169	0.331	-0.331	0.243	0.064	-0.316	0.376*
Naming	High	-0.192	-0.036	0.315	0.236	0.176	0.204	0.243	-0.341	0.186	0.069	-0.316	0.405*
Shopping list	Low	-0.174	-0.050	0.180	0.110	0.166	0.133	0.394*	-0.311	0.129	0.025	-0.316	0.397*
Recall	High	-0.174	-0.100	0.231	0.142	0.153	0.131	.415*	-0.364*	0.120	0.122	-0.316	0.422*
Serial	Low	-0.118	-0.108	0.236	0.164	0.296	0.100	0.376*	-0.311	0.232	0.153	-0.316	0.407*
Subtraction	High	-0.187	-0.079	0.304	0.239	0.241	0.206	0.195	-0.244	0.195	0.058	-0.316	0.342
Walking with Obstacles (Obstacle Hitting Rate)													
Auditory	Low	0.067	0.093	-0.124	-0.051	-0.406*	0.160	-0.175	-0.130	-0.214	-0.230	0.598**	-0.202
Stroop Test	High	0.067	0.390*	-0.230	-0.051	0.000	-0.038	0.037	0.164	0.037	-0.249	0.598**	0.144
Category	Low	0.151	0.401*	-0.252	-0.109	0.031	-0.200	-0.053	0.262	0.142	-0.237	0.720**	0.048
Naming	High	0.318	0.090	0.038	0.079	-0.326	-0.052	-0.161	-0.130	0.067	0.101	0.598**	0.017
Shopping list	Low	0.067	0.067	-0.193	0.103	-0.127	0.237	-0.175	-0.130	-0.214	-0.249	0.598**	0.083
Recall	High	0.221	0.452*	-0.250	-0.301	-0.146	-0.293	0.202	0.134	-0.006	-0.219	0.527**	0.264
Serial	Low	0.301	0.103	-0.023	0.206	0.024	-0.038	-0.373*	-0.130	0.052	-0.249	0.598**	-0.264
Subtraction	High	0.007	-0.202	0.123	0.250	-0.065	0.323	-0.077	-0.153	0.005	0.040	0.527**	0.168

*: Statistically significant for Spearman's rho analysis (p<0.05); **: Statistically significant for Spearman's rho analysis (p<0.01).

Table 10 Association between the demographics and dual-task cognitive performance (N=30)

Cognitive Task		Gender	Age (year)	Education years	Highest Education	Stroke Duaration	Stroke Type	Stroke Side	Number of Stroke	Falls in past year (N)	Pre-Stroke Occupation	Living Status	Recovery Percentage
Walking without Obstacles (Number of Correct Responses)													
Auditory	Low	0.149	-0.028	0.082	-0.001	-0.004	-0.156	-0.233	0.101	-0.298	-0.172	0.091	-0.056
Stroop Test	High	0.096	0.083	0.198	0.171	0.208	-0.241	-0.158	0.172	0.212	0.068	-0.125	-0.226
Category	Low	-0.149	0.143	0.378*	0.232	0.048	0.008	0.031	-0.030	-0.077	-0.063	-0.318	0.053
Naming	High	-0.079	0.016	0.464**	0.342	-0.015	-0.010	-0.050	-0.112	0.030	-0.075	-0.272	-0.150
Shopping	Low	.	.	.	.	.	.	.	.	.	.	.	.
list Recall	High	0.081	-0.062	-0.011	-0.023	-0.109	-0.167	-0.360	-0.060	-0.008	-0.181	-0.223	-0.339
Serial	Low	0.009	0.214	0.279	0.205	0.312	0.069	-0.088	-0.043	-0.275	0.012	-0.147	0.033
Subtraction	High	-0.298	0.154	0.136	-0.040	0.248	-0.052	-0.122	0.062	-0.287	0.151	-0.261	-0.163
Walking with Obstacles (Number of Correct Responses)													
Auditory	Low	0.066	0.204	0.229	0.193	0.240	-0.046	-0.251	0.141	-0.200	-0.115	0.114	-0.086
Stroop Test	High	-0.048	0.127	0.121	0.043	-0.185	-0.037	-0.119	-0.104	-0.151	-0.107	-0.182	-0.191
Category	Low	0.031	0.074	0.191	0.042	-0.113	0.113	0.093	-0.104	-0.063	-0.111	0.000	0.027
Naming	High	-0.092	-0.122	0.120	-0.074	-0.048	0.076	0.052	0.029	-0.169	-0.220	-0.091	-0.138
Shopping	Low	.	.	.	.	.	.	.	.	.	.	.	.
list Recall	High	0.023	0.002	0.143	0.030	0.039	-0.196	-0.163	-0.189	-0.079	0.043	-0.211	-0.465*
Serial	Low	-0.279	0.158	0.136	0.055	0.280	0.164	-0.016	-0.001	-0.156	0.158	-0.238	-0.004
Subtraction	High	-0.259	0.214	0.247	0.129	0.226	0.020	-0.289	0.037	-0.318	0.035	-0.250	-0.083
Walking without Obstacles (Reaction Time)													
Auditory	Low	-0.261	-0.236	-0.177	-0.106	0.041	0.175	-0.008	-0.110	0.244	0.157	-0.068	0.010
Stroop Test	High	-0.087	0.045	-0.165	-0.128	0.034	0.078	0.035	-0.138	-0.258	-0.197	0.248	0.321
Walking with Obstacles (Reaction Time)													
Auditory	Low	-0.122	-0.407*	-0.014	-0.034	0.009	0.082	-0.091	-0.158	0.109	0.292	-0.181	-0.135
Stroop Test	High	-0.070	0.029	-0.118	-0.066	0.167	0.023	0.071	-0.031	0.030	0.044	0.248	0.235

*: Statistically significant for Spearman's rho analysis ($p<0.05$)

**: Statistically significant for Spearman's rho analysis ($p<0.01$).