Performance variance on walking while talking tasks: theory, findings, and clinical implications

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Abstract Dual tasks that involve walking and cognitive interference tests are commonly used in mobility assessments and interventions. However, factors that explain variance in dual-task performance costs are poorly understood. We, therefore, examined the moderating effects of two putative constructs, *postural reserve* and *hazard estimate*, on performance on a walking while talking paradigm. Participants were 285 non-demented older adults (mean age=76.9 years; %female=54.4). Postural reserve was operationalized as the presence or absence of clinical gait abnormalities. An empirical factor, based on measures of executive functions, served as a marker for hazard estimate. The moderation effects of postural reserve and hazard estimate on dual-task costs were examined via two-way interactions in a joint linear mixed effect model. Significant dual-task costs were observed for gait speed (95% CI=30.814 to 39.121) and cognitive accuracy (95% CI=6.568 to 13.607). High

hazard estimate had a protective effect against decline in gait speed (95% CI=-8.372 to -0.151) and cognitive accuracy (95% CI=-8.372 to -0.680). Poor postural reserve was associated with reduced decline in gait speed (95% CI=-9.611 to -0.702) but did not moderate the decline in cognitive accuracy (95% CI=-3.016 to 4.559). Assessing postural reserve and hazard estimate can help improve mobility risk assessment procedures and interventions for individuals with cognitive and movement disorders.

Keywords Dual task · Postural reserve · Executive functions · Gait

Introduction

Decline in gait is common in older adults and is associated with increased risk of dementia (Verghese et al. 2002) transition states of cognitive decline (Verghese et al. 2008, 2012) and other adverse outcomes including disability, placement in nursing homes, and mortality (Montero-Odasso et al. 2005; Newman et al. 2006; Studenski et al. 2011; Verghese et al. 2011). The relationship between specific cognitive functions and gait performance in non-demented older adults is reproducible, robust, and evidenced by studies that involve different methodologies (Holtzer et al. 2006, 2012a; for review see Yogev et al. 2005).

Allocation of attention to competing task demands, as assessed in dual tasking, is considered a distinct facet of the executive functions (Holtzer et al. 2004, 2005). The advantage of using this approach is that attention demands are experimentally manipulated,

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and the causal effect of taxing the attention system on task performance can be directly measured. When implemented in the context of mobility assessment, dual tasking requires that participants walk or maintain balance while performing a secondary cognitive interference task (Camicoli et al. 1997; Li et al. 2001; Lindenberger et al. 2000). Dual tasks that involve walking can be conceptualized as an attention-demanding mobility stress test that was recently shown to predict the risk of frailty, disability, and mortality in older adults (Verghese et al. 2013). Moreover, dual-task paradigms afford a rehabilitative training framework well as a window into the effect of cognitive remediation on mobility in normal (Verghese et al. 2010a) as well as disease populations such as those with dementia (Schwenk et al. 2010; Verghese and Holtzer 2010) and Parkinson's disease (Yogev-Seligmann et al. 2012a).

However, a considerable portion of the variance in performance on dual-task paradigms remains unexplained. Hence, identifying factors that account for individual differences in dual tasking is of scientific and clinical importance. Theories and explanations for the effect of aging on dual-task costs in cognitive paradigms include decline in speed of processing (Salthouse 1996; Somberg and Salthouse 1982) response selection bottleneck (Hartley 2001; Hartley and Little 1999) and reduced executive supervisory control and attention resources (Glass et al. 2000; Holtzer et al. 2004, 2005). However, the magnitude and theoretical underpinning of the effect of aging on dual tasking remain controversial (Meyer et al. 2001). Factors that explain dual-task costs and task prioritization effects on paradigms that include mobility as the primary task are even less researched and understood. Explicitly manipulating task instructions influenced the extent and distribution of dual-task performance costs on both the mobility and cognitive interference tasks in older adults (Verghese et al. 2007a; Yogev-Seligmann et al. 2010) and in patients with Parkinson's disease (Yogev-Seligmann et al. 2012b). Under conditions that emphasize equal importance for both tasks, a “posture first” hypothesis suggesting that individuals, especially older adults, are likely to prioritize walking or balance over cognitive task performance received some support (Gerin-Lajoie et al. 2005; Li et al. 2001; Schrodtt et al. 2004) but findings to the contrary have also been reported in healthy individuals (Lindenberger et al. 2000) and in Parkinson's disease patients (Bloem et al. 2001; Yogev et al. 2005).

A recent review by Yogev-Seligmann and colleagues attempted to provide a conceptual framework suggesting that two putative constructs may underlie

dual-task performance costs and task prioritization strategies in paradigms that involve mobility and cognitive interference tasks (Yogev-Seligmann et al. 2012c). According to these authors, *postural reserve* reflects the individual's capacity to respond to postural threats representing the physical integrity of sensory, motor, muscle, and skeletal systems. *Hazard estimate* is conceived as an aspect of executive functions (EF) that is concerned with planning, assessment of self-limitations, risk estimations, and judgment. It is critical to emphasize that EF are multi-faceted (Holtzer et al. 2005; Miyake et al. 2000). In this context, the suggested operational definition of hazard estimate also represents a relatively broad survey of abilities that are typically thought of as domains of EF. Importantly, as recognized by the authors, the measurement and validation of these two putative concepts are limited at this point and their existence has been, to a large degree, inferred indirectly from studies that did not necessarily aim to measure them directly. The current study was specifically designed to determine the effect of postural reserve and hazard estimate on a dual-task paradigm that involved walking and a secondary cognitive interference task. Postural reserve was operationalized as the presence or absence of clinical gait abnormalities that were assessed during a structured neurological examination. Hazard estimate was operationalized by creating a factor/domain score that was based on several neuropsychological tests of EF. We hypothesized that both postural reserve and hazard estimate would moderate the effect of dual-task interference. Specifically, we predicted that higher (i.e., better) hazard estimate would have a protective effect against dual-task costs on both the walking and cognitive interference task. We further predicted that higher (i.e., better) postural reserve would be associated with increased dual-task costs on walking. This latter hypothesis, although somewhat counterintuitive, is consistent with the model proposed by Yogev-Seligmann et al. (2012a). Finally, we explored whether hazard estimate influenced the moderating effect of postural reserve on dual-task performance costs.

Methods

Participants

Participants in this study were recruited from an ongoing cohort study of older adults entitled “Central Control of

Mobility in Aging” (CCMA). The primary aims of the study are to determine cognitive and brain predictors of mobility in aging. Potential participants 65 and older, identified from a population list of lower Westchester county, NY, were first contacted by mail and then by telephone inviting them to participate. A structured telephone screening interview was administered to potential participants to assess for eligibility. The telephone interview consisted of verbal consent, a brief medical history questionnaire, mobility questions (Baker et al. 2003) and validated cognitive screens to exclude dementia (Galvin et al. 2005; Lipton et al. 2003). Exclusion criteria were: inability to speak English, inability to ambulate independently, dementia, significant loss of vision and/or hearing, current or history of neurological or psychiatric disorders, recent or anticipated medical procedures that may affect mobility, and receiving hemodialysis. After completing the telephone interview eligible individuals were scheduled for two in-person visits at the research center. During the visits, participants received comprehensive neuropsychological, cognitive, psychological, and mobility assessments as well as a structured neurological examination. The neuropsychological assessment included the Repeatable Battery for the Assessment of Neuropsychological Status (Randolph et al. 1998) and other tests covering several cognitive domains including literacy, language, visual spatial abilities, attention, memory, and executive functions. We have provided robust longitudinal norms for several of these cognitive measures (Holtzer et al. 2008b). Diagnoses of dementia were assigned according to the *Diagnostic and Statistical Manual of Mental Disorders*, fourth edition (DSM-IV TR, 2000; Association, 2000) at consensus diagnostic case conferences as previously described (Holtzer et al. 2008a). Clinical gait abnormalities were formally assessed during the neurological examination by the study clinician (Verghese et al. 2002). CCMA participants are followed longitudinally at yearly intervals. Written informed consents were obtained at clinic visits according to study protocols and approved by the institutional review board.

Measures

Gait speed (in centimeter per second) served as the outcome and was measured using an instrumented walkway with embedded pressure sensors (GAITRite, CIR systems, Havertown, PA). The GAITRite system is widely used in clinical and research settings, and has excellent psychometric properties. The walkway measures

8.5 m×0.9 m×0.01 m ($L \times W \times H$) with an active recording area of 6.1 m×0.61 m ($L \times W$). Gait speed and the mean gait characteristics demonstrated excellent test–retest reliability in our (reliability of two repeated trials, $r=0.96$; Holtzer et al. 2012b) and in other research settings ($ICC \geq 0.80$; Brach et al. 2008).

Walking protocol

Participants were asked to walk on the instrumented walkway at their usual pace in a quiet well-lit room wearing comfortable footwear and without any attached monitors. The participants walked for one trial under two separate task conditions: (1) normal walk (NW), (2) walking while reciting alternate letters of the alphabet (WWT). In WWT, the participants were asked to pay equal attention to both the walking and cognitive interference task (i.e., equal priority) as previously described (Holtzer et al. 2006, 2012a). Single-task cognitive performance was assessed by asking participants to recite alternate letters of the alphabet while standing for 10 s. The order of the three tasks was counterbalanced to reduce practice effects. In this single-task condition, the responses generated within the 10-s interval were recorded. In WWT, however, responses generated during the duration of the task, which varied among participants, were recorded.

Postural reserve The presence of clinical gait abnormalities (due to either neurological or non-neurological causes) was evaluated by study clinician during structured neurological examination by examining walking patterns as previously described (Verghese et al. 2002). Clinical gait abnormalities provide an independent proxy assessment of the sensory, motor, balance, and cortical components of the postural reserve construct, and have been associated with perturbations of posture such as falls (Verghese et al. 2010b). The study clinician did not administer the dual-task walking protocol. Hence, postural reserve was assessed independently of the participants' performance on the experimental walking protocol.

Hazard estimate In order to obtain a broad-based empirical measurement of hazard estimate, few neuropsychological tests that are commonly used to assess EF were utilized. Each test was first z transformed. Then an overall empirical domain was computed by averaging the z transformed individual test scores. The specific tests were Digit Symbol (total number correct; Wechsler

1997); letter fluency (FAS; total number of words; Benton 1976); category fluency (using procedures from the Boston Diagnostic Aphasia Examination; animals, fruits, and vegetables; Goodglass 1983); Trail Making Test (seconds to completion for Form B; Reitan 1958), and the Attention Index of the RBANS (Randolph et al. 1998).

Covariates

Structured clinical interviews were used to identify self-reported medical diagnoses. Consistent with our previous studies (Holtzer et al. 2007; Verghese et al. 2008; Holtzer et al. 2006), dichotomous rating (presence or absence) of diabetes, chronic heart failure, arthritis, hypertension, depression, stroke, Parkinson's disease, chronic obstructive lung disease, angina, and myocardial infarction was used to calculate a disease comorbidity summary score (range 0–10). Additional covariates included age, education, and gender.

Statistical analysis

Demographic characteristics, medical history, gait speed, and cognitive test performance were tabulated for the entire sample. A joint linear mixed effects model using robust variance estimate (Diggle et al. 2002; Liang and Zeger 1986; Verbeke G 2009) was utilized to examine the effect of dual tasking on gait speed and cognitive accuracy. The moderating effects of postural reserve and hazard estimate on dual-task performance costs were tested via two-way interactions of

task×postural reserve and task×hazard estimate. Task in this model is a two-level within-person repeated measure representing the change from single- to dual-task conditions in gait speed and cognitive accuracy. Data were inspected descriptively and graphically, and model assumptions were formally tested. In addition to postural reserve and hazard estimate, the fully adjusted analyses controlled for gender, age, education, and disease comorbidity. Statistical analyses were performed using SAS 9.2 (SAS Institute Inc., Cary, N.C.).

Results

Participants

The current study included 285 non-demented participants with complete mobility and cognitive baseline data. The sample had a mean age (76.9ys; ± 7.0), education (14.53ys; ± 2.99), and gender distribution (%female=54.4) that broadly approximates the demographic characteristics of older adults who reside in our catchment area. The disease comorbidity summary score (1.204 $\pm$ 1.03) was indicative of relatively good health. Baseline cohort characteristics are presented in Table 1.

Hazard estimate: Descriptive statistics for the individual neuropsychological tests that contributed to hazard estimate are provided in Table 1. Postural reserve: Of the 285 participants 157 had clinical gait abnormalities of which 142 were of mild and 15 were

Table 1 Summary of sample characteristics, cognitive functions, and gait velocity at baseline

Total sample, <i>n</i>	285		
Women, <i>n</i> (%)	155 (54.4)		
	Mean (SD)	Median	Range
Age years	76.9 (± 7.00)	76.00	65.00–95.00
Education years	14.53 (± 2.99)	14.00	5.00–28.00
Disease comorbidity index	1.204 (± 1.03)	1.00	0.00–5.00
RBANS attention (index total score)	100.42 (± 13.62)	101.00	65.00–134.00
Digit symbol total score	53.45 (± 13.40)	53.00	0.00–88.00
Letter fluency total score	39.54 (± 13.44)	38.00	8.00–80.00
Category fluency total score	41.29 (± 10.92)	41.00	9.00–76.00
Trails B completion time (s)	129.55 (± 60.04)	118.97	13.00–300.00
Gait velocity NW (cm/s)	99.69 (± 23.41)	98.29	26.70–170.19
Gait velocity WWT (cm/s)	69.89 (± 25.63)	67.80	13.50–148.00
Alphabet single task (% correct)	91.66 (± 12.28)	100.00	25.00–100.00
Alphabet dual task (% correct)	83.39 (± 16.94)	87.50	22.22–100.00

Note: *RBANS* attention Repeatable Battery for the Assessment of Neuropsychological Status Attention Index score, *NW* normal pace walk, *WWT* walking while counting

of moderate severity. Subtypes were as follows: 90 non-neurological, 58 neurological, and 9 were unclassified. None of the participants had Parkinsonian gait. Results of the unadjusted and fully adjusted joint linear mixed effects models that were used to assess the effect of dual tasking on gait speed and cognitive performance are summarized in Tables 2 and 3, respectively. The main and moderating effects of hazard estimate and postural reserve were not materially different in the two models. Hence, results from the fully adjusted model are described below. Significant dual-task costs were observed for gait speed (estimate=34.968; 95% CI=30.814 to 39.121) and cognitive accuracy (estimate=10.088; 95% CI=6.568 to 13.607) among those with low hazard estimate and low postural reserve. Significant two-way interactions revealed that hazard estimate status (median split) moderated the effect of dual-task interference on both gait speed (estimate=-4.562; 95% CI=-8.372 to -0.151) and cognitive accuracy (estimate=-4.526; 95% CI=-8.372 to -0.680). The decline in gait speed due to task interference in individuals with high compared to low hazard estimate was significantly smaller (see Fig. 1a). Similarly, the decline in cognitive accuracy due to task interference in individuals with high compared to low hazard estimate was significantly smaller (see Fig. 1b). Postural reserve moderated the effect of dual-task interference on gait speed (estimate=-5.156; 95% CI=-9.611 to -0.702) but not on cognitive accuracy (estimate=-0.771; 95% CI=-3.016 to 4.559). Individuals with high compared to low postural reserve demonstrated greater decline in gait speed (Fig. 1c) but not in cognitive accuracy (Fig. 1d). Finally, in exploratory analysis,

non-significant three-way interactions revealed that hazard estimate had not moderated the relationship between postural reserve and the declines in gait speed (estimate=8.832; 95% CI=-0.001 to -17.665) or cognitive accuracy (estimate=3.870; 95% CI=-8.960 to 6.725).

Discussion

Although commonly used in mobility assessments of normal and disease populations, much of the variance in dual-task performance costs in paradigms that involve walking and cognitive interference tasks remains unexplained (Hausdorff et al. 2008). We, therefore, undertook the current study to determine whether two putative constructs, postural reserve and hazard estimate, influenced the effect of dual-task interference on gait and cognitive performance in a cohort of community residing non-demented older adults. Our findings show that hazard estimate moderated the effect of dual-task interference on gait speed and cognitive performance. Specifically, high hazard estimate status had a protective effect against dual-task performance costs (see Fig. 1a–b for visual depiction). Measures of EF were previously related to walking performance when assessed separately in single- and dual-task conditions in normal aging (Holtzer et al. 2006, 2012b) and in Parkinson's disease (Yogev et al. 2005). However, to our knowledge, this study is the first to demonstrate that a broad-based measure of EF explained variance in the decline in performance from single- to dual-task conditions for both the primary gait and secondary cognitive interference tasks.

Table 2 Unadjusted Joint linear mixed effect model: moderation effects of hazard estimate and postural reserve on dual-task performance

Variable	Estimate	<i>t</i>	95% CI	<i>P</i>
Single vs. dual task (gait)	34.973	16.57	30.817 to 39.125	<0.001
Single vs. dual task (cognition)	10.096	5.65	6.575 to 13.616	<0.001
Hazard estimate (gait)	13.257	4.71	7.711 to 18.803	<0.001
Hazard estimate (cognition)	6.926	3.48	3.009 to 10.843	<0.001
Postural reserve (gait)	-13.406	-4.67	-19.060 to -7.752	0.001
Postural reserve (cognition)	0.023	0.01	-3.833 to 3.881	0.990
Hazard estimate×task (gait)	-4.569	-2.04	-8.979 to -0.158	0.042
Hazard estimate×task (cognition)	-4.541	-2.32	-8.389 to -0.692	0.020
Postural reserve×task (gait)	-5.151	-2.28	-9.604 to -0.697	0.023
Postural reserve×task (cognition)	0.784	0.41	-3.003 to 4.572	0.683

Table 3 Adjusted joint linear mixed effect model: moderation effects of hazard estimate and postural reserve on dual-task performance

Variable	Estimate	<i>t</i>	95% CI	<i>P</i>
Single vs. dual task (gait)	34.968	16.57	30.8141 to 39.121	<0.001
Single vs. dual task (cognition)	10.088	5.64	6.5689 to 13.6071	<0.001
Hazard estimate (gait)	11.5356	4.21	6.1436 to 16.9276	<0.001
Hazard estimate (cognition)	6.796	3.42	2.888 to 10.704	<0.001
Postural reserve (gait)	−9.429	−3.18	−15.262 to −3.595	0.001
Postural reserve (cognition)	−1.224	−0.61	−5.190 to 2.742	0.544
Hazard estimate×task (gait)	−4.562	−2.04	−8.973 to −0.151	0.0427
Hazard estimate×task (cognition)	−4.526	−2.32	−8.372 to −0.680	0.021
Postural reserve×task (gait)	−5.156	−2.28	−9.611 to −0.702	0.023
Postural reserve×task (cognition)	0.771	0.40	−3.016 to 4.559	0.688
Age (gait)	−0.815	−4.87	−1.144 to −0.486	<0.001
Age (cognition)	0.175	1.80	−0.016 to 0.367	0.072
Gender (gait)	−0.212	−0.09	−4.686 to 4.260	0.925
Gender (cognition)	3.299	2.26	0.432 to 6.174	0.024
Education (gait)	0.603	1.60	−0.139 to 1.345	0.110
Education (cognition)	0.588	2.51	0.127 to 1.048	0.012
Comorbidity score (gait)	−2.588	−2.68	−4.491 to −0.686	0.007
Comorbidity score (cognition)	0.178	0.27	−1.127 to 1.485	0.788

Postural reserve is a putative construct proposed to characterize the individual's capacity to respond to postural threats representing the physical integrity of sensory, motor, muscle, and skeletal systems (Yogev-Seligmann et al. 2012b). The integrity of postural reserve can be inferred indirectly by comparing healthy individuals to those who suffer from diseases known to affect movement and postural stability. In the current study, however, we measured postural reserve directly, as determined by the presence or absence of clinical gait abnormalities during the structured neurological examination (Verghese et al. 2002). Importantly, postural reserve was assessed independently of the participants' performance on the dual-task paradigm. Our findings revealed that dual-task performance costs in gait speed but not in cognitive accuracy were moderated by postural reserve status (see Fig. 1c, d). Specifically, individuals with high compared to low postural reserve demonstrated greater decline in gait speed due to dual-task interference. This finding, although counterintuitive, suggests that at least among non-demented older adults, poor postural reserve protects against decline in gait speed when cognitive load is increased. This finding can be construed as consistent with a more refined “posture first” approach that is specifically applicable for individuals whose postural stability is

compromised. This explanation is also consistent with hypothetical trajectories of dual-task performance costs, stratified by postural reserve and hazard estimate status that were previously described (Yogev-Seligmann et al. 2012c). However, it is noteworthy that postural reserve status did not moderate dual-task costs on the cognitive task. Hence, there is no direct behavioral evidence to suggest that individuals with low postural reserve prioritized gait over the cognitive task.

Limitations Hazard estimate, as defined herein, moderated the effect of dual-task interference on gait speed and cognitive accuracy. However, the cognitive abilities captured by this putative construct are consistent with previous definitions of components of EF. Hence, future construct validation studies are needed to determine the utility of using hazard estimate, a more narrowly defined term, instead of executive functions. The moderating effects of both postural reserve and hazard estimate on dual-task performance costs should be replicated and examined in disease populations with known movement disorders and balance dysfunctions to increase the generalizability of our findings to clinical settings. Further, examination of longitudinal effects on these putative constructs as well as the gait and cognitive outcomes would be critical to further

Fig. 1 **a** Moderating effect of hazard estimate (*HE*) on the decline in gait speed. **b** Moderating effect of hazard estimate (*HE*) on the decline in cognitive accuracy. **c** Moderating effect of

postural reserve (*PR*) on the decline in gait speed. **d** Moderating effect of postural reserve (*PR*) on the decline in cognitive accuracy

establish their temporal relationship. The use of gait speed as a single dependent measure is justified statistically and in light of the literature implicating this measure in critical clinical outcomes such as falls, disability, and mortality (Montero-Odasso et al. 2005; Newman et al. 2006; Studenski et al. 2011; Verghese et al. 2011). However, the moderating effects reported herein should be examined in relation to other quantitative gait measures as well.

Clinical implications Converging evidence for cognitive control of mobility exists from studies of different populations including but not limited to normal aging (Holtzer et al. 2011), transition states of cognitive and motor decline in aging (Verghese et al. 2008, 2013), dementia (Verghese et al. 2002, 2007b), multiple sclerosis (Benedict et al. 2011; D'Orio et al. 2012), and Parkinson's disease (Yogev et al. 2005). The use of dual tasking as a mobility stress test that is designed to experimentally increase cognitive load has been increased in recent years. We have recently demonstrated

that walking while talking predicted the risk of frailty, disability, and mortality in older adults (Verghese et al. 2012). Moreover, mobility interventions that include dual-task protocols have also been successfully implemented in patients with dementia (Schwenk et al. 2010) and Parkinson's disease (Yogev-Seligmann et al. 2012a). Our findings indicate that both postural reserve and hazard estimate moderate dual-task performance. Hence, assessing both constructs can help identify patients at risk of performing poorly on paradigms that involve walking and cognitive interference tasks. Moreover, this information can also be used to administer interventions that are tailored to the patient's strengths and weaknesses. In addition, cognitive training of attention and executive functions enhanced gait performance, especially when assessed under dual-task conditions (Verghese et al. 2010a). Hence, interventions that include both cognitive remediation as well as multi-dimensional mobility training may optimize the maintenance and recovery of mobility in normal aging and in populations with movement and balance disorders.

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