Examining the relationship between specific cognitive processes and falls risk in older adults: a systematic review

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Abstract

Purpose—Recent evidence suggests that impaired cognition increases seniors' risk of falling. The purpose of this review was to identify the cognitive domains that are significantly associated with falls or falls risk in older adults.

Methods—We conducted a systematic review of peer-reviewed journal articles published from 1948 to present, focusing on studies investigating different domains of cognitive function and their association with falls or falls risk in adults aged 60 years or older. In accordance with Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, we completed a comprehensive search of MEDLINE, Pubmed, and EMBASE databases to identify studies

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Specific Remarks

This systematic review aims to establish which cognitive domains are associated with falls or falls risk. Twenty-two out of 25 studies report executive functions and/or dual-task to be highly associated with falls or falls risk. Specifically, executive functions are related to falls risk and dual-task is correlated with falls and falls risk.

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examining the association between cognitive function and falls or falls risk. With an expert in the field, we developed a quality assessment questionnaire to rate the quality of the studies included in this systematic review.

Results—Twenty-five studies were included in the review. We categorized studies based on two related but distinct cognitive domains: 1) executive functions, or 2) dual-task ability. Twelve studies reported a significant association between executive functions and falls risk. Thirteen studies reported that dual-task performance is a predictor of falls or falls risk in older adults. Three studies did not report an association between cognition and falls risk.

Conclusion—Consistent evidence demonstrated that executive functions and dual-task performance were highly associated with falls or falls risk. The results from this review will aid healthcare professionals and researchers in developing innovative screening and treatment strategies for mitigating falls risk by targeting specific cognitive domains.

Keywords

falls; systematic review; cognition; executive function; older adults

Introduction

Falls are a major health care problem for seniors and health care systems [e.g., 1]. Approximately 30% of community-dwellers over the age of 65 years experience one or more falls annually [1]; falls are the third leading cause of chronic disability worldwide [1]. In the US, the estimated annual cost for falls-related injuries exceeded 9 billion dollars for those aged 65 years or older in 2004 [2], highlighting the substantial economic burden of falls. A review study completed by Davis and colleagues [2] showed that globally, falls and falls-related injuries cost 23.3 billion in the USA and 1.6 billion for older adults in the UK. Thus, given that our ageing population is growing at an unprecedented rate, identifying the major risk factors for falls is an increasing priority.

Studies have attributed falls as a consequence of impaired physiological functions. Specifically, reduced muscle strength, impaired gait/mobility, and impaired balance are key falls risk factors [3–5]. Impaired neurocognitive function is also a key risk factor for falls [3,4,6]. Indeed, those with mild cognitive impairment are twice as likely to experience a fall as those without such impairment [3]. Importantly, the potential negative consequences of falls – including reduced quality of life, disability, and even death – are often most severe among individuals with cognitive decline [7].

While impaired global cognitive function has been identified as a risk factor for falls [3], the specific cognitive domains that are most related to falls are just beginning to be understood [4]. Early studies of the relationship between cognitive function and falls used only measures of global cognition [3], such as the Mini-Mental Status Examination (MMSE). More recent studies, however, have focused on specific domains of cognitive function – such as executive functions and dual-task ability – and their association with falls or falls risk [8,9]. Executive functioning is a complex and broad construct. Generally, it refers to our higher-level cognitive skills. Such skills include the ability to inhibit inappropriate

responses, selectively attend to relevant information, and plan and strategize. In contrast, dual-tasking refers to our ability to perform two tasks simultaneously, such as walking while talking. Impaired performance on one or both tasks is referred to as dual-task costs, and result from our limited cognitive resources [10]. While executive functions may certainly affect the ability for one to dual-task (by affecting prioritization strategies or attention to the task, for example), dual-task paradigms are designed to specifically assess the interaction between cognitive and physical functioning [11]. A better understanding of which cognitive processes are associated with falls will guide the development and refinement of future screening and falls prevention strategies.

Critically, falls prevention is well recognized as a vital component of fracture prevention as falls are the primary cause of hip [12] and upper limb fractures [13]. Fractures, especially of the hip, are particularly disabling consequences of falling [14]. Individuals with low bone mass (i.e., osteopenia and osteoporosis) are at high risk of sustaining fall-related fractures. Each standard deviation decrease in femoral neck bone density increases the age-adjusted risk of hip fracture 2.6 times [15].

For our systematic review, it is important to distinguish between falls and falls risk. A commonly used definition of a fall is “*unintentionally coming to the ground or some lower level other than as a consequence of sustaining a violent blow, loss of consciousness, sudden onset of paralysis as in stroke or an epileptic seizure*” [16]. Falls are measured by counting number of events (i.e., falls) within a period of time – either retrospectively (e.g., recall over a specified time period) or prospectively (e.g., monthly calendars). In contrast, falls risk is defined as “*the possibility of a fall happening*” [17]. Falls risk can be assessed clinically through specific risk assessment tools such as the Physiological Profile Assessment (PPA) [18], or using measures of mobility such as gait speed [19].

To our knowledge, no review has been completed to highlight the specific domains of cognition related to falls. Therefore, we are presenting a systematic review focused on the association between cognitive function and falls or falls risk among seniors. In particular, we will examine which specific cognitive processes are related to falls or falls risk.

Materials and methods

In accordance with Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) [20] guidelines, we conducted a comprehensive search of MEDLINE, Pubmed, and EMBASE databases to identify studies that examined the association between cognitive function and falls or risk factors for falling. We included studies published from 1948 through May 3, 2011, in the English language, and of humans aged 60 years and older. We included the following in our search terms and medical subject headings: cognition, executive functions, dual task, and falls. We manually searched the references of retrieved articles to trace 16 additional potentially relevant papers.

Selection of studies

We selected peer reviewed published studies that included different domains of cognitive function (e.g., executive functions and dual tasking) as an outcome. We excluded the

following types of studies -- studies that did not examine specific cognitive processes (e.g., only measured global cognitive function), intervention studies that focused on improving cognitive function or reducing falls, protocol studies, studies that did not include falls or falls risk, any case report or case series studies, and samples which included those with significant neurodegenerative disease (e.g., Alzheimer's disease). After critical review of the titles and abstracts and the list of references of articles in our full text review, 9 full text manuscripts met our inclusion criteria, and 16 additional articles were selected through reference search (Figure 1).

Data extraction and data synthesis

We developed a standardized form to extract information from the published manuscripts included in our systematic review. Extracted information included: author(s), year of publication, journal of publication, impact factor, study sample, study design, primary and secondary outcome, falls or falls risk measured, cognitive domains measured, and results from the studies. Two authors performed data extraction (CLH and LSN) and two authors (JCD and TLA) independently checked the extracted data. Any discrepancies were discussed and resolved by all authors.

Quality assessment

In the literature, two main study designs (i.e., cross-sectional and prospective) were used to examine the association between cognitive function and falls or falls risk. The quality of each study was assessed using the seven questions that we developed. The questionnaire was independently reviewed by an expert in the area. The seven questions included: 1) Was the falls-related outcome valid? The outcome was considered valid if a) falls were monitored prospectively using falls calendars; or b) falls risk was determined by an established measure of risk (i.e. postural stability, gait speed, etc.); 2) Was cognition assessed using a standardized tool? We defined standardized tool as a neuropsychological assessment that has been applied in greater or equal to two studies that were authored by different research groups; 3) Did the author(s) present a sample size or power calculation?; 4) What was the study design?; 5) Was there a control group or condition for the task?; 6) Are the main outcomes to be measured clearly described in the introduction or methods section?; and 7) Are the characteristics of the study population clearly described in the introduction or methods section? Two authors (CLH and LSN) independently evaluated each study and any discrepancies were discussed and reviewed by two authors (JCD and TLA). We allocated either a "+" indicating the item was addressed by the authors or a "-" indicating the item was absent.

Results

Literature search – overview of studies identified

Our review consists of 25 articles in total, with three papers discussed in both executive functioning and dual-task sections [21,9,22]. After a detailed review of titles, abstracts, and full text from our search of Pubmed, Embase, and Medline databases, nine out of 1350 studies met our inclusion criteria (Figure 1). The other 16 articles were selected based on key author searches as well as searching references of included papers. The list of 25 studies

included 14 cross-sectional studies, ten prospective cohort studies with study length varying from six months to eight years, and one study that contained both prospective and cross-sectional components (Table 1). The results of the included studies are summarized in Table 1.

Executive functions – Twelve studies

Twelve studies focused on comparing performance on standardized neuropsychological tests between senior fallers and non-fallers. Results from these studies suggest that executive functions - the ability to focus, selectively attend, and strategize - is highly associated with falls and falls risk [23]. Key executive functions include response inhibition, set-shifting, and information processing speed [24].

A prospective cohort study examined the relationship between cognitive function and falls rate over an eight year period [23]. In addition to measuring global cognition using the MMSE, the authors measured three specific cognitive processes: verbal reasoning (an executive function, measured by the Similarities test), immediate memory (measured by immediate picture recall test), and processing speed (measured by Digit Symbol Substitution). They found that baseline MMSE and verbal reasoning scores predicted falls prospectively over the eight year follow-up period. Additionally, within subjects, poorer performance in immediate memory and processing speed were associated with increased rates of falling -- 5% and 12%, respectively.

In a five-year prospective study, Watson and colleagues [25] recruited community dwelling older adults and administered physical (gait speed, body mass index, and ankle-arm index) and cognitive (MMSE, EXIT-15, Digit copying, and Letter Comparison) tests. They found poorer performance in response inhibition, attention, and working memory to be strongly associated with declines in gait speed ($p<0.001$ for all correlations).

Herman and colleagues [21] examined the relationship between executive functions and falls in a prospective cohort study over a two-year period. In this study, response inhibition was assessed using a computerized test battery, which included the Go-No-Go and Stroop tests [21]. The authors found that those who experienced a fall during the two-year follow up period had significantly worse baseline performance on the executive functioning test than those who did not fall during the follow up ($p=0.038$) [21]. Furthermore, those with lower executive functioning scores, based on quartile rankings, were three times more likely to fall than those with higher executive functioning scores [21]. Focusing on a subset of participants who were previously considered “non-fallers” based on one-year retrospective reports at baseline, those with lower executive functioning scores transitioned from non-faller to faller status during the two-year period sooner than those with higher executive functioning scores [21].

In a cross-sectional study, Lord and colleagues [26] found that compared with non-fallers, seniors with a history of falls in the past 12 months performed significantly worse ($p<0.01$) on a choice-stepping reaction time task – a reaction time performance test where participants were asked to step on illuminated panels as quickly as possible. Seniors with a history of falls also perform significantly worse on the neuropsychological battery which included: 1)

Digit Symbol Substitution, a measure of processing speed; 2) Stroop Test, a measure of selective attention and response inhibition, or the ability to focus on task relevant information while inhibiting pre-potent responses; and 3) Trail Making B Test, a measure of set shifting, or the ability to go back and forth between multiple tasks or mental sets.

Interestingly, a prospective cohort study demonstrated that the relationship between choice-stepping reaction time (as described above) and falls was mediated by both physiological and cognitive function [27]. Specifically, using a path-analysis model, the authors identified that hand reaction time and postural sway mediated the ability of the choice step reaction time to predict multiple falls during a 12-month follow-up period [27]. In turn, quadriceps strength, visual contrast sensitivity, and Trail Making B performance was found to mediate reaction time and postural sway [27].

A second cross-sectional study found that compared with non-fallers, seniors with a history of falls performed significantly worse on tests of executive functions ($p=0.047$, measured by the interference phase of the Stroop test), attention ($p=0.012$, measured by the non-interference phase of the Stroop test), and motor skills ($p=0.013$, measured by a finger tapping and hand-eye coordination test), but not on tests of memory (measured by verbal and non-verbal memory tests), information processing (measured by one-digit, two-digit, and three-digit arithmetic tests), and global cognition (measured by computing the average score of the tests) [28]. These results concur with those of Holtzer and colleagues [8]. In their cross-sectional study, Holtzer and colleagues [8] demonstrated that of three separate cognitive factors (i.e., verbal IQ, processing speed/executive attention, and memory), only speed/executive attention was negatively associated ($OR=0.495$, $p=0.02$) with history of single or recurrent falls [8].

In another cross-sectional study, McGough and colleagues [29] recruited sedentary older adults with MCI. Gait speed was assessed over a 2.4-meter course and general mobility was assessed using the Timed Up and Go test (TUG) – which requires participants to get up as quickly as they can from a sitting position, walk three meters, turn around, walk back to the chair, and sit back down. To assess cognition, participants were given the Trail Making B test and the Stroop test. The authors reported that both gait speed and TUG scores were significantly associated with Trail Making B and Stroop performance ($p<0.005$ for all correlations). Specifically, poorer performance on tests of executive functioning was associated with slower gait speed.

Lastly, in a cross-sectional analysis of a randomized controlled trial by Liu-Ambrose and colleagues [30] individuals with probable mild cognitive impairment (MCI), as defined by a score of less than 26/30 on the Montreal Cognitive Assessment (MoCA) [30], were found to have greater postural sway than those without MCI. The MoCA is a brief screening tool for MCI [30] with high sensitivity and specificity and includes an assessment of executive functions. Individuals with probable MCI also scored significantly worse ($p=0.05$) on three executive function measures – set-shifting, updating, and response inhibition, as measured by Trail Making B, Digits backward, and Stroop, respectively [4]. Furthermore, in a sub-analysis of the same randomized controlled trial, Liu-Ambrose and colleagues [31]

demonstrated that improved selective attention and conflict resolution, as measured by the Stroop, were significantly associated with improved gait speed ($r=0.26$, $p<0.007$).

In summary, five prospective studies found that processing speed, verbal memory, set-shifting, response inhibition, and attention are the key domains of executive functions related to falls risk [23,27,25,21]. Similarly, one sub-analysis of a randomized controlled trial found response inhibition and selective attention to be associated to falls risk [31]. Lastly, seven cross-sectional studies found declines in attention, processing speed, response inhibition, and set-shifting to be associated with increased falls risk in older adults [26,28–30,8].

Dual-task studies – Sixteen studies

Sixteen studies administered a dual-task paradigm requiring participants to perform a cognitive task while concurrently completing a physical performance task, such as walking or maintaining stability. Recent evidence suggests that maintaining postural stability during walking depends on both higher-level cognitive functions and sensorimotor processes [32–34]. Furthermore, walking requires more attention in seniors than younger adults [32,35,36]. Thus, we would expect those with impaired cognitive function – such as fallers – to have difficulty with dual-task performance. Indeed, 13 out of the 16 studies reported that dual task performance was significantly associated with falls or falls risk factors ($p < 0.05$).

In a cross-sectional study investigating the influence of a cognitive task on postural stability recovery [37], participants were asked to verbally respond to a two-frequency (high/low) auditory stimulus while maintaining stability on a forward and backward translating force platform. The authors found that seniors with impaired balance tend to stabilize more slowly under the dual-task condition compared to the non-fallers [37]. In a subsequent study, Brauer and colleagues [38] extended these findings by demonstrating that step-balance-recovery is more attention demanding for balance impaired seniors as compared with healthy seniors.

A cross-sectional study conducted by Condon and colleagues [39] found that, compared to their non-falling counterparts, seniors at higher risk of falling showed greater sway during dual-task performance on a dynamic platform. Participants were asked to perform the balance test while concurrently counting backwards by threes from a randomly selected three-digit number. These findings were replicated by Shumway-Cook and colleagues [40], who conducted a cross-sectional study examining the effects of performing cognitive tasks on concurrent postural stability. They found that seniors with a history of falls exhibited increased sway while counting backwards. Another cross-sectional study showed similar results [22]. The subjects were asked to walk while performing three different cognitive tasks – simple, complex, and arithmetic. Simple and complex tasks required the participants to complete a multiple-choice questionnaire based on a list of texts they listened to while walking. For the arithmetic task, the subjects calculated a serial subtraction of sevens from 500. The authors reported that for seniors with a history of falls, walking while under cognitive load is associated with increased swing time variability - an indicator of poor balance.

Similar results were discussed in a cross-sectional study consisted of 57 hospitalized fallers and non-fallers (Kressig et al., 2007). These older adults were asked to complete a dual-task

assessment that required them to walk 12 meters at normal pace while counting backwards from 50 by series of one. The authors found increased stride time variability in fallers during the dual-task condition. In addition, the combination of physical and cognitive tests was associated with the occurrence of a first fall.

Another cross-sectional study conducted by Hauer and colleagues [41] found that for seniors with a history of falls and diagnosed with MCI, dual-task performance was significantly reduced ($p<0.05$) compared to senior fallers without cognitive impairment. Study participants were asked to undergo a lower limb maximal strength test while computing simple and complex arithmetic. The greatest decline in the limb strength performance was found to be under the complex dual-task condition.

Finally, in a cross-sectional study [42] that examined the relationship between falls history and the ability to complete a visual-spatial decision task while walking 20 meters, the authors found that reduced gait speed while performing the cognitive task was associated with increased risk of recurrent falls.

An early prospective study showed that walking while simultaneously talking is associated with falls [43]. In this particular study, Lundin-Olsson and colleagues [43] observed cognitively impaired (MMSE score range from 18–26) older adults' tendency to stop walking once they were engaged in a conversation. They found of all the study participants, individuals that stopped walking when talking displayed a significantly poorer (i.e., less safe) and slower gait ($p<0.001$) [43].

To further investigate the relationship between walking and talking in fallers, a prospective study investigated the reliability and validity of the walking while talking (WWT) test as a predictor of falls [44]. In the WWT, participants are asked to recite letters of the alphabet (e.g., a, b, c; WWT simple) or alternate letters of the alphabet (e.g., a, c, e; WWT complex) while walking 40 feet. The authors reported that performance on the WWT test was significantly reduced ($p<0.02$) in senior fallers compared with non-fallers. Furthermore, Verghese and colleagues [44] concluded that WWT was both reliable and valid in falls prediction because they found WWT complex had a high specificity (95.6%) and poorer performance on the simple and complex WWT ($OR=7.02$, 13.7 respectively) was predictive of falls over 12 months. Similarly, Liu-Ambrose and colleagues [9] used the same WWT test in a cross-sectional study examining the influence of executive functions on dual-task performance. They reported that set-shifting was independently associated with WWT performance, after accounting for age, time to walk 40 feet without talking, and global cognition as measured by MMSE ($p=0.05$) [45].

The prospective cohort study described above under the executive functions section also included a dual-task component [21]. The authors found that senior fallers exhibited reduced performance on a dual-task test compared to non-fallers [21]. The study participants were asked to walk on a 25-meter long walkway while calculating serial-three subtractions from a three-digit number [21]. Gait variability during dual-task performance – but not single task performance – was predictive of prospective falls ($p=0.02$) [21]. Similar findings were

reported in a study by Beauchet et al. [46], where slower walking speeds while concurrently counting backwards from 50 was associated with recurrent falls.

Of the 16 studies that examined the association between dual-task performance and falls risk, three studies reported divergent results from the general trend we found in this systematic review. In a prospective study examining the association between dual-task ability and falls [47], participants were asked to count backwards from 50 while walking. Unexpectedly, better dual-task performance was associated with a greater occurrence of falls. Another prospective study showed that dual-task performance (walking 12 meters while reciting names of animals or professions) did not predict falls better than single-task performance (walking 12 meters without the cognitive task) [48]. These results also concur with a study by Beauchet et al. [49], who found that dual-task gait speed did not provide greater predictive power for time to first fall over single-task gait speed.

In summary, nine cross-sectional studies and four prospective studies found that dual-task ability is highly related to falls or falls-risk. In contrast, one study found no relationship between dual-task performance and falls; another study found a reverse relationship, where better dual-task performance was positively related to falls; and one study found dual-task performance showed similar predictive strength as single-task gait speed.

Quality of included studies

For the 25 studies included in this systematic review, we had ten prospective studies, 14 cross-sectional studies, and one study that had both prospective and cross-sectional components. Out of these 25 studies, only 15 studies used a valid and reliable method to measure falls (Table 2). For the quality assessment, we considered falls measurements valid if they assessed falls prospectively. Eighteen out of 25 studies used a standardized tool to assess cognition, which we defined as “a cognitive assessment that has been used two or more times in published studies”. None of the 25 studies included a power or sample size calculation. Nineteen out of 25 studies used a control group to compare against the “faller/falls-risk” group. Of the seven questions used in quality assessment, the validity question and power calculation question most often received negative scores. Questions that received mostly positive scores were whether cognition was assessed using a standardized tool; were the main outcome clearly described in the introduction or methods; were the patient characteristics clearly described in the introduction or methods; and whether there was a control group. Question one received a 70% overall rater agreement between authors (CLH and LSN) and the remaining questions (questions two to seven) received a 100% overall rater agreement between authors (CLH and LSN).

Discussion

We conducted the first systematic review examining the relationship between specific cognitive processes and falls or falls risk. Based on our review, we found that the two areas of cognitive abilities most associated with falls or falls risk are executive functions and dual-task ability. This finding is supported by the current prevailing concept that common geriatric syndromes, such as cognitive decline and falls, share common risk factors and pathways [51].

First, we found that executive functions are strongly associated with both falls and falls risk. Specifically, the studies we reviewed found that senior fallers, or those at-risk for falls, had impaired performance on tests of set-shifting, response inhibition, and selective attention relative to their non-falling counterparts. Evidence from neuroimaging studies provides insight into possible underlying mechanisms for this association. Specifically, cerebral white matter lesions (or leukoaraiosis) are associated with both reduced executive functioning [52] and gait and balance abnormalities [53,54,6,55]. Cerebral white matter lesions may interrupt frontal lobe circuits responsible for normal gait and balance or they may interfere with long loop reflexes mediated by deep white matter sensory and motor tracts [6]. In addition, the periventricular and subcortical distribution of white matter lesions could interrupt the descending motor fibers arising from medial cortical areas, which are important for lower extremity motor control [55]. It is important to note that many of the pathological changes in the brain (e.g., white matter lesions and reduced frontal-subcortical volume) associated with reduced executive functions are clinically silent, but nevertheless prevalent in seniors [52]. Additionally, the relationship between impaired executive functions and falls may stem from the fact that certain components of executive functioning are required for falls-prevention strategies, falls-recovery, and balance control [23,26]. For example, Anstey and colleagues [23] suggest set shifting is essential in recovery from tripping, while visuo-spatial memory is important for balance, and processing speed is critical for maintaining safe mobility.

Notably, the results of our review suggest that executive cognitive functions, specifically – rather than general cognitive ability – are a key component of falls risk. For example, Hausdorff et al. [28] found that fallers performed worse than non-fallers on tests of executive function and attention, but that there were no differences on tests of memory, information processing, or global cognition. Indeed, we found that verbal memory was consistently unrelated to falls or falls risk [21,22,8]. Given that executive cognitive functions are an important component of postural stability, balance, and mobility, and that this relationship is even more pronounced as we age [35,32,33,56], our finding that higher-level processing is related to falls is not surprising.

Second, we found that dual-task ability is significantly different between senior fallers (or those at-risk for falls) and non-fallers. Specifically, senior fallers or those at-risk for falls demonstrated increased sway, slower physical response time, and reduced accuracy (for the cognitive component of the dual-task) while performing two tasks simultaneously. Our findings are in agreement with a previous review on the relationship between dual-task performance and falls [57]. Walking is a highly repetitive human movement. While the maintenance of postural stability during walking was traditionally considered to be an automatic task, recent evidence suggests that it requires both higher-level cognitive functions and sensorimotor processes [32–34]. Furthermore, research using dual-task paradigms suggest that walking requires greater attentional resources as we age [32,35,36]. Importantly, we have limited cognitive resources to distribute to task performance, and without sufficient attention to allocate to a particular task, performance suffers or fails [10]. Thus, impaired dual-task performance in fallers may reflect that they not only require greater resources for basic tasks, but also that they have reduced cognitive resources to allocate for successful task performance.

Results from two separate studies are inconsistent with the evidence provided by most of the studies included in our review. To begin with, Faulkner and colleagues [42] reported that slower walking time as well as slower task reaction time were associated with increased probability of recurrent falls. In this study, participants were asked to count backwards from 50 while concurrently walking 10 meters. The authors cite the rhythmic nature of the dual-task as a possible explanation for their equivocal results. In particular, walking and counting are both highly rhythmic, and two simultaneous rhythmic activities may positively reinforce each other [47]. Ebersbach and colleague [58] similarly reported that improved performance on a finger tapping task is associated with increased falls risk. They explained that rhythmic activities tend to share the same neurobiological networks; therefore two rhythmic activities may have an additive effect on each other [58].

Next, Bootsma-van der Wiel and colleagues [48] showed that dual-task performance did not improve predictive power for falls over single-task performance. However, this observation may be explained by the low difficulty of the dual-task test used in the study. Instead of engaging in conversation with another individual while walking (more cognitively challenging), the participants were asked to only recite names of animal or profession [48]. Hence, both the single- and dual-task tests likely utilized similar amount of cognitive resources, which resulted in no differences between conditions. An alternative explanation is that some of the study participants may have differentially prioritized which component of the dual-task is to be executed and given neural resources first. For example, one subject may allocate all attention on the cognitive performance at the expense of physical performance. This type of between subject variability may have also blurred the true predictive ability of dual-task performance.

Quality of included studies

One concern with the studies included in this review is that none of the studies presented a power calculation or sample size justification. For cross-sectional design studies, in particular, sample size calculations are crucial to ensure the study would detect the between-group differences that are of clinical and statistical significance. Therefore the validity of the results from these studies might be questionable.

A second concern is that 15 studies did not use a validated measure of falls. The gold standard of accurate falls recall is prospective monthly falls calendars [59,60]. The majority of these studies, however, asked the subjects to recall the number of falls that occurred retrospectively. This may result in an underestimated number of falls recorded [62]. However, underreporting falls will still provide us with a conservative estimate of the association between falls and cognitive function at the expense of possible misclassification of a faller as a non-faller.

Future directions

While we now have a foundation for the relationship between cognition and falls in seniors, many follow-up studies are required. First, more prospective studies need to be done, where falls is used as an outcome measure. Second, future studies need to focus on assessing both cognitive and physical functions, so we can better understand how each factor individually

contributes to falls. Third, we need to develop a better understanding of the mechanisms behind how impaired cognition results in falls. Last, there is a need for standardization of measures so that the results of future studies can be directly compared [63].

Limitations

This review is limited to the populations and designs of the studies selected. The studies reviewed in this paper are heterogeneous. Specifically, there is wide variation in the study populations, settings (community versus residential care), cognitive tests used, dual-task paradigms, and ascertainment of falls status. Notably, such heterogeneity between studies and lack of appropriate control comparators led to an inability to make concrete conclusions about the relationship between dual-task performance and falls in one review [63]. Thus, future studies need to focus on using standardized protocols to enable us to make direct comparisons between studies. Also, because cross-sectional and prospective studies are not meant to present causal inference relationship between variables, we cannot conclude that impaired executive functions and dual task performance necessarily cause falls, per se.

Conclusion

This systematic review presents evidence that both executive functions and dual-task performance are highly associated with falls and falls risk. To our knowledge, this is the first systematic review to investigate the specific cognitive processes related to falls. This establishment of the relationship between cognition and falls provides a basis for researchers as well as health care professionals to develop effective falls prevention strategies. Future work needs to focus on establishing a set of standard outcome measures so that direct comparisons between studies can be made, and to elucidate the underlying mechanisms linking impaired cognition and falls in seniors.

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Figure 1.
Flow diagram of selection of studies

Study description, characteristics and results

Table 1

Executive functioning studies						
Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Cognitive domain and tasks	Was cognitive performance related to falls? Summary data
Anstey et al., 2006 IF 3.656	Community-dwelling & residential care N = 539 76.3 years ^a 53% female	Prospective cohort 8 years	Self-reported falls from questionnaire, using the question "Have you had any falls in the past year - including those falls that did not result in injury as well as those that did?"	Falls rate over 8 years prospectively	Verbal reasoning (Similarities test) Processing speed (Digit Symbol Substitution) Global cognition (MMSE)	Incidence Rate Ratio 0.76, 95% CI (0.71–0.83) Incidence Rate Ratio 0.99, 95% CI (0.98–1.00) Incidence Rate Ratio 0.91, 95% CI (0.89–0.93)
Hernan et al., 2010^c IF 3.988	Community-dwelling N = 262 76.3 ± 4.3 years ^a 60.3% female	Prospective cohort 2 years	Self-reported falls using monthly calendars, returned via mail.	Executive function task performance	Memory Executive function Global cognition (MMSE)	Odds ratio 1.05, 95% CI (0.47–2.35) Odds ratio 3.02, 95% CI (1.35–6.78) Odd ratio 1.61, 95% CI (0.67–3.86)
Liu-Ambrose et al., 2010 IF not available	Community-dwelling N = 135 69.6 ± 2.9 years ^a All female	Prospective cohort 12 months	Gait speed at usual pace during 4 meter walk	Changes in executive function Falls-related self-efficacy Gait speed	Set shifting (Trail Making B) Working memory (Digits backwards) Selective attention and response inhibition (Stroop)	Data not available Data not available r = 0.26, p = 0.008
Pijnappels et al., 2010 IF 3.131	Retirement village residents N = 294 79.2 ± 6.5 years ^a 84% female	Prospective cohort 12 months	Number of falls reported via monthly questionnaire	Choice stepping reaction time Physiological functioning Number of falls Cognitive performance	Choice stepping reaction time Set shifting (Trail Making B)	r = 0.231 r = 0.249
Watson et al., 2010 IF 3.988	Community-dwelling N = 909 75.2 ± 2.8 years ^a	Prospective cohort ^d 5 years; Cross-sectional	Gait speed during 20 m walk Timed up and go score	Gait speed Timed up and go score Cognitive performance	Verbal memory (Buschke Selective Reminding Test) Executive function battery	β = 0.027 (SE = 0.007) β = 0.03 (SE = 0.008)

Executive functioning studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Cognitive domain and tasks	Was cognitive performance related to falls?	Summary data
	50.6% female				Psychomotor speed (Boxes and Digit Copying Tests) Attention/perceptual speed (Pattern and Letter Comparison Tests)		$\beta = 0.056$ (SE = 0.008) $\beta = 0.036$ (SE = 0.008)
Hausdorff et al., 2006 IF 1.447	Community-dwelling N = 73 (25 healthy seniors, 18 fallers, 30 Parkinson's patients) 72 years ^a 44% female	Cross-sectional	2 falls in past 12 months, 1 falls in past 6 months via self-report	Performance on cognitive battery	Memory Executive function Attention Information processing speed Motor skills Global cognitive score	No Yes Yes No Yes No	$p = 0.110$ $p = 0.047$ $p = 0.012$ $p = 0.606$ $p = 0.013$ $p = 0.236$
Holtzer et al., 2007 IF 2.949	Community-dwelling N = 172 77.69 years ^a 54.7% female	Cross-sectional	History of falls (12 months) obtained during clinical interview	Relationship between 3 cognitive domains and falls	Verbal IQ Speed/executive attention Memory	No Yes No	Odds ratio 0.635, 95% CI (0.386, 1.044) Odds ratio 0.495, 95% CI (0.314–0.779) Odds ratio 1.243, 95% CI (0.807–1.916)
Liu-Ambrose et al., 2009^c IF 3.988	Community-dwelling N = 140 69.6 ± 3 years ^a All female	Cross-sectional	Walking while talking performance: Walk 20 feet, turn, and return 20 ft to start while reciting letters of the alphabet (simple) or alternate letters (complex)	Executive function performance	Set shifting (Plus-minus task) Working memory (Digits backwards) Selective attention and response inhibition (Stroop)	Yes No No	$r = 0.30$ $r = 0.10$ $r = 0.20$
Liu-Ambrose et al., 2008 IF 2.082	Community-dwelling N = 158 (86 healthy seniors & 72 cognitively impaired seniors) 69.7 ± 2.8 years ^a for healthy seniors and 69.5 ± 3.2 for	Cross-sectional	Physiological Profile Assessment	Physiological Profile Assessment Executive function task performance	Set shifting (Trail Making B) Updating (Digits backwards) Selective attention and response inhibition (Stroop)	Yes Yes Yes	$r = 0.37$ $r = -0.36$ $r = 0.23$

Executive functioning studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Cognitive domain and tasks	Was cognitive performance related to falls?	Summary data
cognitively impaired seniors All female							
Lord et al., 2001 IF 3.988	Residential care N = 477 79.2 years ^a 85% female	Cross-sectional	History of falls (12 months) via self-report (method not specified)	Performance on choice-stepping reaction time Neuropsychological battery	Choice stepping reaction time Set shifting (Trail Making B) Processing speed (Digit Symbol test) Response inhibition and selective attention (Stroop)	Yes Yes Yes Yes	$p < 0.01$ $p < 0.01$ $p < 0.01$ $p < 0.01$
McGough et al., 2011 IF 2.082	Retirement living centre residents N = 201 84.6 ± 5.7 years ^a 80.1% female	Cross-sectional	Gait speed at usual pace during 8-foot walk Timed up and go score	Gait speed Timed up and go score Executive function performance	Set shifting (Trail Making B) Response inhibition and selective attention (Stroop)	Yes Yes	$\beta = -0.267, p < 0.001$ for gait speed; $\beta = 0.290, p < 0.001$ for Timed up and go $\beta = -0.214, p < 0.004$ for gait speed; $\beta = 0.251, p < 0.001$ for Timed up and go
Springer et al., 2006^c IF 4.014	Community-dwelling N = 60 (19 young adults, 24 non-faller seniors, 17 faller seniors) 29.4 ± 4.4 years ^a for young adults, 71 ± 5.9 for non-fallers, 76.1 ± 4.8 for fallers Not specified	Cross-sectional	1 fall(s) in past 6 months via self-report (method not specified)	Executive function task performance	Verbal memory Response inhibition and selective attention (Stroop) Attention (Go-No-Go)	No Yes Yes	$p = 0.537$ $p = 0.023$ $p = 0.005$

Dual-task studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Physical task	Cognitive task	Was cognitive performance related to falls?	Summary data
Beauchet et al., 2007 IF 3.131	Residential care N = 187 84.8 ± 5.2 years ^a 84.5% female	Prospective cohort 12 months	Number of days until first fall	Number of enumerated figures while walking Time to first fall	Walking at usual speed on 10-meter walkway	Counting backwards from 50	Yes	Crude odds ratio 53.0, 95% CI (20.6–136.3), $p < 0.0001$
Beauchet et al., 2008 IF 3.656	Senior housing facility N = 213 84.4 ± 5.5 years ^a 84% female	Prospective cohort 12 months	Number of falls prospectively via monthly telephone interviews using standardized questionnaire	Dual-task walking speed Number of falls prospectively	Walking at usual speed on 10-meter walkway	Counting backwards from 50	Yes	Crude odds ratio 0.60, 95% CI (0.41–0.85), $p = 0.005$
Beauchet et al., 2008 IF 3.988	Senior housing facility N = 187 84.8 ± 5.2 years ^a 84.5% female	Prospective cohort 12 months	Number of falls prospectively via monthly telephone interviews using standardized questionnaire	Dual-task changes in gait mean walking time Time to first fall	Walking at usual speed on 10-meter walkway	Counting backwards from 50	Yes	Crude odds ratio 1.1, 95% CI (0.9–1.1), $p = 0.012$
Bootsma-van der Wiel et al., 2003 IF 3.656	Community-dwelling & residential care N = 380 85 years ^b 65% female	Prospective cohort 12 months	Number of falls via self-report using standardized questionnaire and confirmed by health care practitioner	Dual-task performance as a predictor of falls	Walking as quickly as possible back and forth along a 3-meter line for a total of 12 meters	Name professions or animals	Yes	$p < 0.001$
Herman et al., 2010 IF 3.988	Community-dwelling N = 262 76.3 ± 4.3 years ^a 60.3% female	Prospective cohort 2 years	History of falls (2 years) via self-report using monthly calendars	Gait variability	Walking at usual speed on a 25-meter walkway for 2 minutes	Serial 3's calculation	Yes	Crude odds ratio 1.47, 95% CI (1.13–1.92), $p = 0.055$
Lundin-Olsson et al., 1997 IF 30.758	Residential care N = 58 80.1 ± 6.1 years ^a 72% female	Prospective cohort 6 months	Number of falls prospectively reported by staff (method not specified)	Number of falls prospectively	Walking at usual speed from home to an assessment room	Engaging in conversation	Yes	Data not available
Verghese et al., 2002 IF 3.656	Community-dwelling N = 60 79.6 ± 6.3 years ^a 57% female	Prospective cohort 12 months	Number of falls prospectively via phone interview	Number of falls prospectively	Walking as quickly as possible on a 40-foot walkway for	Reciting letters of the alphabet (simple) Reciting alternate letters of the alphabet (complex)	Yes	Crude odds ratio 7.02, 95% CI (1.7–29.4), $p = 0.009$ Crude odds ratio 13.7, 95% CI (2.3–83.6), $p < 0.001$

Dual-task studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Physical task	Cognitive task	Was cognitive performance related to falls?	Summary data
Brauer et al., 2001 IF 3.988	Community-dwelling N = 27 (14 healthy seniors & 13 balance impaired seniors) 72.1 ± 7 years ^a for healthy seniors & 79.2 ± 7 for balance impaired seniors 72% female	Cross-sectional	Berg Balance Scale score 50/56 and self-reported history of postural imbalance	Auditory choice reaction time Postural recovery	Maintain upright stability during backward platform perturbation	Auditory choice reaction time task	Yes	$p = 0.01$
Brauer et al., 2002 IF 2.576	Community-dwelling N = 43 (15 young adults, 15 healthy seniors, 13 balance impaired seniors) 22.6 ± 5.5 years ^a for young adults, 72.5 ± 6.7 for healthy seniors, 79.2 ± 7 for balance impaired seniors 75% female	Cross-sectional	Berg Balance Scale score 50/56 and self-reported history of postural imbalance	Auditory choice reaction time	Maintain upright stability during backward platform perturbation	Auditory choice reaction time task	Yes	$p < 0.001$
Condron et al., 2002 IF 3.656	Community-dwelling & retirement village residents N = 60 (20 young adults, 20 healthy seniors, 20 seniors with mild increased risk for falls) 26.4 ± 6.1 years ^a for young adults, 73.8 ± 6 years for healthy seniors, 74.8 ± 7.3 years for seniors with increased falls risk 70% female	Cross-sectional	Self report of 1 fall in past 12 months and/or 1 sign of impairment on screening test	Stability (centre of pressure) Performance counting backwards by 3's	Maintain balance	Count backwards by 3's from randomly selected 3 digit number	Yes	$p < 0.001$

Dual-task studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Physical task	Cognitive task	Was cognitive performance related to falls?	Summary data
Faulkner et al., 2007 IF 3.656	Community-dwelling N = 377 78 ± 3 years ^a 52% female	Cross-sectional	Recurrent falls (two or more falls in previous 12 months) via interview	Increase in walking time due to concurrent performance of secondary task	Walking at usual speed on a 20-meter walkway	Reaction time on push-button task Walking time on visual-spatial decision task	Yes	Crude odds ratio 0.72, 95% CI (0.53–0.99), $p = 0.04$ Crude odds ratio 1.42, 95% CI (1.08–1.85), $p = 0.01$
Hauer et al., 2002 IF 2.184	Geriatric rehabilitation hospital N = 45 (22 young adults, 23 seniors with history or injurious falls; 12 cognitively intact, 11 mild/moderately cognitively impaired) 27.7 ± 9 years ^a for young adults, 78.9 ± 5.4 years for cognitively intact seniors, 82.9 ± 5.5 for cognitively impaired seniors Not specified	Cross-sectional	1 fall in the last 6 months via self-report, resulting in hospital admission (method not specified)	Maximal isometric leg strength Number of correct calculations	Leg strength test	Simple (serial 2's) calculations Complex (serial 7's) calculations	Yes	$p = 0.04$ $p = 0.01$
Kressig et al., 2007 IF 1.26	Geriatric hospital N = 57 85 ± 6.6 years ^a 77.2% female	Cross-sectional	Number of falls, identified via the hospital accident reporting system	Stride time variability during walking First fall that occurred during hospital stay	Walking at usual speed on 12-meter walkway	Backward counting from 50 (serial 1's)	Yes	Crude odds ratio 8.6, 95% CI (1.9–39.6), $p = 0.006$
Liu-Ambrose et al., 2009^c IF 3.988	Community-dwelling N = 140 69.6 ± 3 years ^a All female	Cross-sectional	Walking while talking performance	Walking while talking time (simple and complex)	Walking at usual speed on 40-foot walkway	Reciting letters of the alphabet (simple) Reciting alternate letters of the alphabet (complex)	Yes	$\beta = 1.02$ (SE = 0.04) $\beta = 1.55$ (SE = 0.12)
Shumway-Cook et al., 1997 IF 3.988	Community-dwelling N = 60 (20 young adults, 20 healthy seniors, 20 seniors with history of falls)	Cross-sectional	> 2 falls in past 6 months via self-report (method not specified)	Postural stability during dual-task	Postural stability	Language processing (sentence completion) Perceptual matching (Judgment of line orientation)	Yes	$p < 0.0001$

Dual-task studies

Reference, Impact factor	Study sample	Study design, Time horizon	Measurement of falls risk or falls	Primary outcome, Secondary outcome	Physical task	Cognitive task	Was cognitive performance related to falls?	Summary data
	31 ± 6 years ^a for young adults, 74 ± 6 years for healthy seniors, 78 ± 8 for fallers 57% female							
Springer et al., 2006 IF 4.014	Community-dwelling N = 60 (19 young adults, 24 non-faller seniors, 17 faller seniors) 27.7 ± 9 years ^a for young adults, 78.9 ± 5.4 years for cognitively intact seniors, 82.9 ± 5.5 for cognitively impaired seniors Not specified	Cross-sectional	1 fall(s) in past 6 months via self-report (method not specified)	Effects of dual-task on gait speed, swing-time average, and swing-time variability	Walking at usual speed on 2.5-meter walkway	Listen to text (simple) Listen to text + phoneme monitoring (complex) Arithmetic	Yes Yes Yes	Effect size = 0.32, <i>p</i> = 0.034 (for swing-time variability) Effect size = 0.30, <i>p</i> = 0.045 (for swing-time variability) Effect size = 1.14, <i>p</i> < 0.001 (for swing-time variability)

^a mean age;

^b age at study entry;

^c Study included both executive function and dual-task components, listed under each section accordingly;

^d Study included both prospective and cross-sectional analyses

Table 2

Quality assessment of included studies (N=28)

Reference	Was falls-related outcome valid and reliable?	Was cognition assessed using a standardized tool?	Did the authors present sample size calculation?	Study Design	Was there a control group?	Are the main outcomes to be measured clearly described in the Introduction or Methods section?	Are the characteristics of the patients included in the study clearly described in the Introduction or Methods section?
Executive functioning studies							
Anstey et al., 2006, Journal of the American Geriatrics Society	-	+	-	Prospective cohort	+	+	+
Herman et al., 2010, Journal of Gerontology: Medical Sciences	+	+	-	Prospective cohort	+	+	+
Liu-Ambrose et al., 2010, BMC Geriatrics	+	+	-	Prospective cohort	-	+	+
Pijnappels et al., 2010, Age and Ageing	+	+	-	Prospective cohort	-	+	+
Watson et al., 2010, Journal of Gerontology: Medical Sciences	+	+	-	Prospective cohort and cross-sectional	-	+	+
Hausdorff et al., 2006, Experimental Aging Research	-	+	-	Cross-sectional	+	+	+
Holtzer et al., 2007, Neuropsychology	-	+	-	Cross-sectional	+	+	+
Liu-Ambrose et al., 2009, Journal of Gerontology: Medical Sciences	-	+	-	Cross-sectional	-	+	+
Liu-Ambrose et al., 2008, Physical Therapy	+	+	-	Cross-sectional	+	+	+
Lord et al., 2001, Journal of Gerontology	-	+	-	Cross-sectional	+	+	+
McGough et al., 2011, Physical Therapy	+	+	-	Cross-sectional	-	+	+
Springer et al., 2006, Movement Disorders	-	+	-	Cross-sectional	+	+	+
Dual-task studies							
Beauchet et al., 2007, Age and Ageing	+	-	-	Prospective cohort	+	+	+
Beauchet et al., 2008, Journal of the American Geriatrics Society	+	+	-	Prospective cohort	+	+	+
Beauchet et al., 2008, Gerontology	+	+	-	Prospective cohort	+	+	+
Bootsma-van der Wiel et al., 2003, Journal of the American Geriatrics Society	-	+	-	Prospective cohort	+	+	+
Herman et al., 2010, Journal of Gerontology: Medical Sciences	+	+	-	Prospective cohort	+	+	+
Lundin-Olsson et al., 1997, Lancet	-	-	-	Prospective cohort	-	N/A [*]	N/A [*]

Reference	Was falls-related outcome valid and reliable?	Was cognition assessed using a standardized tool?	Did the authors present sample size calculation?	Study Design	Was there a control group?	Are the main outcomes to be measured clearly described in the Introduction or Methods section?	Are the characteristics of the patients included in the study clearly described in the Introduction or Methods section?
Verghese et al., 2002, Journal of the American Geriatrics Society	+	+	-	Prospective cohort	+	+	+
Brauer et al., 2001, Journal of Gerontology	-	-	-	Cross-sectional	+	+	+
Brauer et al., 2002, Gait and Posture	-	-	-	Cross-sectional	+	+	+
Condon et al., 2002, Journal of American Geriatric Society	-	-	-	Cross-sectional	+	+	+
Faulkner et al., 2007, Journal of the American Geriatrics Society	-	-	-	Cross-sectional	+	+	+
Hauer et al., 2002, Archive of Physical Medicine and Rehabilitation	-	-	-	Cross-sectional	+	+	+
Kressig et al., 2007, Aging Clinical and Experimental Research	-	+	-	Cross-sectional	+	+	+
Liu-Ambrose et al., 2009, Journal of Gerontology: Medical Sciences	-	+	-	Cross-sectional	-	+	+
Shumway-Cook et al., 1997, Journal of Gerontology: Medical Sciences	-	+	-	Cross-sectional	+	+	+
Springer et al., 2006, Movement Disorders	-	+	-	Cross-sectional	+	+	+

* Paper did not include a distinct introduction/methods sections

Appendix 1

Search strategy: MEDLINE (OvidSP)

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- 01. *Cognition/or cognition.mp.
 - 02. *Executive function/or executive function.mp.
 - 03. *Accidental falls/or falls.mp.
 - 04. *Attention/or dual task.mp.
 - 05. limit 1 to (english language and full text and humans and “all aged (65 and over)” and english and humans)
 - 06. limit 2 to (english language and full text and humans and “all aged (65 and over)” and english and humans)
 - 07. limit 3 to (english language and full text and humans and “all aged (65 and over)” and english and humans)
 - 08. limit 4 to (english language and full text and humans and “all aged (65 and over)” and english and humans)
 - 09. 5 and 710. 6 and 7
 - 11. 7 and 8
-

Appendix 2

Details of measures

Name of Assessment	Function(s)	Assessment procedure	Scoring	Reference
Digit Symbol Substitution and Digit Copying	Assesses executive functioning - processing speed	Subject is asked to replicate symbols as quickly and accurately as possible under 60 seconds	Number of symbols correctly replicated	Lafont et al., 2010
Stroop	Assesses executive functioning - response inhibition, selective attention	Words of various color is shown and the subject is asked to identify the printed color of the words. The three possible conditions are: neutral - words meaning do not create conflict with printed color (i.e. cow, horse); congruent - printed color reflect the meaning of the words (i.e. "red" printed in red); incongruent - printed color conflict the meaning of the words (i.e. "red" printed in green)	Number of errors and the amount of time to complete task is recorded	Van der Elst et al., 2006
Trail Making A and B	Assesses executive functioning - set shifting	Trail A - on a sheet with range of numbers randomly placed on the page, subject is asked to proceed from number to number in sequential order until reaching the end. Trail B - on a sheet with range numbers and letters from A to L, subject is asked to proceed from number to letter in alternating but sequential order until reaching the end (i.e. 1 to A to 2 to B...)	Number of errors and the amount of time to complete task is recorded	Corrigan et al., 1987
Go-No-Go	Assesses sustained attention, response inhibition, set shifting	Subject is asked to perform a certain action under specific condition and inhibit an action under a different condition	Response time and number of completed trails recorded	Langenecker et al., 2007
WWT Simple and Complex	Assesses dual-tasking	Subject is asked to walking certain distance while verbally complete a cognitive task. Simple - walking and performing simple cognitive task (i.e. reciting names, professions, or simple counting); complex - walking and performing complex cognitive task (i.e. complex calculations such as serial 3s or 7s)	Amount of time to complete task is recorded	Lord et al., 2003
Physiological Profile Assessment (PPA)	Assesses the overall fall risk score	Assesses five physical measures - reaction time, proprioception, visual contrast sensitivity, quad strength, and sway. Reaction time is assessed by responding to a light stimulus; proprioception is assessed by elevating the feet and matching the position of the big toes with a perspex sheet in between; visual contrast sensitivity is assessed by identifying the orientation of a line drawn through the middle of a circular shape of various contrast; quad strength is assessed by the maximum amount of extension of a spring gauge on the dominant leg; sway is assessed by the amount of body displacement in 30 seconds on various surfaces (firm, foam)	Each measure is assessed separately with different weighting and combined to produce an overall score. Lower scores refer to less risk of falling	Lord et al., 2003
Montreal Cognitive Assessment (MoCA)	Assesses general cognition	Assesses eight cognitive domains - visuospatial/executive, naming, memory, attention, language, abstraction, delayed recall, and orientation.	Maximum score of 30; 26 suggests intact cognition	Nasreddine et al., 2005