Cortical Function, Postural Control, and Gait

Executive Functions Are Associated With Gait and Balance in Community-Living Elderly People

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Background. Cognition influences gait and balance in elderly people. Executive functions seem to play a key role in this mechanism. Previous studies used only a single test to probe executive functions, and outcome measures were restricted to gait variables. We extend this prior work by examining the association between two different executive functions and measures of both gait and balance, with and without two different cognitive dual tasks.

Methods. This is a cross-sectional study with randomly selected community-living elderly people. Executive functions were tested with the Trail Making Test Parts A and B and the Stroop Color Word Test; memory with Cambridge Neuropsychological Test Automated Battery (CANTAB) subtests. Patients walked without and with two dual tasks (subtracting serial sevens and animal naming). Main outcomes focused on gait (velocity, stride length, and stride time variability), measured on an electronic walkway, and balance, measured as trunk movements during walking. Associations were assessed with multiple regression models.

Results. One hundred elderly people, with a mean age 80.6 years (range 75–93 years) participated. Both dual tasks decreased gait velocity and increased variability and trunk sway. Executive functions were associated with only stride length variability and mediolateral trunk sway during performance of animal naming as the dual task. Memory was not associated with the gait and balance variables.

Conclusions. In community-living elderly people, executive functions are associated with gait and balance impairment during a challenging dual-task condition that also depends on executive integrity. Next steps will be to explore the value of executive functions in defining fall-risk profiles and in fall-prevention interventions for frail patients.

Key Words: Gait—Balance—Executive functions—Memory—Elderly people.

Walking is traditionally seen as an automatic motor task that requires little, if any, higher mental functions. However, it is becoming increasingly clear that walking is in fact tightly linked to cognitive functioning, and this interplay takes place at several levels (1). First, both gait impairment and cognitive problems are common with aging, and they frequently coincide in elderly people. Second, gait and cognitive problems both have a great impact on quality of life and everyday functioning of older people and their caregivers. In the last decade, evidence has also emerged for an actual pathophysiological interaction between gait and cognition. Having a gait disorder increases the chances of developing non-Alzheimer dementia by threefold (2). Conversely, people with dementia more often have gait disorders and also sustain an increased risk of falling (3,4). This interdependence between cognition with gait and balance can also be found in healthy older people (5). Dual tasks are one method of investigating the effect of cognition on gait and balance control (5). Dual tasks may result in a suboptimal performance in gait, cognition, or both, because attention has to be divided or because of structural inference in neural networks of the frontal and motor cortex (5,6). Another explanation is that the demands of cognition and gait go beyond the limited central processing capacity.

A key cognitive factor in gait and balance control seems to be executive functioning. Executive functions are defined as a set of cognitive skills that are necessary to plan, monitor, and execute a sequence of goal-directed complex actions (7). Older people with poor executive functioning walk slower, have increased stride variability, fall more often, and have poorer performance on complex mobility tasks (8,9). These previous studies clearly show that executive functions play an important role in gait control. In the present study, we aimed to extend this prior work in three ways. First, previous studies probed executive functions with only a single test. In contrast, we aimed to use a more extensive cognitive test battery, including two different executive functioning tests and two memory tests. These memory tests were included because memory decline in old age is highly prevalent, and there has been little study of the effects of memory impairment on gait (8–12). We also included two different
cognitive dual tasks, because execution of a secondary task during walking (talking, route planning) partially depends on executive functions such as concept shifting and mental flexibility (5,6). Second, previous studies concentrated on a selected population of elderly people without dementia or other neurological disorders. Here, we included an unselected population of elderly persons living in the community. Finally, because executive functions have thus far only been linked with gait variables, the present study quantitatively studies both gait and balance.

We hypothesize that, in unselected community-living elderly people, executive functions would have a stronger relationship with gait and balance than would memory itself, and that this association would be particularly evident during walking under dual-task conditions.

METHODS

Participants

We performed a cross-sectional study in community-living elderly people. We recruited our participants from the Nijmegen Biomedical Study (NBS), a population-based survey conducted by the Department of Epidemiology and Biostatistics of the Radboud University Nijmegen Medical Centre, which started in 2002–2003. A group of 22,500 age- and gender-stratified, randomly selected adult inhabitants of the municipality of Nijmegen received an invitation to complete a postal questionnaire on lifestyle and medical history. From the second survey in 2005–2006, we randomly invited a subset of 300 elderly people to participate in additional measurements. Participants were eligible if they were 75 years old or older, could walk short distances, understood simple tasks, and were willing to give written informed consent. Exclusion criteria were visual impairments that prevented the participant from reading a newspaper, even with correction or glasses. Baseline characteristics are displayed in Table 1. The institutional review board of the Radboud University Nijmegen Medical Centre approved the study.

Cognitive Measures

We used the Mini-Mental State Examination (MMSE) score (range 0–30; a score <24 indicates clear cognitive impairment) to characterize the participants and assess global cognitive status (13). We assessed executive functions with the Trail Making Test (TMT), a well-established psychomotor test that is used clinically to assess deficits in psychomotor speed (Part A) and mental flexibility (Part B) (7). In this study, we used a ratio score, calculated as (TMT B – TMT A)/TMT A that controls for the effect of motor speed. Furthermore, the Stroop Color Word Test was used as test of response inhibition (7). It measures the ability to suppress an over-learned response (i.e., automatic reading of a word while the incongruent color of the ink has to be named) and consists of three parts: I: reading of color words, II: naming of colors, and III: naming of the color of incongruent color words. In the analysis, we used a ratio score \( \frac{\text{Stroop III} - (\text{I} + \text{II})}{\text{I} + \text{II}} \) to control for motor speed and reading ability. For memory tests, we used subtests of the Cambridge Neuropsychological Test Automated Battery (CANTAB), which includes the Paired Associates Learning (PAL) to assess learning and episodic memory, and Pattern Recognition Memory (PRM) to assess visual recognition memory (14).

Gait and Balance Measures

Quantitative gait analysis was performed with a 5.6-meter-long, 0.89-meter-wide electronic walkway (GAITRite; CIR Systems Inc, Havertown, PA) with sensor pads (12.7 mm...
apart from each other) connected to a computer. The electronic walkway has good concurrent validity and test–retest reliability (15). Balance was measured with two angular velocity transducers (Sway Star; Balance International Innovations GmbH, Iseltwald, Switzerland) that recorded mediolateral and anteroposterior angular velocities at 100 Hz. The device was attached as a small box with a belt to the lower back of the participants and was connected to the computer with a long wire. The software calculated 90% ranges of angular velocities and angles in mediolateral and anteroposterior direction. Primary outcomes of our study were stride variability (stride length and stride time) and mediolateral body sway, all associated with an increased risk of falling (16,17).

During the measurements, participants walked over the walkway on low-heeled shoes. To measure steady-state walking, they started 2 meters before the walkway and walked toward a chair positioned 2 meters behind the walkway. First, the participants were instructed to walk at their preferred, slow, fast, and very fast speed over the walkway without a dual task. Subsequently, they walked at their preferred speed while performing two different dual tasks in a fixed order: subtracting serial sevens from 100, and then naming as many animals as possible during walking over the walkway (verbal fluency task). Participants had to verbalize their answers, permitting us to score secondary task performance. The participants started simultaneously with walking and the cognitive task. We did not prioritize the tasks in the instructions for the participants (18). Single task performance on the cognitive tasks was tested an hour after completion of the walking tests. We had chosen these two cognitive tasks because performance of the serial sevens during walking primarily requires division of attention, and animal naming requires more abstract thinking and word generation [and probably tests more aspects of executive functioning (19)]. We did not use a physical secondary task such as carrying a tray, because such a task would also require more motor coordination and would diminish rescue reflexes by the arms, aspects in which we were not interested.

Statistical Analysis

The baseline gait characteristics of patients were summarized as mean ± standard deviation (SD). We used the coefficient of variation (CV): \( SD/\text{mean} \times 100\% \) as a measure of variability for stride time, stride length, and stride width. We used analyses of covariance (ANCOVA) to compare the outcomes for each primary variable of the three different walks of each participant, and used paired Student \( t \) tests in a secondary analysis to compare the results of the dual-task condition with the reference condition (walking without a dual task). The effect of the addition of a dual task on the gait and balance variables was expressed in effect sizes with Cohen’s \( \delta \), of which 0.5 has to be interpreted as a moderate and 0.8 as a large change.

We used multiple linear regression models to investigate the relationship between cognition (as measured by TMT ratio, Stroop ratio, PAL, and PRM), gait (gait velocity, stride length, and time variability), and balance during walking (mediolateral displacement and velocity) with and without a dual task. We ensured that the requirements for linear regression models were fulfilled. We used log transformation in skewed distributions. Potential confounders tested for inclusion in the regression models were use of a walking aid; fear of falling, with Activities-specific Balance Confidence (ABC) score (20); history of falls in the year before measurements; number of medications; age; score on a comorbidity index (Cumulative Illness Rating Scale-Geriatrics; CIRS-G) (21); depressive symptoms (Montgomery–Åsberg Depression Rating Scale [MADRS]) (22), and handgrip strength (23).

A decrease in gait velocity is often used as strategy to maintain balance in more difficult circumstances. Because gait velocity has a strong influence on other gait and balance variables, we investigated the associations of executive function and memory with the primary gait and balance outcomes standardized for gait velocity (24).

All data were analyzed using SPSS statistical software, version 12.0 (SPSS, Chicago, IL). Because of the multiple comparisons, statistical significance for all regression models was accepted at \( p < .01 \).

RESULTS

Of the 300 people who received an invitation to participate, 118 agreed to be approached. Seven eligible people declined participation because they perceived the burden of the measurements as too high, and 11 people could not participate because of an acute illness (themselves or that of their partner). The final sample consisted of 100 persons (36 women) with a mean age of 80.6 years (SD 4.0). The values in Table 1 show that most participants had several health problems, needed some assistance in activities of daily living, and came from all social backgrounds. The participants had a mean gait velocity of 0.96 m/s ± 0.23, with a stride length of 115 cm ± 20 and cadence of 99 steps/min ± 14.

Table 2 displays the primary gait and balance variables during the different dual-task conditions. Of the balance variables, mediolateral trunk displacement increased significantly after the addition of the dual tasks, but mediolateral angular velocity remained unchanged under all conditions. Gait velocity was reduced during dual-task performance. Of the gait variables, variability in stride length and stride time increased after addition of the dual tasks (\( p < .001 \)). The effect sizes varied from 0.37 to 0.75. Standardization for gait velocity showed that both dual tasks significantly increased stride length variability, stride time variability, and mediolateral displacement by 30%–40% (\( p < .01 \)). The mean number of responses on the serial sevens was 3.1 (SD 1.8) and for the animal naming condition 6.5 (SD 1.7). The percentage of correct answers decreased from 90 during the single task to 77 during the dual-task condition for the serial sevens, and from 100 to 97 for the animal naming test (changes not statistically significant).

After addition of the dual task (animal naming) in the multiple regression analysis, the TMT ratio became significantly associated with stride length variability and mediolateral angular velocity (Table 3). Neither of the two memory tests was independently associated with gait or
balance variables (data not shown). CIRS-G, MADRS, ABC, and handgrip strength results were confounders in the multiple regression analyses. During the single task condition, none of the tests for executive function or memory was independently associated with gait and balance variables. Stride width variability remained constant under all conditions.

**DISCUSSION**

This study shows that, in community-living elderly people, mental flexibility, an important aspect of executive function, is independently associated with both an important gait variable (stride length variability) and a measure of balance instability (mediolateral trunk sway), while walking under dual-task circumstances. Both dual tasks influenced gait and balance, but in the multiple regression analysis this effect was seen with only the verbal fluency (animal naming) dual task but not during a mental arithmetic dual task (subtracting serial sevens). Although it can be argued that both dual tasks rely on executive functioning, animal naming probably will apply more cognitive resources than will serial subtraction (7). The larger effect of the verbal fluency dual task on gait and balance may thus be the result of a higher cognitive load; it interferes with frontal neural pathways to a greater extent. Memory tasks were not related to any of the gait or balance measures.

Our results fit in with the results of the group of Alexander and colleagues (30) and Persad and colleagues (31) but are partially in contrast to the results reported by the groups of Hausdorff and colleagues (33) and Holtzer and colleagues (32). They found that even normal walking (without secondary tasks) was related to executive functions, suggesting that simple undisturbed gait is already a complex process that requires input from executive functions (8,32). Corresponding with our results, both groups also found that the associations with executive functions increased further during dual-tasks conditions. Hausdorff and colleagues (8,32) reported that memory was not independently associated with gait performance. There are three possible explanations for the discrepancy. First, we find that both dual tasks are associated with a higher cognitive load on gait and balance than memory tasks.

### Table 2. Gait and Balance Variables With and Without Dual Tasking (Reference Condition); Measured Values and Values Standardized for Gait Velocity in Percentages

<table>
<thead>
<tr>
<th>Outcome Variables</th>
<th>No Dual Task Reference Condition</th>
<th>Cognitive Dual Tasks</th>
<th>Animal Naming</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD Standard (%)</td>
<td>Mean ± SD Standardized Mean ± SD (%)</td>
<td>Mean ± SD Standardized Mean ± SD (%)</td>
</tr>
<tr>
<td>Balance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Displacement M-L, degrees</td>
<td>3.6 ± 1.6</td>
<td>100</td>
<td>4.5 ± 1.6</td>
</tr>
<tr>
<td>Angular velocity M-L, degrees/s</td>
<td>27.6 ± 1.6</td>
<td>100</td>
<td>28.8 ± 1.4</td>
</tr>
<tr>
<td>Gait</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gait velocity, m/s</td>
<td>0.96 ± 0.23</td>
<td>NA</td>
<td>0.91 ± 0.28</td>
</tr>
<tr>
<td>Stride length variability, %CV</td>
<td>2.3 ± 1.9</td>
<td>100</td>
<td>3.0 ± 2.0</td>
</tr>
<tr>
<td>Stride time variability, %CV</td>
<td>1.4 ± 2.7</td>
<td>100</td>
<td>2.6 ± 1.9</td>
</tr>
</tbody>
</table>

*Notes: Mean ± SD (standard deviation) refers to measured values. All means are back-transformed from the log-transformed values, except gait velocity. Standardized mean ± SD (%) refers to percent change in the variable relative to the reference condition (walking without a dual task; set at 100%) after standardization for gait velocity. Data were tested for difference versus reference condition (walking without a dual task) with analyses of covariance.

$p < .001; \beta < .01$ (paired t tests, relative to the reference condition).

ML = mediolateral trunk sway; %CV = coefficient of variation; $R^2$ = percentage of explained variation in the outcome variable by the regression model in %.

### Table 3. Multiple Linear Regression Analysis of the Association of Executive Function With Gait and Balance Variables in Community-Living Elderly People During Walking Without Dual Task and Under a Dual-Task Condition (Animal Naming)

<table>
<thead>
<tr>
<th>TMT Ratio</th>
<th>Stroop Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Dual Task</td>
<td>Animal Naming</td>
</tr>
<tr>
<td>β</td>
<td>$R^2$</td>
</tr>
<tr>
<td>ML displacement, degrees</td>
<td>0.99</td>
</tr>
<tr>
<td>ML angular velocity, degrees/s</td>
<td>0.57</td>
</tr>
<tr>
<td>Gait</td>
<td></td>
</tr>
<tr>
<td>Gait velocity, m/s</td>
<td>−0.03</td>
</tr>
<tr>
<td>Stride length variability, %CV</td>
<td>1.2</td>
</tr>
<tr>
<td>Stride time variability, %CV</td>
<td>0.000</td>
</tr>
</tbody>
</table>

*Significant associations.

TMT ratio = Trail Making Test (TMT part B − part A)/TMT part A; Stroop ratio = Stroop Color Word Test ratio ((Stroop III − (I + II))/(I + II)); ML = mediolateral trunk sway; %CV = coefficient of variation; $R^2$ = percentage of explained variation in the outcome variable by the regression model in %.
others used absolute differences in test scores (10,11). The use of absolute differences, however, may have increased the contrast between the extremes in test scores and have made a spurious finding of an association more likely. Second, in contrast to previous studies, we have applied a correction for multiple comparisons, which obviously has restricted the number of independent associations, but results in statistically more robust findings. Third, our population of community-living elderly people is different than the idiopathic fallers or healthy older adults in the studies of Hausdorff and colleagues (8,12) and the younger and quicker (mean gait velocity 1.20 m/s) participants in the InChianti study (10,11). However, the participants in the Einstein aging study (32) were comparable in gait velocity and TMT performance; therefore, population differences do not seem to be the main explanation.

A major strength of our study is that we examined both gait and balance variables during walking. Our results showed that frontal executive functioning was related not only to stride length variability [an important gait variable that is related to falls by elderly persons and patients with neurological diseases (33)], but also to balance instability during walking (as reflected by an increased mediolateral trunk sway related to lateral falls and hip fractures). Another strength is that we have used several cognitive tests and two different cognitive dual tasks. Executive function consists of various, complex cognitive processes that differ in nature and, consequently, cannot be assessed using one single test. We have selected the TMT and the Stroop test because they represent executive abilities that are probably most important to everyday walking: mental flexibility and response inhibition. An explanation for the difference in results between the TMT and Stroop test could be that the ability to adapt to changing circumstances during walking requires more mental flexibility, tested with the TMT, than response inhibition, measured by the Stroop test. We refrained from including additional executive function tests because the limited attention span of our elderly participants could have influenced their performance negatively by fatigue and decreased motivation. Another concern would be the increased risk of finding a chance association when the number of variables increases. Such risks were already considered for the present experimental design, which was essentially an explorative study with many possible comparisons. To accommodate this, we selected the most important outcome variables before the start of the study, and set the α level at 0.01.

We should note one additional drawback, related to the use of the relatively short (5.6 m) electronic walkway, which limited the number of steps available (on average 5.6 steps, SD 1.4) for analysis in each walk. This may have reduced the precision of our measurements compared to approaches in which participants wear pressure-sensitive insoles during prolonged walking episodes (9). However, Holzer and colleagues and Coppin and colleagues measured gait velocity over an equally short distance. Furthermore, even our short walkway was sensitive enough to detect effects of dual tasking on gait variability. Furthermore, previous studies have shown that changes in trunk sway under dual-task circumstances can be detected during a comparably short walking trajectory (34). Changes in stride length variability, stride time variability, or trunk sway cannot be used on their own to indicate the risk of falling in individual patients, and have to be combined with all other clinical findings. Future studies should explore the underlying pathophysiological mechanisms behind the associations of executive functions with gait and balance, as well as their ability to predict the development of gait disorders and risk of falling.

Conclusion
This study provides additional insight in the interaction of executive functions and memory with gait and balance control during walking in community-living elderly people: Executive functions are associated with gait and balance, but only in a dual-task condition. In future research, the pathophysiology and further clinical implications should be investigated.

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Contributors: Marianne van Iersel, Roy Kessels, and Marcel Olde Rikkert contributed to study design, conduct, analysis and writing of the manuscript. Bas Bloem and André Verbeek contributed to data analysis and writing of the manuscript.

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