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Intra-individual variability in gait and in cognitive performance are not related in the elderly

Alison L. Sukits¹, Robert D. Nebes², April J. Chambers¹, Aaron Ledgerwood¹, Edythe M. Halligan², Subashan Perera³, and Rakié Cham¹

¹Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA

²Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA

³Department of Medicine, University of Pittsburgh, Pittsburgh, PA

Abstract

As humans age, the amount of intra-individual variability (IIV) present in both their gait and their cognitive performance tends to increase. Both gait and cognitive IIV are associated with attentional control and with cerebrovascular disease, suggesting that the IIV in gait and cognitive function should be strongly correlated in the elderly. In this study temporal gait variability was determined from a sixty second period of walking. Cognitive variability was determined from two decision-time tasks assessing inhibition. Despite the presence of substantial amounts of gait and cognitive IIV in 71 elderly individuals, there were no significant correlations between measures of cognitive and gait IIV, suggesting that different factors drive IIV in the motor and cognitive performance of older individuals. These results are not consistent with the common cause theory of aging, which predicts that cognitive and sensorimotor performance should show related declines due to age-related disruption of a common neurological substrate.

INTRODUCTION

As people age, many show increased variability in their gait, a change which has been associated with falls and mobility disability (Brach, Studenski, Perera, VanSwearingen & Newman, 2007; Hausdorff, Rios & Edelberg, 2001). Variability is evident as fluctuations in both spatial (e.g., step length) and temporal (e.g., stance time) aspects of walking. Increased fluctuations in the gait of the elderly are found both moment to moment and across sessions falling days or weeks apart (Li, Aggen, Nesselrode, & Baltes, 2001; Huxhold, Li, Schmiedek, Smith & Lindenberger, 2011). A number of sources for this amplification of intra-individual variability (IIV) in gait have been examined including medical and physical conditions (Hausdorff et al., 2001), sensorimotor decrements (Callisaya, Blizzard, McGinley, Schmidt & Srikanth, 2010) and recently, age-related decrements in attentional control (Herman, Mirelman, Giladi, Schweiger & Hausdorff, 2010). This latter view is supported by studies in which gait variability is measured both with and without a concurrent cognitive task (Schaefer & Schumacher, 2011). Gait inconsistency increases when older individuals have to combine walking with cognitive operations as simple as saying the alphabet (Verghese et al., 2002). This suggests that as individuals age, attention is increasingly involved in the central control of gait, reflecting a loss of automaticity (Woollacott & Shumway-Cook, 2002; Montero-Odasso, Verghese, Beauchet & Hausdorff, 2012).

A parallel line of research has examined IIV in cognitive performance (Hultsch, Strauss, Hunter, Levy-Bencheton & Strauss, 2008) especially in the form of inconsistent response time (RT) on attention-demanding tasks (West, Murphy, Armilio, Craik, & Stuss, 2002). Cognitive IIV tends to rise with normal aging (Hultsch et al., 2008; Williams, Hultsch, Strauss, Hunter & Tannock, 2005) with many older persons consistently showing substantial RT variability both within a testing session and between sessions (Rabbitt, Osman, Moore & Stollery, 2001). Such individuals also tend to exhibit greater moment-to-moment variability in RT across tasks assessing different cognitive domains (Hultsch et al., 2008). Thus, the degree of cognitive IIV appears to be a systematic and stable characteristic of individuals. The increased cognitive IIV demonstrated by some older persons has been attributed to fluctuations, or even a breakdown, in the stability of their executive or attentional control systems (West et al., 2002).

There are a number of reasons to expect that the degree of cognitive IIV and gait IIV present in an individual should be related. First, problems with attentional control or executive function have been postulated to underlie increased IIV in both cognition (Jackson, Balota, Duchek & Head, 2012; MacDonald, Li & Bäckman, 2009) and in gait (Herman et al., 2010; Verrel, Lövdén, Schellenbach, Schaefer & Lindenberger, 2009). Thus, the same persons who show elevated gait IIV might be expected to show increased cognitive IIV. Second, white matter pathology has been associated with increased moment to moment variability in both cognitive performance (Walhovd & Fjell, 2007) and gait (Rosano, Brach, Studenski & Longstreth, 2007). Finally, findings of an increasing co-variation between cognitive and sensorimotor performance with advancing age have led to the hypothesis (Li & Lindenberger, 2002; Baltes & Lindenberger, 1997) that disruptions of both cognitive and motor functioning result from a “common cause” – deterioration of a common neurological substrate leading to increased fluctuations in the accuracy and speed of information processing, with an associated reduction in performance stability (Rabbitt et al., 2006). Such a decline in what Li et al. (2004) term “processing robustness” could underlie the increased IIV found both in cognition and in gait. If true, then, as suggested by Strauss, MacDonald, Hunter, Moll & Hultsch (2002), consistency of cognitive and motor performance might be expected to be strongly related.

The present study examined the magnitude of the correlation existing in healthy older adults between the IIV present in various components of their gait and in their performance on response-time measures of cognitive performance. We are aware of two previous studies that compared IIV in cognitive performance and in gait. Strauss et al. (2002) examined variability across four weekly testing sessions in word and story recognition latency and in the number of steps needed to walk in a complete circle. While there was a significant correlation between IIV in the number of steps to walk a circle and response-time IIV on the memory tasks, this was true only for individuals who were demented and not for the normal elderly. Li et al. (2001) tested normal elderly individuals multiple times over the course of 25 weeks, comparing their between-session gait IIV (time and number of steps taken to walk in a circle and to walk a 10 foot linear path) to IIV in their text recall and spatial recognition. Composite scores were derived reflecting fluctuations across the sessions in participants' walking (both time and number of steps) and in their memory. While there were several significant correlations between factors representing cognitive and sensorimotor variability, the direction of these correlations was not consistent in that gait IIV correlated positively with fluctuations in text memory but negatively with variability in spatial recognition. The reason for this inconsistency in the direction of the correlations between gait and cognitive IIV across sessions is not clear.

In the present study, participants were tested in a single session during which they walked an oval track for periods of one minute either with no cognitive demand (single-task condition)

or while carrying out a concurrent cognitive task (dual-task condition). In addition to the gait testing, several other cognitive tasks were administered while participants were seated. These tasks varied in their attentional demand and the primary outcome was time to make a decision. Data from this study thus allow us to examine how the amount of decision time variability seen in cognitive tasks correlates with the variability present in gait parameters in the same individuals. Do individuals showing high gait variability also tend to show greater amounts of decision time variability when both types of variability are tested within a single testing session?

METHODS

Participants

Seventy-one individuals aged 70 to 85 (34 females) were recruited from the community. All testing procedures were approved by the University of Pittsburgh Institutional Review Board and participants signed an informed consent prior to any experimental procedures. An extensive health history was obtained focusing on conditions that might affect mobility. Information on their current medical conditions and medications was also available in most cases from their primary-care physician. To participate in this study an individual could not have a history or signs of central nervous system disease (e.g. stroke), vertigo, Meniere's disease, orthostatic hypotension or peripheral neuropathy (assessed by tuning fork). Participants had to have a binocular visual acuity (corrected) of at least 20/40. Since some experimental conditions presented auditory stimuli through earphones, participants had to be able to accurately detect 95% of a string of digits presented at a self-selected volume. Individuals who had weight-bearing pain, lower limb surgery within five years of testing or who walked with an assistive device were excluded. Persons with a history of major psychiatric disease or a score of 15 or more on the 30-item Geriatric Depression Scale (Yesavage et al., 1983) were also excluded. Participants could not be taking prescription psychoactive medications (e.g., narcotics, benzodiazepines, sedatives). To exclude individuals with a clinically significant cognitive impairment, the Repeatable Battery for the Assessment of Neuropsychological Status (Randolph, 1998) was administered and anyone whose age-normed index score fell more than 1.5 standard deviations (SD) below the mean was excluded, as was anyone who scored more than 1.5 SD below the mean on any two subtests.

Cognitive challenge

Prior to gait testing, each participant's backward digit span (WAIS -R) was individually determined as being the longest digit string correctly recalled in reverse order on at least one of two trials. There were two different walking conditions. In the *single-task* condition, the participant continuously walked around an oval track without any concurrent cognitive activity. In the *dual-task* condition, participants performed the gait testing while listening through earphones to a series of digit strings of a length equal to their backward span. As soon as each string was complete, participants were to recall the digit string in reverse order. Their response was immediately followed by presentation of the next string. This continued for the entire walking period with approximately five recall trials occurring over this time. The order of the conditions was randomized between participants but remained constant within an individual across all gait trials. In all conditions participants were told to walk at a self-selected comfortable pace. In the dual-task condition no instructions were given favoring either walking or memory performance and any participants who asked about task priority were told to give equal emphasis to both activities. The analyses reported here were conducted on gait measures obtained during the dual-task condition since gait variability is accentuated in such conditions (Woollacott & Shumway-Cook, 2002). However, use of IIV

results from the single-task condition in the correlational analyses yielded essentially the same results as those from the dual-task condition.

Gait Assessment

Each participant was provided with the same style polyvinyl-soled shoes, instrumented with custom on-off membrane footswitches for temporal identification of heel-contact and toe-off during gait. Data were collected by an electronics pack worn on the participant's waistband and transmitted wirelessly to a Bluetooth receiver. Additionally, participants were outfitted with retro-reflective markers. Using a Vicon motion capture system (Vicon, Centennial, CO) gait speed was calculated based on the average velocity in the anterior-posterior direction of a marker on the sternum. Heel contact and toe events were temporally determined based on the footswitches and spatially determined from the time-synched motion capture data. Specifically, these events were identified by tracking markers placed on the heel and toe tip of each foot. Step length was calculated as the anterior-posterior distance between the two heel markers at sequential heel contacts. Participants walked for 60 seconds around an outlined oval track (approximately 5 laps) while data were collected. Only data from the 4.6 meter straight section of the track were processed. It was assumed that different bouts of straight walking represented instances of the same underlying stochastic process and thus, after elimination of the data collected on the curves, that the participant could be considered to be continuously walking and that the data on the individual straight sections could be merged together into one trial. On average, 62 steps were used for analysis. Two 60-second trials were collected for each walking condition.

Measures of gait variability

While variability in the temporal aspects of gait have been particularly associated with walking disability in the elderly (Brach et al., 2007; Hausdorff et al., 2001), older individuals also show increased variability in an important spatial aspect of their gait - step length (Verrel, Lövdén & Lindenberger, 2012). Therefore, in this study we examined both types of variability. Temporal gait measures used were stance time, double support time and step time (the time from heel contact of one foot to the heel contact of the other foot), while the spatial gait measure used was step length. As our measure of variability, we used the standard deviation of performance collected during the second 60 second trial of each walking condition (the first trial was considered practice; however, analyses of results from the first trial were essentially the same as reported here).

Measures of cognitive variability

The cognitive tasks, performed while the participant was seated, were derived from Nassauer and Halperin (2003) and measured choice response time under four different conditions each of which consisted of 40 trials. The first task measured the time participants took to decide the direction in which an arrow was pointing. The arrow appeared in the center of a computer screen pointing either left or right. Participants rested their right and left index fingers on response buttons; if they saw → they pressed the right-hand button while if they saw ← they pressed the left-hand button. The computer recorded the time from stimulus presentation to response as well as accuracy. A second task had same stimuli but differed in the required response with the participant having to press the button on the side opposite the direction the arrow pointed (e.g., if they saw → they were to press the left button). Thus, this task produced a *Response Conflict* in which the participant had to inhibit an over-learned spatially-compatible response in order to make a response that was spatially incompatible with the presented stimulus.

A third task had two different conditions in both of which an arrow appeared either to the right or to the left of the central fixation point and the participant pressed the button on the

side toward which the arrow pointed. The difference between the two conditions lay in the relationship between the direction in which the arrow pointed and the side on which it appeared. In one condition, the arrow's location and its direction were congruous (e.g., → to the right of fixation). Thus, the spatial location of the arrow and direction it pointed reinforced the decision to press the same button. In the second condition, arrow location and the direction it pointed were incongruous (e.g., → to the left of fixation) producing a *Perceptual Conflict*. This condition required that the participant ignore the arrow's spatial location and respond instead to the direction it pointed.

The cognitive IIV measures used in this analysis came from the Perceptual Conflict and Response Conflict conditions since tasks making the greatest demand on executive control (in this case, inhibitory function) result in the largest IIV in older persons (West et al., 2002). These conditions also produced the greatest mean IIV's and greatest between-participant differences in IIV in the present results. (Use of IIV data from the other RT conditions in the correlational analyses, yielded essentially the same results as those reported here). Since there were only 40 trials per measure, task learning should have a fairly minimal effect on the participants' IIV. The measure of cognitive variability was the standard deviation of an individual's RTs on each of these two conditions.

Statistical analysis

To investigate the relationships between gait IIV and cognitive IIV, Pearson correlation coefficients (r) were computed between each temporal and spatial variability measure and each cognitive variability measure. We computed partial correlation coefficients controlling for gait speed, mean RT and both. The rationale for controlling for gait speed was that temporal variability is influenced by gait speed (Beauchet et al., 2009; Kang & Dingwell, 2008). The rationale for controlling for mean RT was that the mean and standard deviation for a set of RT trials are often correlated (Faust, Balota, Spieler & Ferraro, 2009), as was the case in this study. To assess robustness of results, we performed a set of sensitivity analyses using coefficient of variation instead of standard deviation to quantify variability in both gait and RT. Statistical significance was set at 0.05, and all statistical analyses were conducted using SAS® version 9.3 (SAS Institute Inc., Cary, NC).

RESULTS

Participant demographics, as well as gait and cognitive variables are found in Table 1. Participants had a mean age of 76, were well-educated with an average of 15 years of schooling, and were close to age-adjusted norm in general neuropsychological performance. Their walking speed averaged 1.14 m/s with all individuals walking at least 0.82 m/s.

The three measures of temporal gait variability were all significantly correlated with each other ($r = 0.62, 0.75$ and 0.80 ; all $p < 0.001$). The two measures of cognitive variability were also significantly correlated ($r = 0.52$; $p < 0.001$). In contrast, none of the measures of temporal gait IIV correlated significantly with either of the measures of cognitive IIV (Table 2) with partial correlations (controlling for both gait speed and mean RT) ranging from $r = -0.03$ to -0.19 . Correlations of step length IIV and cognitive IIV were of a similar strength ($r = -0.15$ and -0.18) and also did not reach significance (Table 2). Results were similar when controlling for only mean gait speed or mean RT or neither. While the focus of this paper was on comparing variability in cognitive and motor performance, we also examined whether there were any significant correlations between the mean response times on the two cognitive tasks and the mean spatial and temporal gait measures and there were not (data not shown).

DISCUSSION

This analysis was performed to determine whether there was a relationship in elderly individuals between the degree of intra-individual variability present in their gait and in their cognitive performance. It was hypothesized that the amount of gait inconsistency present would be positively correlated with the amount of cognitive inconsistency based on literature showing that both are affected by older individuals' attentional ability and by their WMH burden (Herman et al., 2010; Jackson et al., 2012; MacDonald et al., 2009; Verrel et al., 2009) and on studies suggesting a common neurobiological cause for the increased co-variation between cognitive and sensorimotor performance with advancing age (Li & Lindenberger, 2002; Li et al., 2004). However, no significant relationships were found between multiple measures of both temporal and spatial gait IIV and of cognitive response time IIV.

There are several methodological differences between the present study and the two previous studies that examined the relation between cognitive and gait variability in normal elderly (Li et al., 2001; Strauss et al., 2002). Those studies both used variability in memory recall or recognition performance for their cognitive measure and looked at IIV across multiple weeks of testing. By contrast, the present study measured IIV in response time for making simple decisions about spatial relationships and examined short-term fluctuations in performance within a single testing session. The results of the present study are consistent with one of the previous studies (Strauss et al., 2002) in finding no significant correlations between measures of cognitive and gait variability, but not with the other (Li et al., 2001) which did find a composite measure of spatial and temporal gait IIV correlated significantly with verbal recall and with spatial recognition (although the direction of the relationship was not the same for the two correlations). Since our results were consistent with one and not the other of these two studies, the methodological differences in the nature of the cognitive measure and the time interval over which the IIV was determined seem unlikely to be the source of the difference in the results between the results of Li et al. and those of Strauss and the present study.

One possible explanation for the lack of a positive correlation between gait and cognition in our study at least could be that there was insufficient between-subject differences in one or both types of IIV. The rigorous selection criteria used in this study yielded a very healthy, high-functioning group of older individuals. Such an older sample could have a narrow range of cognitive and/or gait IIV thus limiting our ability to detect a correlation. However, the gait speed and the gait variability results presented here fall within values previously reported by others for healthy, community-dwelling older adults (Callisaya et al., 2010, Brach, Studenski, Perera, VanSwearingen & Newman, 2008). The cognitive variability measures from the response time data are also comparable to previous studies of normal aging. For example, Duchek et al. (2009) reported a mean coefficient of variation of approximately 0.22 in normal elderly on two measures of inhibitory function (Stroop task and Simon task) similar to those used in this study. The mean coefficient of variation in the present sample was similar (0.23; SD =0.07) for the Perceptual Conflict condition and even larger (0.34; SD =0.16) for the Response Conflict condition. Thus, the present sample of older individuals does not appear to have a restricted range of variability in measures of either cognitive or gait variability. However, it should be noted that the increased moment to moment variability seen in the performance of the elderly may make it more difficult to detect consistent relationships between the degree of motor and cognitive variability present in such individuals (Huxhold, Li, Schmiedek, Smith & Lindenberger, 2011).

It is also possible that asking participants to perform a digit-recall task while walking (i.e., dual-tasking) may have actually reduced their gait IIV making it more difficult to detect a

relation with cognitive IIV. That is, even though participants were not instructed to give priority to the digit recall task, their attentional focus may have shifted to it causing their walking performance to become more automatic and thus less variable. Such an effect has been found in dual-task studies of postural control (Huxhold, Li, Schmiedek, & Lindenberger, 2006). However, this is usually only seen in dual-task conditions that make a minimal demand on attention. Our dual-task condition was specifically designed to be performed at the limit of an individual's ability (i.e., at each participant's backward digit span). Also, when we examined gait IIV in the single-task condition where participants simply walked with no concurrent memory task, there were still no significant correlations of gait and cognitive IIV (results not shown). Alternatively, our dual-task condition may not have produced a sufficient demand on the type of cognitive-control operations that Lindenberger, Marsiske and Baltes (2000) have argued are important to maintain postural control in the elderly. While we did use stimulus lists set to an individual's backward digit span, the nature of this recall task may not have required the type of cognitive supervision necessary for sensorimotor integration and coordination in the elderly, thus not producing sufficiently large gait IIV.

With respect to the common cause hypothesis, previous studies (Li & Lindenberger, 2002; Rabbitt et al., 2006) suggested that deterioration of a common neurological substrate may underlie the substantial cross-sectional correlations found between the cognitive and sensorimotor declines in older individuals. This common cause theory suggests that a strong relation between intraindividual variability in elderly participants' gait and their cognitive performance might be expected, as was noted by Strauss et al. (2002). However, the present results did not show any significant correlations between gait and cognitive IIV. Recent work (Lindenberger & Ghisletta, 2009) examining the relation of sensory (visual) and cognitive (memory) change in a large sample of elderly across 13 years also did not provide the strong evidence for a common cause in rates of change over time that was expected based on the earlier cross-sectional results. These results have raised questions as to whether cognitive and sensorimotor declines seen with aging always share a similar etiology such as a common neurobiological basis. Our present results also argue against the generality of the common cause account of interrelated changes in cognitive and sensori-motor aging, in that there was not a substantial relation between cognitive and motor IIV in normal older persons.

In summary, despite a literature showing that gait and cognitive variability in older individuals are both associated with several common individual characteristics (i.e., attentional ability and WMH burden), we did not find the expected high correlation between these two types of intra-individual variability. This would suggest that other factors are differentially driving the greater inconsistency found in many older persons' gait and cognitive performance.

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Table 1

Participant demographics, gait and cognitive results.

	Mean (SD)	Range
Demographics		
Age (years)	75.68 (4.04)	70.25 – 85.13
Education (years)	15.25 (3.07)	9 – 20
RBANS total index score	102.44 (11.71)	78 – 125
Gait Measures		
Gait Speed (m/s)	1.14 (0.15)	0.82 – 1.41
Double Support Time (ms)	57.89 (23.74)	14.40 – 132.43
Double Support Time Variability (ms)	14.20 (5.23)	5.22 – 41.67
Stance Time (ms)	635.20 (75.97)	495.70 – 866.67
Stance Time Variability (ms)	25.56 (8.36)	13.30 – 52.57
Step Time (ms)	581.62 (61.88)	455.15 – 762.50
Step Time Variability (ms)	27.02 (10.65)	10.20 – 64.96
Step Length (cm)	62.98 (6.95)	48.10 – 82.94
Step Length Variability (cm)	3.14 (0.95)	1.71 – 6.79
Cognitive Measures		
Response Conflict mean RT (ms)	669.78 (225.10)	351.80 – 1339.71
Response Conflict mean Variability(ms)	254.81 (189.00)	53.73 – 771.84
Perceptual Conflict mean RT(ms)	645.90 (125.12)	403.21 – 964.74
Perceptual Conflict mean Variability (ms)	152.79 (73.39)	47.09 – 475.09

Table 2

Pearson partial correlation coefficients between temporal gait variability and cognitive variability.

Gait Variability Measure	Cognitive Variability Measure	Pearson Correlation Coefficient (<i>r</i>)	<i>p</i> value
Double Support Time	Response Conflict	−0.188	0.122
Stance Time	Response Conflict	−0.161	0.188
Step Time	Response Conflict	−0.029	0.815
Step Length	Response Conflict	−0.177	0.143
Double Support Time	Perceptual Conflict	−0.184	0.131
Stance Time	Perceptual Conflict	−0.087	0.477
Step Time	Perceptual Conflict	−0.108	0.378
Step Length	Perceptual Conflict	−0.155	0.200