

Original Research Report

The Role of Movement-Specific Reinvestment in Visuomotor Control of Walking by Older Adults

Liis Uiga, PhD,^{1,2} Catherine M. Capio, PhD,^{1,2} Donghyun Ryu, PhD,³ William R. Young, PhD,⁴ Mark R. Wilson, PhD,⁵ Thomson W. L. Wong, PhD,¹ Andy C. Y. Tse, PhD,⁶ and Rich S. W. Masters, DPhil^{1,2}

¹School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong. ²Te Huataki Waiora Faculty of Health, Sport and Human Performance, University of Waikato, Hamilton, New Zealand. ³Institute for the Psychology of Elite Performance, School of Sport, Health and Exercise Sciences, Bangor University, UK. ⁴College of Health and Life Sciences, Brunel University, London, UK. ⁵College of Life and Environmental Sciences, University of Exeter, UK. ⁶Department of Health and Physical Education, The Education University of Hong Kong, Hong Kong.

Address correspondence to: Liis Uiga, PhD, Te Huataki Waiora Faculty of Health, Sport and Human Performance, University of Waikato, Private Bag 3105, Hamilton 3240, NZ. E-mail: liisu@waikato.ac.nz.

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Abstract

Objectives: The aim of this study was to examine the association between conscious monitoring and control of movements (i.e., movement-specific reinvestment) and visuomotor control during walking by older adults.

Method: The Movement-Specific Reinvestment Scale (MSRS) was administered to 92 community-dwelling older adults, aged 65–81 years, who were required to walk along a 4.8-m walkway and step on the middle of a target as accurately as possible. Participants' movement kinematics and gaze behavior were measured during approach to the target and when stepping on it.

Results: High scores on the MSRS were associated with prolonged stance and double support times during approach to the stepping target, and less accurate foot placement when stepping on the target. No associations between MSRS and gaze behavior were observed.

Discussion: Older adults with a high propensity for movement-specific reinvestment seem to need more time to “plan” future stepping movements, yet show worse stepping accuracy than older adults with a low propensity for movement-specific reinvestment. Future research should examine whether older adults with a higher propensity for reinvestment are more likely to display movement errors that lead to falling.

Keywords: Attention, Conscious monitoring and control, Falls and mobility problems, Skill.

Most falls by older adults occur during locomotion (Berg, Alessio, Mills, & Tong, 1997; Prince, Corriveau, Hébert, & Winter, 1997; Rubenstein, 2006). Falling can cause diminished physical, psychological, and social functioning (van der Meulen, Zijlstra, Ambergen, & Kempen, 2014), so older adults often display increased motivation to walk safely, which manifests as increased conscious processing of locomotor movements. Evidence suggests that conscious

processing can disrupt the automaticity of well-learned movements and increase, rather than reduce, the probability of movement errors (Masters & Maxwell, 2008).

According to the theory of reinvestment (Masters, 1992; Masters & Maxwell, 2008; Masters, Polman, & Hammond, 1993), “... relatively automated motor processes can be disrupted if they are run using consciously accessed, task-relevant declarative knowledge to control the mechanics

of the movements on-line” (Masters & Maxwell, 2008, p. 160). The process of conscious, step-by-step movement processing, which is thought to utilize resources of working memory (Baddeley, 2007), can slow performance and raise opportunity for movement errors (Beilock & Carr, 2001; Masters & Maxwell, 2008). The theory of reinvestment proposes that the tendency to consciously process movements (i.e., movement-specific reinvestment) is a function of personality, situation, and environment and therefore varies from one person to another and from one situation to another (Masters & Maxwell, 2008; Masters et al., 1993).

There is increasing evidence of an association between movement-specific reinvestment and older age during locomotion. For example, Wong, Masters, Maxwell, and Abernethy (2008) and Wong, Masters, Maxwell, and Abernethy (2009) showed that older adults who had previously fallen displayed higher propensity for movement-specific reinvestment and increased awareness of their limb movements during walking, compared with older adults who had not fallen. Uiga, Capio, Wong, Wilson, and Masters (2015) extended these findings by showing that older adults who had not fallen, yet displayed a high propensity for movement-specific reinvestment, displayed increased awareness of their own limb movements and decreased awareness of the external environment during walking, compared with older adults with a low propensity for movement-specific reinvestment. Comparable results were recently reported by Young, Olonilua, Masters, Dimitriadis, and Williams (2016), who showed that older adults who stopped walking when talking displayed higher individual propensities for movement-specific reinvestment and allocated more attention to movement processing. Overall, these results suggest that a high propensity for movement-specific reinvestment in older adults is associated with movement focused attention, which is potentially accompanied by online processing of visuomotor information deemed to be important for successful walking behavior. To date, no research has specifically examined the relationship between the propensity for movement-specific reinvestment and visuomotor control during walking by older adults.

Although healthy walking typically is thought to involve minimal conscious control (i.e., to be automatic), age-related changes in cognitive and physical functioning, have been proposed to lead to a locomotor strategy that is characterized by compensatory conscious processes (Clark, 2015). For example, in older adults compared with young adults, increased brain activation and decreased interhemispheric inhibition during postural and locomotor tasks have been reported (Papegaaij, Taube, Baudry, Otten, & Hortobágyi, 2014; Zwergal et al., 2012). It has been suggested that increased brain activation is used to compensate for structural and functional changes in other areas of the brain and allows for allocation of greater neuronal resources to maintain performance levels (Mattay et al., 2002; Ward & Frackowiak, 2003). However, not all older

adults show increased activation or decreased interhemispheric inhibition, which implies that there are differences within the elderly population (Cabeza, 2002). We believe that these differences can partially be explained by individual differences in the propensity that people have for conscious monitoring and control of their movements.

Conscious processes are attention demanding and slow (compared with nonconscious or reflexive processes), and utilize working memory capacity (Beilock & Carr, 2001; Masters & Maxwell, 2008; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Consequently, conscious processes are likely to lead to decrements in walking performance (Clark, 2015). For example, older adults need more time to plan their stepping movements than young adults (Chapman & Hollands, 2006, 2010), yet they exhibit worse stepping accuracy (Caetano et al., 2016). It has been suggested that the locomotor control system benefits from feed-forward planning of limb movements in tasks that require accurate stepping (Hollands & Marple-Horvat, 1996, 2001; Patla, Adkin, Martin, Holden, & Prentice, 1996). Hollands and Marple-Horvat (1996) argued that “... the neural computations to swing the leg accurately to a target are largely in place by the time that the foot lifts from the ground ...” (p. 354). It is ironic that taking more time to plan a targeting step results in worse foot placement accuracy. These findings suggest that conscious control of movements, as well as information processing speed and working memory capacity, are likely to play an important role in movement preparation by older adults.

Research has additionally stressed the importance of online control for fine-tuning foot placement following the preparatory stance phase (Chapman & Hollands, 2006, 2007; Reynolds & Day, 2005; Young & Hollands, 2010; Young, Wing, & Hollands, 2012). For example, Reynolds and Day (2005) demonstrated that when vision was removed during the swing phase before stepping on a target, decrements in stepping accuracy occurred. Furthermore, early gaze transfer away from a target, in order to plan future actions, has been found to correlate positively with stepping errors (Chapman & Hollands, 2006, 2007; Young & Hollands, 2010; Young et al., 2012). Chapman and Hollands (2006) argued that this maladaptive gaze behavior is likely to be adopted to compensate for attention deficits, anxiety or other concerns about future movements. As movement-specific reinvestment normally increases in situations in which people are highly motivated to perform well, it is likely to be associated with online control of movements in situations that require planning of threat-related future actions (e.g., avoid stumbling across obstacles after stepping on a target).

We have argued that conscious processes that are slow, demanding, and consume working memory capacity, are likely to be closely linked with visuomotor control during walking by older adults. However, the direct relationship between these variables is unknown. The primary aim of this experiment was to investigate the association between

the propensity for conscious processing of movements (measured by the Movement-Specific Reinvestment Scale; Masters, Eves, & Maxwell, 2005) and visuomotor control during walking by older adults. We asked older adults to walk along a walkway, during which they were required to step on the middle of a stepping target as accurately as possible before continuing to walk between two obstacles. We measured walking kinematics and gaze behavior during approach to the target and when stepping on the target. Based on previous literature, we expected scores on the MSRS to be associated with movement kinematics and gaze behavior during preparatory movement planning and during online control when finalizing foot placement. Specifically, we expected higher scores on the scale to be associated with longer preparatory stance times and earlier gaze transfer from the target to plan future stepping movements. The secondary aim of the experiment was to examine the relationship between movement kinematics and gaze behavior and levels of anxiety, balance confidence, processing speed, task-switching and verbal and visuospatial working memory capacity.

Method

Participants

Ninety-two Hong Kong community-dwelling older adults participated in the experiment (Mean age = 69.23 years, $SD = 3.67$ years, range = 65–81 years). Participants were recruited via local elderly community centers and by word-of-mouth. The experimental protocol was approved by the institutional ethics committee and written informed consent was obtained from all participants before data collection.

Participants were first contacted over the telephone and asked to respond to questions about their medical history and mobility. Participants were excluded from the experiment if they reported any physical or neurological impairment, used medications with potential to affect balance and/or used walking aids. Upon arrival at the laboratory, participants were further screened. The mobility and physical functioning of the participants was measured using the Timed Up-and-Go test (Podsiadlo & Richardson, 1991). Participants were excluded from the study if they took more than 20 s to complete the task (Mean time = 10.33, $SD = 1.78$) and/or showed instability when turning. Older adults able to complete the TUG test within 20 s have been argued to have sufficiently good mobility to walk in the community and show independence in activities of daily living (Podsiadlo & Richardson, 1991). Cognitive functioning was measured using the Cantonese version of the Mini-Mental State Examination (MMSE; Chiu, Lee, Chung, & Kwong, 1994; Folstein, Folstein, & McHugh, 1975). Participants were excluded from the study if they scored less than 24/30. A score lower than 24 is generally considered to be an indicator of cognitive impairment (Tombaugh & McIntyre, 1992). Visual acuity was assessed using a Tumbling E eye chart. Participants were excluded

from the study if they had static visual acuity worse than 20/40. Additionally, participants were excluded if they failed Ishihara's color blindness test (Ishihara, 1917) or if they reported difficulty when questioned by the experimenter in distinguishing between high (1,000 Hz) and low (500 Hz) pitched tones presented via computer speakers (indicative of hearing loss).

Apparatus

Participants were asked to wear their own flat-soled comfortable shoes. Ball-shaped reflective markers were instrumented on each foot on the following bony landmarks: dorsomedial aspect of the first metatarsal head, dorsolateral aspect of the fifth metatarsal head, posterior projection of the calcaneus, and anterior projection of the space between the second and third metatarsal heads.

The position of each marker was tracked using a three-dimensional Qualisys ProReflex motion capture system (Qualisys AB, Gothenburg, Sweden) at a sampling frequency of 120 Hz. The system incorporated six infrared cameras that were positioned around the testing area (Figure 1). The system was calibrated to a measurement volume ca 1.5 m high, 4.5 m long, and 2 m wide. Data were transferred to Qualisys Track Manager software and later analyzed using MATLAB (Mathworks, Inc., MA).

A binocular head-mounted EyeLink II (SR Research Ltd, Mississauga, ON) eye-tracker was used to record eye movements. The system was calibrated and validated by asking each participant to trace and fixate target dots on a

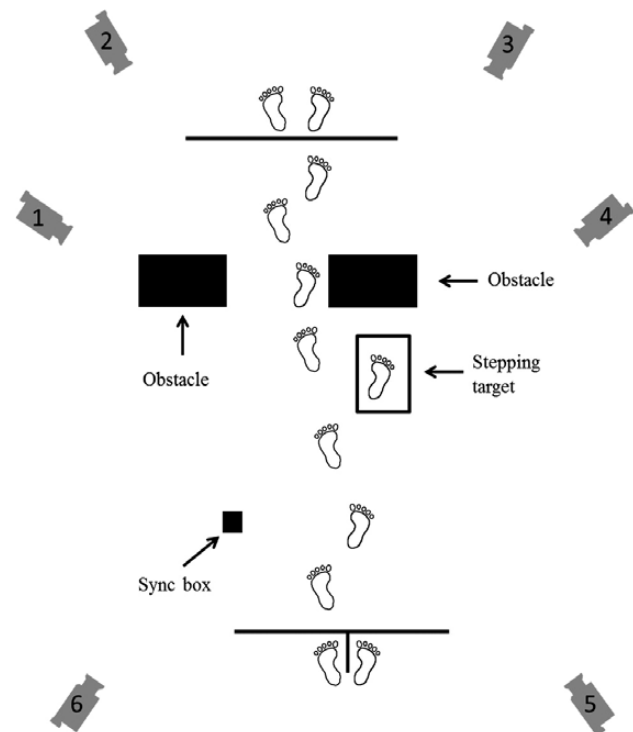


Figure 1. Schematic diagram of the experimental setup.

13-point reference grid and corrected by using a depth-correction option. The Scene Camera option allowed for documentation of participant's eye movements in relation to a video image recorded by a forwards facing head-mounted scene camera at a sampling frequency of 30 Hz. The frame-by-frame analysis was subsequently used to determine the location of eye movements.

Motion capture and eye-tracking systems were synchronized, and the experiment was controlled using a customized software program designed in LabVIEW Application Builder 2010 (National Instruments, Inc.).

Setup and Procedure

Participants were fitted with the eye-tracker and reflective markers and were required to walk along a 4.8-m walkway at their own comfortable pace. The walkway contained a stepping target and two obstacles (Figure 1). The stepping target (43 cm length \times 27.2 cm width \times 0.5 cm height) was made of high-density red foam and was positioned 2 m from the starting line. Participants were asked to step on the stepping target by positioning the middle of their right foot in the center of the target (marked with a small red sticker) as accurately as possible. The two obstacles (34 cm length \times 22.5 cm width \times 28.5 cm height/36 cm length \times 24 cm width \times 14 cm height) were made of plastic that was covered with paper and were positioned 82 cm apart. The distance between the target and the obstacle behind it was 26 cm. Neither the target nor the obstacles were fixed to the floor to prevent tripping if a participant's foot came into contact with them. Each trial was initiated by a light that was positioned on top of a box (23 cm length \times 17.5 cm width \times 14.5 cm height) that was placed to the left of the participant, approximately 1 m from the starting line. Participants were asked to fixate on the light at the start of each trial and instructed to start walking when the light switched off.

Participants completed 30 walking trials. During 20 of the trials, one auditory probe (either 500 Hz or 1,000 Hz) was initiated at a random time during the walk. Following probe trials, participants were required to answer yes/no attention focus questions (i.e., internal, external, and body location questions) related to the moment at which the auditory probe occurred. The aim of this part of the study was to examine the relationship between movement-specific reinvestment and attention during locomotion by older adults. The findings related to attention focus have been reported in another previously published article (Uiga et al., 2015).

During the remaining 10 trials, there were no auditory tones and participants were simply instructed to walk along the walkway and step on the middle of the stepping target as accurately as possible. We emphasized our instructions very clearly and ensured that participants were convinced that no tones would be presented. For the purpose of this study, we analyzed the data for the 10 trials in which no

We found that the majority of the kinematic and gaze outcome variables were significantly different between the 20 trials during which attention focus questions were asked and the 10 trials during which no attention focus questions were asked. We decided to analyze the data for the 10 trials only, therefore avoiding potential confounding of probed attention focus.

Dependent Variables and Data Analyses

The Chinese version of the Movement-Specific Reinvestment Scale (MSRS; Masters et al., 2005; Wong et al., 2008, 2009) was used to measure individual predisposition for conscious monitoring and control of movement (i.e., movement-specific reinvestment). The scale comprises 10 items divided into two subscales. The Conscious Motor Processing subscale measures the individual propensity to consciously control movements (e.g., "I am always trying to think about my movements when I carry them out"). The Movement Self-consciousness subscale measures the individual propensity to monitor "style" of movement (i.e., movement awareness) and making a good impression when moving in public (e.g., "I am concerned about my style of moving"). The items are rated on a 6-point Likert scale from *strongly disagree* (1) to *strongly agree* (6). Thus, cumulative scores ranged from 10 to 60, with higher scores reflective of higher propensity for movement-specific reinvestment. The MSRS has been shown to have high internal consistency and test-retest reliability (Masters & Maxwell, 2008). The internal consistency of the Scale in the present study, as measured using Cronbach's alpha, was found to be good ($\alpha = .898$).

Self-confidence related to postural balance was measured using the Chinese version of the Activities-specific Balance Confidence (ABC) Scale (Mak, Lau, Law, Cheung, & Wong, 2007; Powell & Myers, 1995). The ABC Scale assesses self-perceived confidence in ability to maintain balance during a range of indoor and outdoor functional activities (e.g., "How confident are you that you will not lose your balance or become unsteady when you walk up or down stairs?"). The scale comprises 16 items that are rated using a 0% to 100% distribution for level of confidence in performing the tasks, with 100% the highest level of confidence.

Levels of anxiety were measured using the anxiety subscale of the Chinese version of the Hospital Anxiety and Depression Scale (HADS; Leung, Ho, Kan, Hung, & Chen, 1993; Zigmond & Snaith, 1983). The 14-item scale consists of two subscales that measure anxiety and depression, respectively. The items are rated on the scale from 0 to 3. Scores for each subscale range from 0 to 21, with higher scores indicative of higher levels of anxiety or depression, respectively.

The trail making test (TMT A and B; Partington & Leiter, 1949) was used to measure speed of cognitive processing and executive functioning. TMT-A required

participants to draw a line connecting a series of encircled Arabic numbers from 1 to 25 on a sheet of paper as quickly and accurately as possible. TMT-B required participants to draw a line connecting a series of encircled Arabic numbers and Chinese numbers (e.g., 1 to 一, 一 to 2, 2 to 二, 二 to 3, 3 to 三) as quickly and accurately as possible (Lu & Bigler, 2000). The amount of time required to complete the task represents the task performance, with longer times reflective of worse performance. TMT-A score has been argued to reflect the level of visual search and perceptual speed, whereas TMT-B score reflects the level of executive functioning, task-switching in particular (Sanchez-Cubillo et al., 2009).

Verbal working memory performance was assessed using a backwards digit span test (Ramsay & Reynolds, 1995). The test required participants to listen to a sequence of numbers and subsequently verbally report the sequence in reversed order. The length of the sequence increased by one item until the participant failed to recite the sequence correctly on two consecutive attempts. The longest sequence that a participant was able to correctly reproduce marked verbal working memory performance.

Visuospatial working memory performance was assessed using a reversed Corsi Block tapping test (Corsi, 1972). The Corsi apparatus consisted of nine black blocks that were mounted on a board. The task required participants to memorize a sequence of blocks tapped by the examiner and reproduce the sequence in reversed order. The length of the sequence increased by one until the participant failed to recite the sequence correctly on two consecutive attempts. The longest sequence that participant was able to correctly reproduce marked visuospatial working memory performance.

Movement Kinematics

Kinematic data were filtered at a low cut off frequency set at 10 Hz. "Heel contact" and "toe off" events were identified using a protocol employed by Hreljac and Marshall (2000) and subsequently by Young and Hollands (2010) and Young and colleagues (2012). Toe off was defined by the minimum vertical displacement of the toe marker. Heel contact was defined by the maximum vertical acceleration of the heel marker. "Stance" phases were defined by the time difference between the heel contact and toe off. "Swing" phases were defined by the time difference between toe off and heel contact. "Double support" phases were defined by the time duration when both feet were in ground contact (i.e., time difference between heel contact of the front foot and toe off of the back foot). Foot placement error was defined by the absolute distance between the center of the target and the middle of the foot (i.e., mid-point between the heel and the toe markers and the first and the fifth metatarsal) at the time of foot contact on the target. Foot placement variability was calculated by taking the standard deviation of foot placement error for all completed trials.

Gait speed was calculated by taking the mean velocity of the center-of-mass marker over a 3-m section that started 2 m before the target. The primary dependent kinematic variables calculated were: (a) foot placement error; (b) foot placement variability; (c) mean stance duration for preceding right foot; (d) mean stance duration for preceding left foot; (e) mean stance duration on the target; (f) mean swing duration of the targeting right foot; (g) mean swing duration of the targeting left foot; (h) mean double support duration pretarget; (i) mean double support duration on target; and (j) gait speed.

Gaze Behavior

For each data sample, the EyeLink Data Viewer computed instantaneous velocity and acceleration that were compared with set thresholds of 30 degrees of visual angle per second for velocity and 8,000 degrees of visual angle per second squared for acceleration. Saccade onset occurred when either of these thresholds was exceeded. Saccade offset occurred when the eye movements dropped back to below the set thresholds. That time point was also marked as the time of fixation onset. The duration of total gaze fixation on the target, obstacle or other items outside the walkway was calculated as the sum of each fixation occurring between the end of the saccade made to a relevant item and the start of the next saccade away from that particular item. Additionally, the time of gaze transfer away from the target in respect to heel contact inside the target was calculated. The primary dependent gaze variables calculated were: (a) total fixation duration on target; (b) last fixation duration on target; (c) fixation duration on walkway before target; (d) fixation duration on obstacle behind the target; (e) fixation duration on items outside the walkway; and (f) early gaze transfer (i.e., time difference between gaze transfer off target and heel contact on target).

Statistical Analysis

Correlation and regression analyses were conducted to examine the relationship between movement kinematics, gaze behavior, MSRS and levels of anxiety, balance confidence, processing speed, task-switching and verbal and visuospatial working memory capacity. First, partial Pearson's product-moment correlation coefficients were used to calculate estimates adjusted for age, gender, and MMSE scores. Significant correlations were then followed up by separate stepwise linear regression analyses to determine the independent contributions of the MSRS, anxiety, balance confidence, processing speed, task-switching and verbal and visuospatial working memory capacity to stepping behavior, and gaze control. At Step 1, age, gender, and MMSE scores were entered to control for their effect. At Step 2, variables that were significantly correlated either with the kinematic or gaze measures were entered. Data were checked for outliers using Cook's distance, and none

of the cases were found to have a value greater than 1, a value that has been recommended as a reason for concern. Data were further checked for normality, linearity, homoscedasticity, and multicollinearity. Violations, if any, are reported in the Results section. To account for multiple comparisons, the Benjamini–Hochberg procedure was employed, with the false discovery rate set at the 5% level (Benjamini & Hochberg, 1995).

Results

Table 1 presents the characteristics of participants. Ninety-two participants were tested, but technical limitations precluded use of movement kinematics data for 7 participants and gaze data for 31 participants. Movement kinematics data were lost due mainly to overlapping reflective markers that hindered tracing foot motion. Eye movement data were lost mainly during the downwards saccade when pupil detection was impaired.

Significant correlations were found between MSRS and foot placement error ($r = .31, p = .006$), right foot stance duration ($r = .24, p = .031$), left foot stance duration ($r = .38, p = .001$), on target stance duration ($r = .25, p = .028$), double support duration before target ($r = .23, p = .042$), and double support duration on target ($r = .32, p = .004$). HADS-anx was found to be significantly correlated with time spent fixating on the walkway in front of the target ($r = .43, p = .002$) and fixation duration outside the walkway ($r = -.29, p = .041$). No other significant correlations were evident between kinematic or gaze variables and anxiety, balance confidence, processing speed, task-switching or verbal and visuospatial working memory capacity (Table 2).

Table 1. Characteristics of Participants ($n = 92$) Presented as Mean (SD) or Percentage Values

Variables	Mean (SD) or %
Demographic data	
Age	69.23 (3.67)
Gender	81.5% F; 18.5% M
Height (cm)	155.28 (6.69)
Weight (kg)	56.87 (9.35)
Cognitive and physical function	
Movement-Specific Reinvestment Scale (/60)	30.89 (13.88)
Mini Mental State Examination (/30)	29.21 (0.99)
Hospital Anxiety and Depression Scale, anxiety subscale (/21)	4.18 (2.83)
Trail making test part A (s)	47.21 (16.15)
Trail making test part B (s)	81.44 (41.34)
Verbal working memory span (backwards)	4.67 (1.72)
Visuospatial working memory span (reversed)	5.01 (0.76)
Activities-specific Balance Confidence Scale (/100%)	86.74 (12.28)

Significant correlations were followed up by separate stepwise linear regression analyses. Supplementary Figure 1 presents the regression coefficients (B), standard error of regression coefficient ($SE B$), beta coefficients (β), and model statistics ($R, R^2, \Delta R^2$).

MSRS and Movement Kinematics

When age, gender, and MMSE scores were controlled for, significant regression models were found for foot placement error [$F(4, 80) = 3.359, p = .014$], for left foot stance duration [$F(4, 80) = 7.120, p = .001$], and for double support duration on target [$F(4, 80) = 7.476, p = .011$], with higher scores on the MSRS associated with larger foot placement error and longer stance and double support durations. Nonsignificant models were found for right foot stance duration [$F(4, 80) = 2.295, p = .066$], for on target stance duration [$F(4, 80) = 1.905, p = .118$], and for double support duration pretarget [$F(4, 80) = 1.247, p = .298$].

HADS-anx and Fixation Durations

When age, gender, and MMSE scores were controlled for, a significant regression model was found for fixation duration pretarget [$F(4, 55) = 4.533, p = .003$], with higher levels of anxiety associated with longer time spent fixating the walkway in front of the target. A nonsignificant regression model was found for fixation duration outside walkway [$F(4, 55) = 1.806, p = .141$]. A visual examination of the scatterplot and histogram suggested that the assumption of normality was violated. This result likely occurred because the majority of the participants ($n = 41$) did not fixate on anything else besides the items on the walkway.

Discussion

The primary aim of the experiment was to explore the relationship between propensity for movement-specific reinvestment (i.e., inclination for conscious monitoring and control of their movements) and visuomotor control during walking by older adults. We expected movement-specific reinvestment, as measured by the MSRS, to be associated with preparatory and online control phases of movement execution when stepping on a target. Our results clearly confirm that the propensity for movement-specific reinvestment plays a role in the preparatory phase of accurate movement planning. In particular, MSRS was positively associated with left foot and double support stance times before stepping on a target. It has been shown previously that older adults, especially those at high risk of falling, need more time to plan their stepping movements, yet display worse stepping accuracy (Caetano et al., 2016; Chapman & Hollands, 2006, 2010; Uemura, Yamada, Nagai, & Ichihashi, 2011). Consistent with the literature, we show that older adults with a high propensity

Table 2. Correlation Matrix for Cognitive and Physical Function Tests and Kinematic and Gaze Variables During Walking

Variables	MSRS	ABC	HADS-anx	TMT-A	TMT-B	VM-span	SM-span
MSRS ($n = 92$)		-0.12	0.11	-0.06	-0.16	-0.01	-0.04
Kinematic variables ($n = 85$)							
Foot placement error	0.31*	-0.04	-0.07	-0.01	-0.08	0.07	0.04
Foot placement variability	0.12	0.05	-0.15	-0.05	-0.05	-0.12	-0.16
Right foot stance	0.24*	-0.04	0.12	0.06	-0.14	-0.02	0.01
Left foot stance	0.38*	-0.02	0.07	0.03	-0.13	0.03	-0.09
In target stance	0.25*	-0.04	0.07	0.07	-0.09	0.01	-0.004
Right foot swing	0.14	0.09	0.12	0.02	-0.05	-0.17	-0.09
Left foot swing	0.14	0.04	0.12	0.04	-0.09	-0.12	0.18
Double support pre target	0.23*	-0.11	0.06	0.002	-0.13	0.06	0.12
Double support in target	0.32*	-0.03	-0.05	0.03	-0.07	0.18	-0.18
Gait speed	-0.15	-0.16	0.22	0.12	0.22	-0.02	0.01
Gaze variables ($n = 61$)							
Fixation duration on target	0.12	0.15	0.13	-0.23	-0.20	0.21	-0.07
Last fixation duration on target	0.11	0.16	0.04	-0.19	-0.17	0.22	-0.15
Fixation duration before target	0.07	-0.17	0.43*	0.21	-0.02	-0.12	-0.22
Fixation duration on obstacle	0.22	0.10	0.08	0.009	-0.07	0.11	0.06
Fixation duration outside walkway	-0.21	0.19	-0.29*	-0.12	-0.09	0.24	0.05
Early gaze transfer	0.06	0.05	0.20	-0.25	-0.15	0.25	0.03

Note. MSRS = Movement-Specific Reinvestment Scale; ABC = Activities-specific Balance Confidence Scale; HADS-anx = Hospital Anxiety and Depression Scale = anxiety subscale; TMT-A and TMT-B = trail making test part A and part B, respectively; VM-span = verbal working memory span; SM-span = visuospatial working memory span.

* $p \leq .05$.

for movement-specific reinvestment spend more time planning the targeting step, with less accurate outcomes. During walking, and other complex multijoint movements, central and peripheral information has to be rapidly and accurately integrated to ensure effective movements; however, conscious control of movements prolongs processing and delivery of such information to the cerebrum and can result in inefficient neural commands (Clark, 2015). This potentially explains our findings; however, an alternative explanation is that older adults with a high propensity for movement-specific reinvestment are less able to inhibit the execution of inappropriate motor responses. It is likely that high propensity for consciously processing movement mechanics places demands on working memory that lead to inefficient information processing characterized by decreased inhibitory abilities (Richardson, Eckner, Allet, Kim, & Ashton-Miller, 2017). Schoene, Delbaere, and Lord (2017) have provided partial support for this idea by demonstrating that poor response inhibition is associated with falls in older adults. Future research should, therefore, examine whether inhibition ability moderates the relationship between movement-specific reinvestment and walking by older adults.

We also found no association between MSRS and swing times. Previous research has suggested that conscious processes play a minimal role during that particular phase of a stepping cycle (Hollands & Marple-Horvat, 1996). Perhaps due to its more demanding nature (one-leg support), the swing phase is relatively more difficult to consciously control.

Uiga and colleagues (2015) have previously shown that older adults with a high propensity for movement-specific reinvestment are more aware of their limb movements and less aware of the external environment during walking than older adults with a low propensity for movement-specific reinvestment. Our results extend these findings by showing that this kind of propensity is negatively associated with movement planning and movement execution. Taken together with Wong et al.'s (2008, 2009) finding that older adults with a history of a falling had a significantly higher propensity for reinvestment than older adults without a history of a falling, these findings suggest that older adults with a high propensity for movement-specific reinvestment are likely to miss relevant information in the environment and adopt maladaptive kinematic strategies during walking. This kind of behavior poses a risk for falling, in our view.

We found, however, no evidence that movement-specific reinvestment was related to online control when fine-tuning accurate stepping. That is, MSRS score was not significantly correlated with early gaze transfer from the target with respect to heel contact. This finding suggests that once the movement is planned, there is no need or possibility for consciousness to interfere. However, we recommend caution when interpreting these results, as there is a possibility that the task participants were required to perform was not difficult enough for movement-specific reinvestment to play a role in online control. Previous research has suggested that the extent of early gaze transfer depends on task difficulty. Chapman and Hollands (2007) found that

there were no age-related differences in gaze transfer away from the target with respect to heel contact when there was only one target to step on. However, under double target and obstacle walking conditions older adults at high risk of falling transferred their gaze away from the target significantly earlier than older adults at low risk of falling or young adults. This suggests that when multiple constraints are present, older adults at high risk of falling compensate for worry about their future movements by dividing their attention between the tasks to plan upcoming movements before finalizing on-going ones. In our experiment, participants performed only one accurate stepping movement, which potentially eliminated pressure related to the performance of future movements.

The secondary aim of this experiment was to investigate the relationship between movement kinematics, gaze behavior and anxiety, balance confidence, processing speed, task-switching, and verbal and visuospatial working memory capacity during walking by older adults. Our results showed that levels of anxiety were positively associated with time spent fixating the walkway in front of the target. These results suggest that a strategy employed by older adults to compensate for high anxiety was to fixate the walkway close to their own limbs rather than to direct their gaze directly to the target. We found, however, no direct relationship between anxiety and foot placement error. Similar findings were reported by [Young and colleagues \(2012\)](#), who proposed that anxiety indirectly influences stepping accuracy by encouraging maladaptive gaze strategies.

Additionally, we found that cognitive functions, such as task-switching, processing speed, and working memory capacity, were not associated with movement kinematics and gaze behavior during walking by older adults. These findings are not consistent with some studies (e.g., [Ble et al., 2005](#); [Di Fabio et al., 2005](#); [Holtzer, Verghese, Xue, & Lipton, 2006](#)). For example, [Di Fabio and colleagues \(2005\)](#) showed that older adults with low cognitive functioning made more stepping errors compared with older adults with high cognitive functioning. [Ble and colleagues \(2005\)](#) found that older adults who scored relatively poorly on a trail making test showed reductions in gait speed on a 7-m obstacle-walking course compared with older adults who showed good performance on the test. However, they found no differences between the participants on a simple 4-m course that contained no obstacles. These findings suggest that cognitive functions play a particularly important role during more complex walking tasks that place higher demands on cognitive control than the one we used.

Interestingly, our results revealed no significant relationship between the MSRS and anxiety, processing speed, task-switching, and verbal and visuospatial working memory capacity. This is surprising given that reinvestment is thought to be a function of accessibility to declarative knowledge via working memory and occurs in people worried or anxious about their movement execution ([Masters & Maxwell, 2008](#)). The limited evidence available

on the relationship between MSRS and working memory has reported inconsistent findings. [Buszard, Farrow, Zhu, and Masters \(2013\)](#), for example, found that verbal working memory capacity in children was positively associated with their propensity for movement-specific reinvestment. They also found a positive association in young adults but only for the movement self-consciousness component of the MSRS. On the other hand, in a recent study by [Laborde, Furley, and Schempp \(2015\)](#), no association was found between working memory and MSRS; however, a negative relationship between working memory and the Decision-Specific Reinvestment Scale (DSRS; [Kinrade, Jackson, Ashford, & Bishop, 2010](#)) was reported. Future research should address this issue.

This study is not without limitations. Walking trials with tones were interspersed with walking trials without tones. It is possible that trials with tones, which required cognitive effort, affected walking performance on trials without tones. Furthermore, the level of effort required during trials with tones might have differed between participants as a function of individual differences in listening effort. Effort can impose a cognitive burden that may negatively impact other domains of functioning (e.g., [Pichora-Fuller et al., 2016](#)). Future studies should, therefore, employ objective measures of hearing ability. Additionally, a significant proportion of eye-tracking data were lost due to technical limitations. This is not uncommon; however, it does raise the question of whether certain eye movement behaviors went unnoticed. We found no differences in MSRS scores between participants for whom data were lost or not lost. We, therefore, believe that the lost data did not affect the results of the present study. Finally, we did not measure visuomotor control of walking when participants navigated through the obstacles. Although we think that this is an interesting question, the obstacles in the study were included to simply necessitate pre-emptive visual search during approach to the target, not to form the basis for objective appraisal of walking performance. As participants were not required to step over an obstacle or into any subsequent targets, we decided that it would be difficult to quantify performance when navigating the obstacles.

To conclude, our experiment clearly shows that there is a relationship between the individual propensity for movement-specific reinvestment and visuomotor control during walking. Specifically, high propensity for reinvestment was associated with longer stance and double support times before stepping on a target and with worse foot placement error. It should be noted, however, that the associations between the MSRS and preparatory movement planning were clear but weak, with MSRS uniquely predicting only a small proportion of the variance in movement outcomes (between 8% and 12%). These results suggest that there are other underlying mechanisms that, either in combination with or in isolation from MSRS, determine the specifics of visuomotor control during walking by older adults. Nevertheless, the results suggest that older adults with a high propensity for movement-specific reinvestment are prone to stepping errors that might lead to future falls. The

causality between reinvestment and falling in older adults, however, is yet to be examined.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences* online.

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Conflict of interest

The authors confirm that there are no conflicts of interest.

References

- Baddeley, A. (2007). *Working memory, thought, and action*. New York, NY: Oxford University Press.
- Beilock, S. L., & Carr, T. H. (2001). On the fragility of skilled performance: What governs choking under pressure? *Journal of Experimental Psychology: General*, *130*, 701–725. doi:10.1037/0096-3445.130.4.701
- Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society: Series B*, *57*, 289–300. doi:10.2307/2346101
- Berg, W. P., Alessio, H. M., Mills, E. M., & Tong, C. (1997). Circumstances and consequences of falls in independent community-dwelling older adults. *Age and Ageing*, *26*, 261–268. doi:10.1093/ageing/26.4.261
- Ble, A., Volpato, S., Zuliani, G., Guralnik, J. M., Bandinelli, S., Lauretani, E.,...Ferrucci, L. (2005). Executive function correlates with walking speed in older persons: The InCHIANTI study. *Journal of the American Geriatrics Society*, *53*, 410–415. doi:10.1111/j.1532-5415.2005.53157.x
- Buszard, T., Farrow, D., Zhu, F. F., & Masters, R. S. W. (2013). Examining movement specific reinvestment and working memory capacity in adults and children. *International Journal of Sport Psychology*, *44*, 351–366. doi:10.7352/IJSP2013.44.351
- Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*, 85–100. doi:10.1037/0882-7974.17.1.85
- Caetano, M. J., Lord, S. R., Schoene, D., Pelicioni, P. H., Sturnieks, D. L., & Menant, J. C. (2016). Age-related changes in gait adaptability in response to unpredictable obstacles and stepping targets. *Gait & Posture*, *46*, 35–41. doi:10.1016/j.gaitpost.2016.02.003
- Chapman, G. J., & Hollands, M. A. (2006). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture*, *24*, 288–294. doi:10.1016/j.gaitpost.2005.10.002
- Chapman, G. J., & Hollands, M. A. (2007). Evidence that older adult fallers prioritise the planning of future stepping actions over the accurate execution of ongoing steps during complex locomotor tasks. *Gait & Posture*, *26*, 59–67. doi:10.1016/j.gaitpost.2006.07.010
- Chapman, G. J., & Hollands, M. A. (2010). Age-related differences in visual sampling requirements during adaptive locomotion. *Experimental Brain Research*, *201*, 467–478. doi:10.1007/s00221-009-2058-0
- Chiu, H. F. K., Lee, H. C., Chung, W. S., & Kwong, P. K. (1994). Reliability and validity of the Cantonese version of mini-mental state examination—A preliminary study. *Hong Kong Journal of Psychiatry*, *4*, 25–28.
- Clark, D. J. (2015). Automaticity of walking: Functional significance, mechanisms, measurement and rehabilitation strategies. *Frontiers in Human Neuroscience*, *9*, 246. doi:10.3389/fnhum.2015.00246
- Corsi, P. M. (1972). Human memory and the medial temporal region of the brain. *Dissertation Abstracts International*, *34*, 819B.
- Di Fabio, R. P., Zampieri, C., Henke, J., Olson, K., Rickheim, D., & Russell, M. (2005). Influence of elderly executive cognitive function on attention in the lower visual field during step initiation. *Gerontology*, *51*, 94–107. doi:10.1159/000082194
- Folstein, M. F., Folstein, S. E., & McHugh, P. R. (1975). “Mini-mental state”. A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198. doi:10.1016/0022-3956(75)90026-6
- Hollands, M. A., & Marple-Horvat, D. E. (1996). Visually guided stepping under conditions of step cycle-related denial of visual information. *Experimental Brain Research*, *109*, 343–356. doi:10.1007-BF00231792
- Hollands, M. A., & Marple-Horvat, D. E. (2001). Coordination of eye and leg movements during visually guided stepping. *Journal of Motor Behavior*, *33*, 205–216. doi:10.1080/00222890109603151
- Holtzer, R., Verghese, J., Xue, X., & Lipton, R. B. (2006). Cognitive processes related to gait velocity: Results from the Einstein aging study. *Neuropsychology*, *20*, 215–223. doi:10.1037/0894-4105.20.2.215
- Hreljac, A., & Marshall, R. N. (2000). Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics*, *33*, 783–786. doi:10.1016/S0021-9290(00)00014-2
- Ishihara, S. (1917). *Tests for color-blindness*. Handaya, Tokyo: Hongo Harukicho.
- Kinrade, N. P., Jackson, R. C., Ashford, K. J., & Bishop, D. T. (2010). Development and validation of the decision-specific reinvestment scale. *Journal of Sports Sciences*, *28*, 1127–1135. doi:10.1080/02640414.2010.499439
- Laborde, S., Furley, P., & Schempp, C. (2015). The relationship between working memory, reinvestment, and heart rate variability. *Physiology & Behavior*, *139*, 430–436. doi:10.1016/j.physbeh.2014.11.036

- Leung, C. M., Ho, S., Kan, C. S., Hung, C. H., & Chen, C. N. (1993). Evaluation of the Chinese version of the hospital anxiety and depression scale. A cross-cultural perspective. *International Journal of Psychosomatics*, *40*, 29–34.
- Lu, L., & Bigler, E. D. (2000). Performance on original and a Chinese version of trail making test part B: A normative bilingual sample. *Applied Neuropsychology*, *7*, 243–246. doi:10.1207/S15324826AN0704_6
- Mak, M. K., Lau, A. L., Law, F. S., Cheung, C. C., & Wong, I. S. (2007). Validation of the Chinese translated activities-specific balance confidence scale. *Archives of Physical Medicine and Rehabilitation*, *88*, 496–503. doi:10.1016/j.apmr.2007.01.018
- Masters, R. S. W. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British Journal of Psychology*, *83*, 343–358. doi:10.1111/j.2044-8295.1992.tb02446.x
- Masters, R. S. W., Eves, F. F., & Maxwell, J. P. (2005). Development of a movement specific reinvestment scale. In T. Morris, P. Terry, S. Gordon, S. Hanrahan, L. Ievleva, G. Kolt, et al. (Eds.), *Proceedings of the ISSP 11th World Congress of Sport Psychology*, Sydney, Australia.
- Masters, R. S. W., & Maxwell, J. P. (2008). The theory of reinvestment. *International Review of Sport and Exercise Psychology*, *1*, 160–183. doi:10.1080/17509840802287218
- Masters, R. S. W., Polman, R. C. J., & Hammond, N. V. (1993). ‘Reinvestment’: A dimension of personality implicated in skill breakdown under pressure. *Personality and Individual Differences*, *14*, 655–666. doi:10.1016/0191-8869(93)90113-H
- Mattay, V. S., Fera, F., Tessitore, A., Das, S., Callicott, J. H., & Weinberger, D. R. (2002). Neurophysiological correlates of age-related changes in human motor function. *Neurology*, *26*, 630–635. doi:10.1212/WNL.58.4.630
- van der Meulen, E., Zijlstra, G. A., Ambergen, T., & Kempen, G. I. (2014). Effect of fall-related concerns on physical, mental, and social function in community-dwelling older adults: A prospective cohort study. *Journal of the American Geriatrics Society*, *62*, 2333–2338. doi:10.1111/jgs.13083
- Papegaaij, S., Taube, W., Baudry, S., Otten, E., & Hortobágyi, T. (2014). Aging causes a reorganization of cortical and spinal control of posture. *Frontiers in Aging Neuroscience*, *6*, 28. doi:10.3389/fnagi.2014.00028
- Partington, J. E., & Leiter, R. G. (1949). Partington’s pathways test. *Psychological Service Center Journal*, *1*, 11–20.
- Patla, A. E., Adkin, A., Martin, C., Holden, R., & Prentice, S. (1996). Characteristics of voluntary visual sampling of the environment for safe locomotion over different terrains. *Experimental Brain Research*, *112*, 513–522. doi:10.1007/BF00227957
- Pichora-Fuller, M. K., Kramer, S. E., Eckert, M. A., Edwards, B., Hornsby, B. W., Humes, L. E., ... Wingfield, A. (2016). Hearing impairment and cognitive energy: The framework for understanding effortful listening (FUEL). *Ear and Hearing*, *37* (Suppl. 1), 5S–27S. doi:10.1097/AUD.0000000000000312
- Podsiadlo, D., & Richardson, S. (1991). The timed “Up & Go”: A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*, 142–148. doi:10.1111/j.1532-5415.1991.tb01616.x
- Powell, L. E., & Myers, A. M. (1995). The activities-specific balance confidence (ABC) scale. *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences*, *50A*, M28–M34. doi:10.1093/gerona/50A.1.M28
- Prince, F., Corriveau, H., Hébert, R., & Winter, D. A. (1997). Gait in the elderly. *Gait & Posture*, *5*, 128–135. doi:10.1016/S0966-6362(97)01118-1
- Ramsay, M. C., & Reynolds, C. R. (1995). Separate digits tests: A brief history, a literature review, and a reexamination of the factor structure of the test of memory and learning (TOMAL). *Neuropsychology Review*, *5*, 151–171. doi:10.1007/BF02214760
- Reynolds, R. F., & Day, B. L. (2005). Visual guidance of the human foot during a step. *The Journal of Physiology*, *569*, 677–684. doi:10.1113/jphysiol.2005.095869
- Richardson, J. K., Eckner, J. T., Allet, L., Kim, H., & Ashton-Miller, J. A. (2017). Complex and simple clinical reaction times are associated with gait, balance, and major fall injury in older subjects with diabetic peripheral neuropathy. *American Journal of Physical Medicine & Rehabilitation*, *96*, 8–16. doi:10.1097/PHM.0000000000000604
- Rubenstein, L. Z. (2006). Falls in older people: Epidemiology, risk factors and strategies for prevention. *Age and Ageing*, *35*(Suppl. 2), ii37–ii41. doi:10.1093/ageing/af084
- Sanchez-Cubillo, I., Periañez, J. A., Adrover-Roig, D., Rodríguez-Sánchez, J. M., Ríos-Lago, M., Tirapu, J., & Barceló, F. (2009). Construct validity of the trail making test: Role of task-switching, working memory, inhibition/interference control, and visuo-motor abilities. *Journal of the International Neuropsychological Society*, *15*, 438–450. doi:10.1017/S1355617709090626
- Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review*, *84*, 1–66. doi:10.1037/0033-295X.84.1.1
- Schoene, D., Delbaere, K., & Lord, S. R. (2017). Impaired response selection during stepping predicts falls in older people—A cohort study. *Journal of the American Medical Directors Association*, *18*, 719–725. doi:10.1016/j.jamda.2017.03.010
- Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. *Psychological Review*, *84*, 127–190. doi:10.1037/0033-295X.84.2.127
- Tombaugh, T. N., & McIntyre, N. J. (1992). The mini-mental state examination: A comprehensive review. *Journal of the American Geriatrics Society*, *40*, 922–935. doi:10.1111/j.1532-5415.1992.tb01992.x
- Uemura, K., Yamada, M., Nagai, K., & Ichihashi, N. (2011). Older adults at high risk of falling need more time for anticipatory postural adjustment in the precrossing phase of obstacle negotiation. *The Journals of Gerontology, Series A: Biological Sciences and Medical Sciences*, *66*, 904–909. doi:10.1093/gerona/glr081
- Uiga, L., Capio, C. M., Wong, T. W., Wilson, M. R., & Masters, R. S. (2015). Movement specific reinvestment and allocation of attention by older adults during walking. *Cognitive Processing*, *16*(Suppl. 1), 421–424. doi:10.1007/s10339-015-0685-x
- Ward, N. S., & Frackowiak, R. S. J. (2003). Age-related changes in the neural correlates of motor performance. *Brain*, *126*, 873–888. doi:10.3389/fnhum.2013.00142
- Wong, W. L., Masters, R. S., Maxwell, J. P., & Abernethy, B. (2008). Reinvestment and falls in community-dwelling older

- adults. *Neurorehabilitation and Neural Repair*, *22*, 410–414. doi:10.1177/1545968307313510
- Wong, W. L., Masters, R. S., Maxwell, J. P., & Abernethy, B. (2009). The role of reinvestment in walking and falling in community-dwelling older adults. *Journal of the American Geriatrics Society*, *57*, 920–922. doi:10.1111/j.1532-5415.2009.02228.x
- Young, W. R., & Hollands, M. A. (2010). Can telling older adults where to look reduce falls? Evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance. *Experimental Brain Research*, *204*, 103–113. doi:10.1007/s00221-010-2300-9
- Young, W. R., Olonilua, M., Masters, R. S., Dimitriadis, S., & Williams, A. M. (2016). Examining links between anxiety, reinvestment and walking when talking by older adults during adaptive gait. *Experimental Brain Research*, *234*, 161–172. doi:10.1007/s00221-015-4445-z
- Young, W. R., Wing, A. M., & Hollands, M. A. (2012). Influences of state anxiety on gaze behavior and stepping accuracy in older adults during adaptive locomotion. *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences*, *67*, 43–51. doi:10.1093/geronb/gbr074
- Zigmond, A. S., & Snaith, R. P. (1983). The hospital anxiety and depression scale. *Acta Psychiatrica Scandinavica*, *67*, 361–370. doi:10.1111/j.1600-0447.1983.tb09716.x
- Zwergal, A., Linn, J., Xiong, G., Brandt, T., Strupp, M., & Jahn, K. (2012). Aging of human supraspinal locomotor and postural control in fMRI. *Neurobiology of Aging*, *33*, 1073–1084. doi:10.1016/j.neurobiolaging.2010.09.022