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Cognitive-Motor Interference during Functional Mobility after Stroke: State of the Science and Implications for Future Research

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Abstract

Cognitive-motor interference (CMI) is evident when simultaneous performance of a cognitive task and a motor task results in deterioration in performance in one or both of the tasks, relative to performance of each task separately. The purpose of this review is to present a framework for categorizing patterns of CMI and to examine the specific patterns of CMI evident in published studies comparing single-task and dual-task performance of cognitive and motor tasks during gait and balance activities after stroke. We also examine the literature for associations between patterns of CMI and history of falls, as well as evidence for the effects of rehabilitation on CMI after stroke. Overall, this review suggests that during gait activities with an added cognitive task, people with stroke are likely to demonstrate significant decrements in motor performance only (cognitive-related motor interference) or decrements in both motor and cognitive performance (mutual interference). In contrast, patterns of CMI were variable among studies examining balance activities. Comparing people post-stroke with and without a history of falls, patterns and magnitude of CMI were similar for fallers and non-fallers. Longitudinal studies suggest that conventional rehabilitation has minimal effects on CMI during gait or balance activities. However, early phase pilot studies suggest that dual-task interventions may reduce CMI during gait performance in community-dwelling stroke survivors. It is our hope that this innovative and critical examination of the existing literature will highlight the limitations in current experimental designs and inform improvements in the design and reporting of dual-task studies in stroke.

Keywords

gait; balance; dual task; rehabilitation

Cognitive-motor interference (CMI) occurs when simultaneous (dual-task) performance of a cognitive and a motor task results in deterioration of performance in one or both tasks, relative to performance of each task separately (single-task performance).[1] Cognitive-motor

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dual-task performance is highly relevant to everyday living; for example, we frequently walk in the community while conversing with a companion or walk through the grocery store while recalling items for purchase. Therefore, a diminished capacity for dual-task performance may significantly impede functional mobility activities and community participation.

The presence of a decrement in performance under dual-task conditions has been used as evidence for the idea that the processing capacity of the brain is limited.[1] Thus, CMI reflects the competing demands of the two tasks for access to limited processing resources within the brain.[2-3] Performance of any one task is assumed to require some proportion of the limited processing capacity; therefore, the more demanding the task, the greater the proportion of resources required. If the processing demands of the combined tasks exceed the total capacity, task performance is compromised.

In any cognitive-motor dual-task situation, there are nine possible scenarios for performance outcome, relative to single-task performance of each task. We propose a classification system to describe these potential patterns of interference (Table 1). Some patterns are more likely than others, but for illustration of the concept, we describe all nine possibilities. The possible outcomes are: (1) *no interference* (performance of either task does not change relative to single-task performance), (2) *cognitive-related motor interference* (cognitive performance remains stable while motor performance deteriorates), (3) *motor-related cognitive interference* (motor performance remains stable while cognitive performance deteriorates), (4) *motor facilitation* (cognitive performance remains stable while motor performance improves), (5) *cognitive facilitation* (motor performance remains stable while cognitive performance improves), (6) *cognitive-priority trade off* (cognitive performance improves while motor performance deteriorates), (7) *motor-priority trade off* (motor performance improves while cognitive performance deteriorates), (8) *mutual interference* (performance of both tasks deteriorates), or (9) *mutual facilitation* (performance of both tasks improves).

Given that deterioration in performance can occur as an apparent trade-off of attentional resources (e.g., prioritization of one task over the other task) or inadequate attentional resources for the combined tasks (e.g., decline in one task with no reciprocal change in the other task), it is imperative to measure performance of both the cognitive and motor tasks in both single and dual-task conditions, to accurately interpret and characterize CMI. The pattern of CMI likely depends on several factors, including the types of tasks; levels of difficulty; instructions regarding which, if any, task to prioritize; and the characteristics of the person performing the task (e.g., cognitive and motor abilities, fear of falling, distractibility).[4-9]

There is evidence from several studies that CMI significantly impacts gait[10-21] and balance[15,22-30] after stroke. A recent meta-analysis[2] examined CMI during walking in healthy individuals and individuals with neurological disorders, including stroke. The findings suggested that CMI can be detected in numerous parameters of gait, and that CMI effects on gait speed, in particular, can distinguish healthy individuals from those with neurological disorders.[2] A critical limitation of the previous review is that it focused exclusively on CMI effects on gait performance, ignoring the concurrent effects on cognitive performance. Thus, it is not known whether the findings from the meta-analysis reflect true interference effects on gait, or cognitive-motor trade-offs. In addition, the previous review pooled studies from a range of neurological populations; since the underlying neurological pathology in stroke, Parkinson's disease, and Alzheimer's disease differs vastly, the findings from this meta-analysis have limited clinical usefulness for clinicians interested in treating CMI-related deficits after stroke.

The purpose of the current review is to examine observed patterns of CMI during gait and balance activities among adults with stroke using the classification framework in Table 1, and to explore how personal and task characteristics may influence CMI. Therefore, we focus exclusively on research studies that reported statistical analyses of CMI in both the motor (gait or balance) and cognitive tasks. We also review the state of the evidence for rehabilitation of CMI after stroke. In discussing the findings, we make recommendations for future research. This is not intended to be a systematic review, but, rather, a thought-provoking critical examination of the state of the science investigating CMI, with identification of trends in the patterns of CMI after stroke. Our hope is that this innovative approach will highlight limitations in current experimental designs and lead to improved quality and reporting of dual-task studies in stroke.

Cognitive-Motor Interference during Gait Activities

A comprehensive and rigorous search using multiple databases revealed that there are presently 12 studies (published in English) that have examined CMI during gait after stroke.[10-21] Seven of these (involving six unique cohorts) included statistical analyses examining CMI in both the cognitive and motor task and are the focus of this review.[13-19]

Summary of Sample Characteristics

Sample characteristics for the seven reviewed studies are presented in supplementary Table S1. Sample size ranged from 8 to 50; however, the study including 50 participants comprised only 33 with stroke (the remaining participants had sustained brain injuries due to other etiologies).[14] The average age of participants ranged from 46 to 77 years. Most studies reported mean post-stroke onset greater than 6 months,[13,15-19] with four studies reporting mean post-stroke onset greater than 1 year.[13,15,19-20] However, variability in time since stroke was large in most studies. One of the seven studies involved participants during inpatient rehabilitation.[14] Samples tended to include more men than women, which is perhaps not surprising given the age ranges of the participants; between the ages of 55 and 75 years, the incidence of stroke is 1.25-1.50 times higher in men than women.[31] Studies reporting side of stroke (5 of the 7 studies) often included more participants with right hemisphere than left hemisphere stroke. This is possibly due to the exclusion of participants with language deficits.

Few studies classified the severity of motor impairments, so it is difficult to summarize motor impairment severity in the studied samples. The most frequently used motor impairment measure was the Fugl-Meyer,[16-18] with scores indicating mild to moderate motor impairment. Mean self-selected (single-task) gait speed, reported in six of the seven studies, ranged from 0.35 m/s to 0.99 m/s. Motor impairment and gait speed are important factors to consider when interpreting gait-related CMI, since it was recently reported that lower extremity motor impairment assessed on the Fugl-Meyer and single-task gait speed were consistently related to CMI on a variety of gait metrics in participants with chronic stroke.[30]

Overall, participants in these studies demonstrated a range of cognitive abilities, from grossly intact to mild or moderate impairment. Three studies excluded participants with "major cognitive impairments" but did not report measures of cognitive abilities.[14-15,19] Other studies measured cognitive abilities on global tests (e.g., Short Portable Mental Status Questionnaire[16], or the Mini-Mental State Examination[17-18]), or comprehensive batteries addressing multiple cognitive domains.[13,16-18]

Measures of Gait and Cognitive Performance

There was a diverse array of gait and cognitive tasks used in the dual-task experiments (online supplementary data, Table S2). Gait tasks included: continuous walking around oval-shaped[13,17-18] or elliptical tracks,[16] or straight line walking with turns[14] for 1-5 minutes; walking on a treadmill,[19] and traversing a 5-meter walkway.[15] None of the studies reported giving specific instructions regarding which task to prioritize during the dual-task conditions, with the exception that Dennis et al.[13] included a fast-walking condition in addition to a self-selected walking task; instructing participants to walk at their fastest speed could imply prioritization of walking speed.

To assess gait performance, most studies measured gait speed[13,15,18-19] and stride duration.[14,18-19] Less commonly examined gait parameters were stride length,[15,18] double limb support duration,[17] cadence,[16,18] stride duration variability,[14,18] swing duration,[17] and temporal symmetry.[17] The dependent variables used to assess cognitive performance varied according to the nature of the cognitive task. They included: number of items recalled from a shopping list (required articulation *after* completion of the motor task);[15] number of correct responses and response latency of word generation (e.g., naming “things to eat”), simple arithmetic (e.g., 5 + 6), identifying target word pairs in a word list presented via headphones;[14] indicating whether the hour and minute hands on a clock would be in the same half area of the clock (i.e., left/right/top/bottom) or not for a given time (hereafter referred to as the ‘clock task’), for which both reaction time[14,18] and accuracy of responses[13-14,18] were measured; reaction time and accuracy in an auditory 1-back task;[18] linguistic measures of speech (e.g., pauses per utterance);[16,18] response latency in a probe reaction time task;[19] and number of correct responses when counting backward by 3s.[13] In all studies, single-task cognitive performance was measured while sitting.

Summary of Findings

Table 2 summarizes the statistically significant CMI effects in gait and cognitive measures, as reported in each of the seven studies, and classifies the observed pattern of CMI according to the framework presented in Table 1. In reporting the major findings, we concentrate on the gait parameters for which there are the most data: gait speed and stride duration.

The pattern of CMI during gait after stroke appears to be often *cognitive-related motor interference*, with some cognitive-motor task combinations producing *mutual interference.* Compared to single-task walking, there was a statistically significant decrease in self-selected gait speed when walking while remembering a 7-item shopping list,[15] generating spontaneous narrative,[18] performing the clock and 1-back tasks,[18] and counting backward by 3s.[13] The statistically significant declines in gait speed during dual-task conditions in these studies ranged from 0.06 m/s to 0.2 m/s (Cohen's *d* 0.18 to 0.66). There were simultaneous significant decrements in the number of shopping list items recalled[15] and some linguistic measures of speech production (e.g., increased number of pauses[18]) (*mutual interference*); however, in most instances, significant CMI effects on gait speed occurred without significant changes in cognitive performance (*cognitive-related motor interference*).[13-14,17-18]

Similar patterns of CMI were observed for other spatiotemporal parameters of gait (Table 2). For example, a statistically significant increase in stride duration without a concurrent decrement in cognitive task performance (*cognitive-related motor interference*) was found during the simple arithmetic[14] and clock tasks.[14,18] For other cognitive tasks, *mutual interference* was observed: significant increases in stride duration occurred concurrently with significant decrements in word generation,[14] identifying word pairs,[14] and some linguistic measures of speech[18] (Table 2). In contrast, Regnaux et al.[19] reported no significant CMI in stride duration, but significant CMI in the probe reaction time task during dual-task conditions (*motor-related cognitive interference*). However, this study involved treadmill walking (speed not reported), which most likely prevented the participants from significantly modulating their stride duration between single and dual-task conditions, as well as using a reaction time task that is likely more sensitive to change than many other cognitive tasks. Nonetheless, the contrast in pattern of CMI between the treadmill and overground walking studies highlights the influence of task-related parameters and suggests caution against comparing across studies using different task demands.

Indeed, differences in individual and/or task-related factors may explain discrepancies in the pattern of CMI between many of the studies. We illustrate this with a further example from the reviewed literature. As discussed above, Plummer-D'Amato et al.[18] found a significant reduction in gait speed with no significant CMI effect on reaction time or accuracy in the clock task (*cognitive-related motor interference*), whereas Dennis and colleagues,[13] using the same clock task, found *no interference* in either preferred gait speed or clock task accuracy (reaction time not reported). The participants in the two studies were, on average, similar in age and single-task walking speed (supplementary Table S1), however, the cohorts differed in average post-stroke onset duration, with the participants in the study by Dennis et al. being considerably more chronic (mean post-stroke duration: 25 months, range: 7-50 months) than the Plummer-D'Amato et al. cohort (mean post-stroke duration: 8.7 months, range: 2.5-17.0 months). It may be that stroke chronicity is an important individual factor moderating CMI, such that individuals with more chronic stroke may have reacquired greater automaticity of walking, and subsequently, are less susceptible to CMI. In support of this hypothesis, Haggard et al.,[14] who used the same clock task in a group of patients during inpatient rehabilitation (i.e., a subacute cohort), found significant CMI in both stride duration and clock task accuracy (*mutual interference*). Thus, there may be a continuum of CMI related to the reacquisition of gait automaticity after stroke, from mutual interference to cognitive-related motor interference to no interference as automaticity is reacquired. The relationship between stroke chronicity and CMI should be explored more systematically in future research.

In summary, the existing research suggests that after stroke, the type of cognitive task and/or individual characteristics influence whether cognitive and gait performance both decline (*mutual interference*) or only gait performance declines (*cognitive-related motor interference*) during dual-task conditions. Rarely is cognitive performance affected without a concurrent decrement in gait (*motor-related cognitive interference*). While several other studies have reported significant CMI on gait after stroke,[10-12,20-21] the interpretation of the pattern of CMI in those studies is limited by the omission of findings related to cognitive performance during dual-task conditions, or the absence of statistical analyses of data.

Cognitive-Motor Interference during Postural Control and Balance Activities

Our comprehensive search revealed that there are presently 10 studies (published in English) that have examined CMI during postural control and balance activities in people with stroke.[15,22-29,32] Six of these studies (involving four unique cohorts) included statistical analyses of motor and cognitive task performance during dual-task conditions and are the focus of this review.[15,23-24,26-27,32]

Summary of Sample Characteristics

Sample characteristics for the six studies are presented in supplementary Table S1. Sample size ranged from 33 to 76 participants with stroke, often with slightly more men than women. The average age of stroke participants ranged from 61 to 67 years. Four of the studies[23-24,27,32] involved participants with subacute stroke (average time post-stroke 68-70 days), three of which used the same cohort, while the remaining two studies involved participants with chronic stroke (average time post-stroke 16.3 months[15] and 8.3 months[26]). Like the research on gait, studies reporting side of stroke (5 of the 6 studies) tended to include more participants with right hemisphere than left hemisphere stroke.

On average, the subacute cohorts involved participants who required some manual assistance for gait and daily activities, indicated by median/mean scores on the Functional Ambulation Classification[23,27,32] and the Barthel Index.[24] Lower extremity motor functioning in the participants with subacute stroke was variable, classified by Brunnstrom stage (median IV, range II-VI).[23,27,32] Balance and functional ability of the participants with chronic stroke was generally better than those with subacute: on average, participants with chronic stroke had good gross motor function as assessed by the Rivermead Motor Assessment[15,26] and could walk without assistance[15] or stand independently for at least 15 seconds.[26] Berg Balance Scale scores indicated mild-moderate balance deficits in one of the chronic cohorts.[26]

In general, the participants in the reviewed studies had grossly intact global cognition. Several studies used a cognitive screening test, such as the Mini Mental State Examination, to assess global cognition, or a battery of neuropsychological tests to assess specific cognitive domains. Many of the participants in the studies of subacute stroke had unilateral spatial neglect.[23-24,27,32]

Measures of Balance and Cognitive Performance

Five studies examined postural control in quiet standing;[15,23,26-27,32] while one study examined CMI effects on postural control during unsupported sitting.[24] A description of the motor and cognitive tasks used in these studies is provided in supplementary Table S2. Postural control was frequently assessed by measuring sway path and area.[15,24,26] Others measured motor performance via standing weight bearing asymmetry[23,27] or by conducting non-linear analyses of time series data for the center of pressure trajectories, both globally[32] and independently for the paretic and nonparetic limbs.[27]

The dependent variables used to assess cognitive performance varied according to the nature of the cognitive task. They included: number of items recalled from a shopping list (required articulation *after* completion of the motor task);[15,26] number of valid words named in a category word generation task,[24] and number of errors in an arithmetic task requiring participants to indicate the correctness of single-digit additions (e.g., 3+5=7).[23,27,32] In all studies, single-task cognitive performance was measured while sitting. In the study examining CMI during unsupported sitting, the single-task cognitive performance was evaluated in supported sitting.[24]

None of the studies reported giving specific instructions regarding task prioritization during dual-task conditions, with the exception that Hyndman et al.[26] explicitly instructed the participants to place equal importance on both tasks.

Summary of Findings

Table 3 summarizes the statistically significant changes in balance and cognitive measures during dual-task conditions, as reported in each of the six studies, and classifies the observed pattern of CMI according to the framework presented in Table 1.

The pattern of CMI for measures of postural sway (e.g., sway path) was *motor facilitation* or *mutual interference.* Specifically, two studies[15,26] examining postural sway during standing showed that compared to single-task standing, sway significantly reduced in both mediolateral and anterior-posterior directions during dual-task standing while remembering a 7-item shopping list (no verbalization during motor task), with no significant CMI in the cognitive task performance (*motor facilitation*). Conversely, Harley et al.[24] found a significant increase in sway path length and variability during category word generation, with simultaneous reduction in the number of words generated (*mutual interference*). DeHaart et al.[23] also examined postural sway during dual-task standing; however, it is unclear whether the “small but consistent degree of dual-task interference” (p. 891) on center of pressure velocity was statistically significant.

There are a number of factors that could explain the discrepancies in the observed patterns of CMI on postural sway. In particular, the studies differed in the nature of the cognitive task (verbal versus nonverbal), the nature of the postural task (unsupported sitting versus standing), as well as time post-stroke (subacute versus chronic). *Motor facilitation* was seen in the participants with chronic stroke performing a nonverbal task while standing; *mutual interference* was observed in participants with subacute stroke performing a verbal task while sitting unsupported. It is important to acknowledge that the participants across these studies also differed on other individual characteristics, including mobility and motor function, which may play a role in dual-task performance. Thus, it is premature to draw conclusions based on any one of these factors. Rather, these observations should be used to design research questions to be tested empirically.

Different patterns of CMI were found for other measures of postural control during performance of an arithmetic task in participants with subacute stroke, suggesting that the observed pattern of CMI depends somewhat on the parameters used to assess motor performance. DeHaart et al.[23] and Roerdink et al.[27] both reported significant increases in weight bearing asymmetry during dual-task conditions without significant changes in arithmetic task performance (*cognitive-related motor interference*). During the same arithmetic task, *cognitive-related motor interference* was also observed for dimensionality[32] and regularity (sample entropy)[27,32] of the center of pressure time series, but *no interference* was found for local stability (Lyapunov exponent) or center of pressure variability.[32]

In summary, the existing body of research suggests that after stroke, performing a cognitive task has a significant effect on some parameters of postural control; however, the pattern of CMI is highly variable and may be related to task factors (e.g., postural demands, verbal or cognitive demands) and/or individual factors, such as time post-stroke and severity of motor and balance impairments. At least three other studies have examined postural control during simultaneous performance of a cognitive task after stroke;[25,28-29] however, the interpretation of the pattern of CMI in these studies is limited by the absence of reported findings related to changes in cognitive performance during dual-task conditions.

Cognitive-Motor Interference and Falls after Stroke

Only two studies have explored differences in gait- or balance-related CMI between post-stroke fallers and non-fallers.[15,26] Fallers and non-fallers were classified according to self-reported history of falls. The *cognitive-related motor interference* effects on gait speed described earlier were the same for both fallers and non-fallers.[15] In contrast, the c*ognitive-related motor interference* effect on stride length was significantly greater for fallers than non-fallers.[15] The *motor facilitation* effect on postural sway during quiet standing (i.e., reduced sway in dual-task condition without any change in cognitive performance) also did not differ significantly between fallers and non-fallers[15] or between repeat fallers and non-repeat fallers.[26] This was despite finding that repeat fallers sway more, on average, than non-repeat fallers.[26] In other words, although repeat fallers had greater sway, the CMI effect on sway did not differ from that of non-repeat fallers.

Effects of Rehabilitation on Cognitive-Motor Interference after Stroke

In light of the impact that CMI has on mobility activities after stroke, we examined whether rehabilitation reduces CMI in motor and cognitive performance. Observations from five longitudinal studies of CMI after stroke provide some insight into the effects of conventional rehabilitation on dual-task performance[12,23,27,32] and changes occurring in the 6-12 month period following hospital discharge.[26] Although Cockburn et al.[12] reported improved stride duration during dual-task conditions in 7 out of 10 patients after rehabilitation, most participants continued to experience notable CMI in cognitive task performance (word generation) and gait (stride duration) at discharge from rehabilitation. These data suggest that *mutual interference* in gait-related dual-task conditions may persist in many people with stroke at discharge. Moreover, several studies involving participants with chronic stroke provide evidence that *cognitive-related motor interference* in gait persists well beyond discharge.[13,15,18] Data from De Haart et al. show that although there was some improvement in (single-task) postural control in participants with subacute stroke, *cognitive-related motor interference* during dual-task standing did not significantly diminish during 12 weeks of inpatient rehabilitation.[23,27,32] Similarly, data from participants with chronic stroke show no significant change in the *motor facilitation* effect on postural sway between 6 and 12 months following discharge from rehabilitation.[26]

There is promising evidence from balance-impaired older adults that dual-task gait training may improve gait performance in dual-task conditions.[33-34] To date, only two published studies have examined dual-task interventions in adult stroke survivors.[35-36] Yang et al.[35] examined a 4-week motor-motor dual-task training intervention in 13 individuals, 1-28 years post-stroke (mean 4.7 years, SD 7.4). The intervention, conducted for 30 minutes, 3 times a week for 4 weeks, consisted of walking while manipulating one or two balls. Compared to a no-intervention control group (n=12) with statistically comparable demographic characteristics and baseline measures, the dual-task training group had significantly greater change values in both single- and dual-task gait speed, cadence, stride duration, and stride length. Performance on the secondary motor task (carrying a tray with empty water-glasses) was not reported. Plummer-D'Amato et al.[36] provided a cognitive-motor dual-task intervention to 6 community-dwelling adults within 12 months of stroke (mean 9.1 months, SD 3.3). The intervention (30 minutes, 3 times per week for 4 weeks) involved concurrent performance of cognitive tasks during gait activities. On average, there was a 65% reduction in CMI on gait speed during the auditory Stroop task post-intervention, and a 28% reduction in CMI on gait speed during the clock task. There was a dual-task benefit on reaction time in both cognitive tasks before and after the intervention. The effect of the intervention on the pattern of CMI could not be determined due to absence of statistical analysis of the CMI effects.

In summary, it appears that conventional rehabilitation does not significantly reduce CMI after stroke. Dual-task intervention studies in stroke are in their infancy. Preliminary evidence shows promise for interventions incorporating dual-task activities to improve dual-task gait in participants with chronic stroke, but further research is necessary to determine the types and doses of intervention needed to produce clinically meaningful changes.

Discussion

We examined CMI from a unique point-of-view by describing patterns of CMI after stroke and the potential influences of personal and task characteristics on CMI. Our novel framework for interpreting CMI provides insights into the nature of the interference. We found that CMI during gait activities was typically *cognitive-related motor interference*[13-14,17-18] or *mutual interference*.[14-18] Although *no interference* and *motor-related cognitive interference* were observed in some gait studies, these patterns were associated with less commonly studied gait metrics, such as stride duration variability,[14,18] or with atypical walking tasks, such as treadmill[19] or fast walking.[13] The pattern of CMI during balance was considerably more variable; studies demonstrated *motor facilitation,*[15,26] *mutual interference,*[24] *cognitive-related motor interference,*[23,27,32] or *no interference*.[27,32] Variability may be due to differences in the parameters of postural control being measured, the demands of the specific tasks, and individual characteristics such as time post-stroke and motor or balance impairment severity.

The frequent pattern of *cognitive-related motor interference* during gait may suggest that people with stroke preferentially prioritize attention to the cognitive task at the cost of gait performance. However, if slowing down is considered an adaptive safety strategy, it could be argued that participants were prioritizing postural control during gait. Thus, while declines in gait speed are viewed within dual-task contexts as “interference,” an important consideration is that motor interference during dual-task walking may not necessarily be a negative phenomenon. Indeed, a recent study reported that older adults who appeared to prioritize the non-gait task during dual-task walking (indicated by larger dual-task costs on gait measures than non-gait task measures) had greater balance confidence than people who showed no apparent prioritization.[37] According to the authors, this may indicate that individuals with greater balance self-efficacy are more likely to shift their attention away from the gait task during dual-task walking. We can only speculate as to whether cognitive-related motor interference during gait results from prioritization of cognitive performance or conscious slowing of gait speed in order to maintain stability. An important direction for future research will be to identify the types of situations/tasks and personal characteristics that influence the strategies used by individuals in different dual-task situations, as this has implications for the design of interventions.

Apparent prioritization of postural control during balance activities was also observed among research in participants with chronic stroke (i.e., reduced postural sway).[15,26] Conversely, in subacute stroke, postural sway increased in dual-task conditions.[24] There were too few studies and too much variability in the types of tasks and measures used to assess CMI to draw any sound conclusions regarding the differences in outcomes reported for postural sway. Nonetheless, the idea that stroke chronicity may influence the pattern of CMI was one hypothesis to emerge from this review. For example, gait related studies showed *mutual interference* in the inpatient rehabilitation phase,[12,14] *cognitive-related motor interference* 7-8 months post stroke,[17] and *no interference* after 2 years post stroke.[13]

Logically, time post-stroke could influence CMI if gait automaticity is reacquired over time. The more automatic a task, the fewer attentional processing resources required to perform the task; therefore, restoration of gait automaticity increases the amount of attentional resources available to perform secondary cognitive tasks. Soon after stroke, motor impairments likely increase the attentional demands of walking. Later, gait may become more automatic, even if kinematic gait deviations remain. Indeed, Canning et al.[11] found that community-dwelling stroke survivors 39 months (SD 19) post-stroke displayed the same level of gait automaticity as healthy age-matched adults, even though the participants with stroke demonstrated impaired lower extremity motor control. The effect of stroke chronicity on CMI after stroke is a testable hypothesis that should be studied empirically. This is an important line of future research to identify the ideal time in the recovery process to target interventions to address dual-task deficits.

The existing literature suggests that there are few differences in CMI during gait and no differences in CMI during balance activities between post-stroke fallers and non-fallers.[15,26] Prospective studies are needed to determine whether CMI predisposes people with stroke to falls, and whether differences in CMI between fallers and non-fallers can be detected with other cognitive tasks.

Two small studies provide preliminary evidence that training dual-task activities may improve dual-task gait performance in chronic stroke. Future research should incorporate comparative designs to determine whether dual-task training is more effective than other rehabilitation approaches. Where feasible, researchers should assess both cognitive and motor performance, and include more than one dual-task combination to evaluate whether training effects transfer to different dual-task situations.

Limitations

Although we conducted a comprehensive and rigorous search of the literature, and reviewed only studies that satisfied specific criteria (stroke population, assessed single and dual-task performance of gait/balance and cognitive task, reported statistical analyses of dual-task effects on both tasks), we did not rate the quality of the studies we reviewed or pool the data for a meta-analysis. The diverse range of cognitive tasks (and related dependent variables) is problematic for performing a meta-analysis of the dual-task effects on cognition. We used statistically significant differences between single and dual-task performance to classify the patterns of interference. Estimates of clinically meaningful effect sizes for dual-task decrement in motor or cognitive performance are needed. We encourage researchers to address the clinical importance of results when discussing dual-task effects. To this end, it would be helpful if investigators measure performance using outcomes with known minimal clinical important difference values, such as gait speed.

Conclusions

Dual-task paradigms may be an effective way to assess preparedness for real-world mobility in stroke survivors being discharged to the community. The pattern of CMI after stroke varies based on task and personal factors. Therefore, dual-task studies will be of most value to clinicians and researchers if effect sizes and statistical significance of dual-task changes in both the motor and cognitive tasks are reported. Cognitive and motor abilities of participants should be carefully characterized using standardized and well-recognized clinical measures. Other important participant characteristics such as time post-stroke, site of lesion, and age should also be reported. Additional consideration of the complexity and difficulty of assigned tasks, particularly cognitive tasks is warranted. Furthermore, studies should examine the degree to which specific instructions regarding task prioritization influence patterns of interference. Thorough reporting in dual-task studies in stroke will improve our understanding of the situations in which mobility is most compromised, and will help clinicians develop interventions to address the specific nature of dual-task-related deficits in stroke.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1

Classification framework for patterns of cognitive-motor interference based on changes in performance of each task in the dual-task condition relative to single-task performance

		Cognitive Performance		
		No Change	**Improved**	**Worsened**
Motor Performance	**No Change**	No dual-task interference	Cognitive facilitation	Motor-related cognitive interference
	Improved	Motor facilitation	Mutual facilitation	Motor-priority trade-off
	Worsened	Cognitive-related motor interference	Cognitive priority trade-off	Mutual interference

Table 2

Summary of statistically significant dual-task effects (decline, improvement, no change) and related dual-task interference patterns among gait studies

Study	Motor measures	Dual-task effects on motor measures	Cognitive measures	Dual-task effects on cognitive measures	Pattern of dual-task interference
Dennis 2009	Gait speed, preferred	Significant decline (counting task only)	Serial 3s counting accuracy	No change	Cognitive-related motor interference
			Clock task accuracy	No change	No interference
	Gait speed, fast	Significant decline (counting task only)	Serial 3s counting accuracy	No change	Cognitive-related motor interference
			Clock task accuracy	Significant decline	Motor-related cognitive interference
Haggard 2000	Stride duration	Significant decline (for all cognitive tasks)	Word generation accuracy and RT	Significant decline (accuracy only)	Mutual interference
			Mental arithmetic accuracy and RT	No change	Cognitive-related motor interference
			Paired associate monitoring accuracy and RT	Significant decline (accuracy only)	Mutual interference
			Clock task accuracy and RT	Significant decline (accuracy only)	Mutual interference
	Stride duration variability	No change	Word generation accuracy and RT	As above	Motor-related cognitive interference
			Mental arithmetic accuracy and RT	As above	No interference
			Paired associate monitoring accuracy and RT	As above	Motor-related cognitive interference
			Clock task accuracy and RT	As above	Motor-related cognitive interference
Hyndman 2006	Gait speed; Stride length	Significant decline	Number of items correctly recalled from grocery list	Significant decline	Mutual interference
Kemper 2006	Cadence	No change	Linguistic measures of language	Significant decline	Motor-related cognitive interference
	Time on task	Significant decline	Linguistic measures of language	As above	Mutual interference
Plummer-D'Amato 2008	Gait speed; Stride length; Cadence	Significant decline (for all cognitive tasks)	1-back RT and accuracy	No change	Cognitive-related motor interference
			Clock task RT and accuracy	No change	Cognitive-related motor interference
			Spontaneous speech: Words/utterance	No change	Cognitive-related motor interference
			Utterances/narrative	Significant decline	Mutual interference
			Words/narrative	Significant decline	Mutual interference

Study	Motor measures	Dual-task effects on motor measures	Cognitive measures	Dual-task effects on cognitive measures	Pattern of dual-task interference
			Fillers/utterance	No change	Cognitive-related motor interference
			Pauses/utterance	Significant decline	Mutual interference
			Clauses/utterance	No change	Cognitive-related motor interference
			Grammar	No change	Cognitive-related motor interference
			New information	Significant improvement	Cognitive-priority trade off
	Stride duration	Significant decline (clock and speech tasks only)	1-back RT and accuracy	As above	No interference
			Clock task RT and accuracy	As above	As above
			Spontaneous speech: (as above)	As above	As above
	Stride duration variability	No change	1-back RT and accuracy	As above	No interference
			Clock task RT and accuracy	As above	No interference
			Spontaneous speech: Words/utterance	No change	No interference
			Utterances/narrative	Significant decline	Motor-related cognitive interference
			Words/narrative	Significant decline	Motor-related cognitive interference
			Fillers/utterance	No change	No interference
			Pauses/utterance	Significant decline	Motor-related cognitive interference
			Clauses/utterance	No change	No interference
			Grammar	No change	No interference
			New information	Significant improvement	Cognitive facilitation
Plummer-D'Amato 2010	DLS total; DLS paretic loading phase	Significant decline	Cognitive performance reported in Plummer-D'Amato 2008	See Plummer-D'Amato 2008	1-back and clock tasks: Cognitive-related motor interference
					Spontaneous speech: As for gait speed, stride length, cadence (see Plummer-D'Amato 2008)
	Swing duration (paretic limb)	Significant decline			As above
	DLS paretic unloading; Swing duration variability; Temporal asymmetry	No change			1-back and clock tasks: No interference
					Spontaneous speech: As for stride duration variability (see Plummer-D'Amato 2008)

Study	Motor measures	Dual-task effects on motor measures	Cognitive measures	Dual-task effects on cognitive measures	Pattern of dual-task interference
Regnaux 2005 (treadmill walking)	Stride duration	No change	Reaction time (probe reaction time task)	Significant decline	Motor-related cognitive interference

Abbreviations: DLS, double limb support duration; RT, reaction time

Table 3

Summary of statistically significant dual-task effects (decline, improvement, no change) and related dual-task interference patterns among balance studies

Study	**Motor measures**	**Dual-task effects on motor measures**	**Cognitive measures**	**Dual-task effects on cognitive measures**	**Pattern of dual-task interference**
De Haart 2004	RMS of COP velocities (AP, ML); Average position of COP (AP, ML)	Dual-task effects unclear	Number of arithmetic errors	No change	Unable to classify
	Weight bearing asymmetry	Significant decline	Number of arithmetic errors	As above	Cognitive-related motor interference
Harley 2006	Sway path length; Variability of sway	Significant decline	Number of valid words in word generation task	Significant decline	Mutual interference
Hyndman 2006	Sway AP; Sway ML	Significant improvement	Number of items correctly recalled from grocery list	No change	Motor facilitation
Hyndman 2009	Sway AP; Sway ML	Significant improvement	Number of items correctly recalled from grocery list	No change	Motor facilitation
Roerdink 2006	COP dimensionality	Significant decline	Cognitive performance reported in De Haart 2004	(No change, see De Haart 2004)	Cognitive-related motor interference
	COP regularity (sample entropy)	Significant decline			Cognitive-related motor interference
	COP local stability (largest Lyapunov exponent); COP variability	No change			No interference
Roerdink 2009	Weight bearing asymmetry	Significant decline	Cognitive performance reported in De Haart 2004	(No change, see De Haart 2004)	Cognitive-related motor interference
	Sway area	No change			No interference
	COP sample entropy	Significant decline (paretic limb only)			Cognitive-related motor interference

Abbreviations: RMS, root mean square; COP, center of pressure; AP, anterior-posterior; ML, medio-lateral