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Healthy older adults demonstrate generalized postural motor learning in response to variable amplitude oscillations of the support surface

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Abstract

Postural motor learning for dynamic balance tasks has been demonstrated in healthy older adults (Van Ooteghem et al. 2009). The purpose of this study was to investigate the type of knowledge (general or specific) obtained with balance training in this age group and to examine whether embedding perturbation regularities within a balance task masks specific learning. Two groups of older adults maintained balance on a constant frequency-variable amplitude oscillating platform. One group was trained using an embedded sequence (ES) protocol which contained the same 15-s sequence of variable amplitude oscillations in the middle of each trial. A second group was trained using a looped sequence (LS) protocol which contained a 15-s sequence repeated three times to form each trial. All trials were 45-s. Participants were not informed of any repetition. To examine learning, participants performed a retention test following a 24-h delay. LS participants also completed a transfer task. Specificity of learning was examined by comparing performance for repeated versus random sequences (ES) and training versus transfer sequences (LS). Performance was measured by deriving spatial and temporal measures of whole body centre of mass (COM), and trunk orientation. Both groups improved performance with practice as characterized by reduced COM displacement, improved COM-platform phase relationships, and decreased angular trunk motion. Improvements were also characterized by general rather than specific postural motor learning. These findings are similar to young adults (Van Ooteghem et al. 2008) and indicate that age does not influence the type of learning which occurs for balance control.

Keywords

aging; balance control; continuous perturbation; learning; platform translation

Introduction

With practice, learners can acquire procedural knowledge about how to perform a motor skill. This knowledge can be general (based on broad features of the skill) or specific (based on regularities in the task environment). The present study represents the third in a series of studies designed to examine 1) whether postural motor learning is general or specific 2) whether age affects the capacity for postural motor learning, and 3) whether age influences the type of learning (general or specific) that occurs for a postural motor task. For all studies, we examined compensatory postural motor learning using a methodology designed to explore implicit sequence learning (Pew 1974; Nissen and Bullemer, 1987; Wulf and Schmidt, 1997; Magill, 1998). This methodology requires learners to produce serial responses to random versus sequentially presented stimuli and examines differential improvements in performance; providing us with an opportunity to examine the specificity of learning for a novel postural motor task.

In 2001, Shea et. al. reported specific learning for a dynamic balance task in young participants who were asked to track a visual signal with corresponding movements of their centre of pressure on a stabilometer (Shea et al. 2001). Participants in the study showed better retention of performance improvements for a repeated sequence of visual elements versus randomly presented stimuli. While movement sequencing might facilitate learning for some motor tasks (e.g. dance, gymnastics), we recently argued that such sequence-specific learning could actually serve to constrain rather than enhance postural motor learning, particularly for a balance task requiring compensatory posture control (Van Ooteghem et al. 2008). In that study, rather than having participants *generate* postural adjustments as done in Shea et al. (2001), they were exposed to continuous, variable-amplitude oscillations of a translating platform and maintained balance by compensating for the postural disturbances. In each trial, a repeated sequence of translation amplitudes was embedded among random platform motion but participants were not informed of this repetition. Performance did improve with practice but learning was no better for the repeated sequence providing evidence for generalized rather than sequence-specific postural motor learning in young adults.

In the present study, we examined the nature of postural motor learning in older adults. Given the incidence of postural instability in this population, we reasoned that understanding the effects of age on learning could have tremendous impact on training efforts in this group. To begin exploring the capacity for older adults to learn a balance task, we exposed them to a repeated sequence of constant frequency, variable-amplitude oscillations of the support surface and examined practice-related improvements in performance (Van Ooteghem et al. 2009). Results revealed preserved postural motor learning as measured by similar rates of improvement in performance between young and older adults and maintenance of behaviours that were better than those observed in early practice. Despite comparable rates of improvement in COM control, age-related differences were identified in the strategies used to maintain balance. A majority of older adults persisted with a rigid, 'platform-fixed' control strategy (limited lower limb joint motion and large COM displacements in space) while young adults shifted toward multi-segmental control that included stabilizing the trunk in space and increasing motion about the hip joint. The simplified control strategy exhibited by older adults is compatible with other reports of age-related postural dyscontrol which shows preference for a rigid control strategy in situations that are likely to lead to loss of stability (e.g. large or fast perturbations) (Horak et al. 1989; Tang and Woollacott 2004).

Since young and older adults in Van Ooteghem et al. (2009) adopted different control strategies during practice with a repeated sequence of postural perturbations, it is also possible that they engaged in different forms of postural motor learning (i.e. specific versus

general). The ‘platform-fixed’ strategy used by older adults demonstrates that this group was tracking platform motion and thus, that the potential for extracting sequence-specific information was optimized due to the direct relationship between multiple sources of sensory input and platform motion. This sequence information would be reflected in differential performance improvements for a repeated versus random sequence of platform perturbations. Acquiring knowledge about the sequence of perturbations would optimize the central nervous system's (CNS) ability to engage in feed-forward control mechanisms that could improve pre-perturbation stability and decrease perturbation intensity (Bhatt et al. 2006). Prediction could be particularly advantageous for older adults because a) balance tasks present a greater challenge to stability due to age-related declines in sensorimotor function and b) the threat of an inappropriate response (i.e. a fall) is greater for this group. As a result, the CNS might sacrifice response flexibility (obtained via generalized-postural motor learning) for stability.

When an embedded-sequence protocol is applied to continuous motor tasks such as balancing on an oscillating platform (Van Ooteghem et al., 2008), it is possible that sequence-specific learning is masked by participants' inability to transition midtrial from a generalized control strategy to one that exploits the repeated sequence. It is also possible that participants do not deem it advantageous to do so, either because it is too inefficient or too risky. Indeed, previous continuous perturbation studies with stepwise increases in translation frequency report gradual transitions between characteristic postural coordination patterns (Buchanan and Horak 2001) that occur over the course of three to five cycles (Dietz et al. 1993; Corna et al. 1999; Bugnariu and Sveistrup 2006). In Van Ooteghem et al. (2008), sequences were composed of 7.5 cycles and as such, it is possible that postural transitions did not occur in this time. It is also possible that participants did not receive enough practice to learn the sequence.

To rule out the possibility that our previous ‘embedded sequence’ protocol masked sequence-learning, we exposed two groups of older adults to one of two sequence-learning protocols. The first protocol - embedded sequence - was similar to that reported previously (Van Ooteghem et al. 2008). In the second protocol (looped sequence), participants were trained using a single training sequence of platform perturbations and then exposed to a “transfer” task which included unique sequences of platform oscillations. This “training and transfer” methodology has also been used to examine sequence learning in serial reaction time tasks by training participants to respond to a repeating sequence of stimuli with corresponding key presses and then observing their reaction time in a transfer task which requires key press responses to stimuli presented in random order (Nissen and Bullemer, 1987). Under these conditions, sequence-specific learning is characterized by a significant disruption to performance from late training to the transfer task. Together, results from the two protocols served to determine if older adults engage in general or specific postural motor learning and to validate a method of examining specific postural motor learning using an embedded sequence of platform perturbations. As a secondary goal of the study, we also examined the capacity for older adults to eventually achieve performances comparable to the young adults reported in Van Ooteghem et al. (2008) by exposing older adults to an extended practice period (50% more exposure to platform motion and 4 times more exposure to a repeated sequence than young adults). We hypothesized that older adults would demonstrate generalized postural motor learning in both experimental protocols and that performance discrepancies would persist between young and older adults despite additional training for the older adult group.

Materials and Methods

Participants

Twenty-one healthy, older adults were randomly assigned to either the embedded-sequence (ES) or looped sequence (LS) protocol. Ten older adults (7 males, 3 females) ranging in age from 54-80 (mean 66 ± 7.8 years) and in height from 157.5 to 183 cm (mean 171 ± 9.2 cm) were trained using the ES protocol. Data from these participants is also reported in Van Ooteghem et al. 2009. Eleven older adults (3 males, 8 females) ranging in age from 60-79 (mean 68 ± 6.4 years) and height from 152.4 to 177.8 cm (mean 166 ± 8.9 cm) were trained using the LS protocol. Prior to inclusion in the study, a telephone questionnaire was administered to ensure that participants were free of disorders that could affect postural control. Clinical examination revealed that one participant was at risk for loss of somatosensory function on the plantar surface of the foot as determined by the Semmes-Weinstein monofilament detection test and three participants exhibited reduced ability to detect 128 Hz vibration on the great toe and the ankle of the right foot. The methods used in the study were approved by the Oregon Health and Science University Institutional Review Board and by the Office of Research Ethics at the University of Waterloo. All participants provided informed consent prior to data collection. In addition, data from 12 young, healthy adults reported previously in Van Ooteghem et al. (2008) were compared with data from older adults in this study. Young adults ranged in age from 19-29 (mean 24.3 ± 2.8 years) and in height from 160 to 183 cm (mean 171 ± 7.4 cm).

Task and Procedures

In this study, two types of platform sequences were used in two protocols (ES and LS) with two groups of older adults. The first, embedded sequence (ES) protocol consisted of a repeated sequence of platform oscillations embedded amongst two random sequences of perturbations. The second, looped sequence (LS) protocol consisted of a single training sequence coupled with a post-training transfer task which included random sequences of perturbations. In both protocols, a retention test was used to investigate learning.

The balance task required participants to stand on a hydraulically driven, servo-controlled platform that could be translated horizontally forward and backward. To prevent falls without restricting motion, subjects wore an industrial safety harness tethered to a sliding hook on an overhead rail. They were instructed to maintain balance while standing with eyes focused on a poster approximately 2m straight ahead and arms crossed at the chest, aiming to avoid stepping, if possible. The platform oscillated at a fixed frequency of 0.5 Hz and variable amplitudes ranging from ± 0.5 cm to the largest amplitude which participants could withstand without taking a step (maximum ± 15 cm). To decrease the likelihood of a step or fall, the platform was offset forward by 6 cm at the start of each trial and the first movement of the platform was always in the backward direction.

Embedded Sequence—In this protocol, trials were composed of three, 15-second segments containing seemingly random oscillations; however, the middle segment was a repeated sequence of platform movements that occurred in every trial (Fig. 1a). Participants were not informed of this repetition. The middle segment contained the same sequence of oscillations as the middle segment in Van Ooteghem et al. (2008). Similar to the modified protocol examined in this previous study, the first and third random oscillation segments were matched for average velocity of translation by deriving the sequences from the pool of amplitudes that defined the middle segment (termed the standard pool). This method ensured that the mean amplitude and velocity of platform translation were the same across segments and decreased the likelihood that the segments would present different degrees of challenge to participants. There were no restrictions on the direction of translation in the random

segments; a forward translation in the repeated middle segment could appear as an oscillation in the forward or backward direction in a random segment. Combined, the three segments produced a 45-second trial. Across trials, every random sequence was unique but all participants received the same set of random sequences. Two participants who were trained using this protocol were unable to maintain balance with their feet in place at the maximum amplitude. For these two participants, platform oscillations were scaled to their maximum (12 and 13 cm).

Data collection began with a 20-second practice trial of constant amplitude translation (8 cm), which served to familiarize participants with continuous platform motion. Testing consisted of six blocks of seven trials, with a 2-minute rest period between blocks. To separate temporary performance effects from more permanent changes in behaviour that would reflect learning (Schmidt and Lee 2005), participants returned for a seven-trial, retention test approximately 24 hours following practice.

Looped Sequence—In this protocol, participants received a 14-second, variable amplitude sequence which looped to create a three-segment trial (Fig. 1b). The difference in segment length relative to the ES protocol (14-sec vs 15-sec respectively) was necessary to directionally match the oscillation at the end of one segment with the beginning of the next segment. Again, participants were not informed of any regularities within or across trials. Each participant had a unique training sequence generated randomly from the standard pool used in the *embedded sequence* protocol to ensure that the average velocity of translation was consistent amongst participants and between protocols. All participants trained using this protocol were able to withstand the maximum platform displacement of ± 15 cm.

Further precautions were taken to ensure consistent levels of difficulty across participants by establishing a criterion to account for large velocity changes at platform zero-crossings that presented as discontinuities in platform motion (described by participants as ‘jerks’). Under conditions of constant frequency and variable amplitude platform motion, the magnitude of velocity change at the zero-crossing is dependent upon the current (N) and previous (N-1) amplitude in the sequence. Using the formula $((N-(N-1)/N)*100)$, we examined the velocity change at each zero-crossing in the repeated sequence of the *embedded sequence* protocol and found that it contained three decelerations (large amplitude N-1 to small amplitude N) and one acceleration (small N-1 to large N) that were driven by successive amplitudes which were $\geq 50\%$ different. In order to match the frequency of discontinuities in the current protocol, any randomly generated training sequence which had more than three decelerations or more than one acceleration violating this criterion was excluded.

Data collection began with a 20-second practice trial of constant amplitude translation (8 cm), which served to familiarize participants with continuous platform motion. Testing consisted of nine blocks of seven trials (50% increase from the *embedded sequence* protocol), with a 2-minute rest period between blocks. To separate temporary performance effects from more permanent changes in behaviour, participants returned for a three-block retention test approximately 24 hours following practice. In the *embedded sequence* protocol, the retention test contained a single block of trials. A longer retention test in the LS protocol was intended to examine retention and possible re-acquisition (Schmidt and Lee 2005). Immediately following the retention test, participants underwent a transfer test to examine whether performance improvements were dominated by general or sequence-specific learning. The transfer test consisted of one block of random trials. Each of these trials was composed of three segments of random amplitude sequences drawn from the standard pool which also met the criteria for number of discontinuities. None of these sequences were previously presented. The same block of transfer trials was given to all participants.

Data Recording—A Motion Analysis System (Santa Rosa, CA) with six cameras captured three-dimensional spatial coordinate information about body segment displacements and the movement of the platform. Reflective markers were placed bilaterally on the following anatomical landmarks: fifth metatarsophalangeal, lateral malleolus, lateral femoral condyle, greater trochanter, anterior superior iliac spine, iliac crest, styloid process, olecranon, acromion process, lateral mandibular joint and on the xyphoid process. A marker was also placed on the back of the platform. Data were sampled at 60 Hz and low pass filtered using a 2nd order, dual pass Butterworth filter with a cut-off frequency of 5 Hz. The position of the centre of mass (COM) of each body segment in the antero-posterior (AP) direction was calculated using the kinematic data and anthropometric data provided by Winter (1990). Whole body COM position (in space) in the AP direction was derived from the weighted sum of the individual segment COM locations using a custom-designed MATLAB program (Mathworks, Natick, MA). Right side marker data were also used to determine trunk segment orientation in the sagittal plane. The trunk segment was defined from the acromion process to the greater trochanter.

Outcome Measures—Mean gain of the COM (COM peak displacement/platform peak displacement) and mean relative phase of the COM (COM time peak/platform time peak) were derived using the methods described in Van Ooteghem et al. (2008) to examine spatial and temporal control of the COM. In addition to COM measures, variability in the alignment of the trunk relative to gravitational vertical (termed trunk tilt variability) was calculated as described in Van Ooteghem et al. (2009). COM phase and gain were chosen for consistency with primary outcome measures identified in previous studies (Van Ooteghem et al. 2008; Van Ooteghem et al. 2009). Trunk tilt variability (TTV) was examined because it previously showed substantial training-related changes in older adults (Van Ooteghem et al. 2009). To compare performances across different sequences of platform motion, trunk tilt variability was normalized to the mean platform velocity change for each segment (ES protocol) and each training sequence (LS protocol).

Data Analyses—To evaluate whether participants improved performance with practice and if they engaged in general or sequence-specific learning, primary outcome measures (COM gain, COM phase, TTV) were analyzed separately for the *embedded sequence (ES)* and *looped sequence (LS)* protocols.

For the ES protocol, two-way (segment type $\times$ training block) repeated measures ANOVAs were used for all statistical comparisons. Outcome measures were compared between segment two (repeated) and segment three (random) similar to Van Ooteghem et al. (2008). Segment one was omitted from the analyses to ensure that events induced by the onset of platform motion did not interfere with the investigation of sequence learning. To examine whether performance differed between sequence types during the acquisition phase, data were analyzed by comparing blocks of trials on day one in a 2 (segment) $\times$ 6 (block) repeated measures ANOVA. Retention performance was analyzed using a 2 (segment) $\times$ 3 (block) repeated measures ANOVA that included early (block 1) and late (block 6) training on day one and the retention test block on day two. Post hoc analyses were conducted using one-way repeated measure ANOVAs for significant interactions between segment type and training block, or Tukey's studentized range (HSD) tests.

For the LS protocol, data from the middle segment of the looped sequence trials were analyzed using one-way repeated measure ANOVAs unless otherwise noted. Restricting the analyses to the middle segment of each trial ensured that any within-trial adaptation that might have occurred did not interfere with our investigation of longer-term learning. Acquisition performance was analyzed by examining data across the nine training blocks on day one. To determine if participants maintained performance improvements following a

delay period, paired t-tests (Bonferroni corrections) were used for planned comparisons between a) the first retention block on day two and the last training block on day one, b) the first retention block on day two and the first training block on day one, and c) the last retention block on day two and the last training block on day one. Sequence-specific learning was also explored using paired t-tests between the first retention block and the transfer block.

To determine whether additional exposure to the moving platform was beneficial to older adults, mixed model ANOVAs were used first to compare the middle segment in six blocks of training for older adults in the ES versus LS protocols to ensure that the two groups of older adults performed similarly despite the change in protocol. For variables that were not significantly different, a mixed model ANOVA between young adults (data from Van Ooteghem et al. 2008) and older adults in the LS protocol for the middle segment of the first six blocks of training was used to explore an age effect. Finally, *post hoc* analyses using Tukey's studentized range (HSD) tests to compare block six (equivalent to 'late' training in the ES protocol) and block nine for the LS group were conducted on the one-way ANOVA that examined acquisition. This analysis was conducted to determine whether additional practice lead to further improvements in performance.

An acceptable significance level for all statistical tests was 0.05 unless otherwise noted and only those trials in which participants avoided taking a step were included. In total, 31/490 trials were omitted from the ES protocol and 21/1001 trials were omitted from the LS protocol.

Results

Embedded Sequence (ES) Protocol

Although significant improvement in postural stability was observed with practice, older adults did not take advantage of the repeated sequence of perturbations to improve balance control. A main effect of block was observed for trunk tilt variability during the acquisition phase on day one ($F(1.3,12.1)=10.474$; $p=0.004$ (Greenhouse-Geisser); Fig 2a) but there were no differences between segment types ($F(1,9)=0.923$; $p=0.362$). COM phase during acquisition also showed a main effect of block ($F(5,45)=37.99$; $p<0.001$; Fig 2b) and no differences between segment types ($F(1,9)=0.93$; $p=0.36$). Finally, there were main effects of training block ($F(5,45)=4.37$; $p=0.002$) and segment type ($F(1,9)=12.95$; $p=0.006$) for COM gain however, the reductions in COM gain were minimal with a mean decrease of 4.6% (0.68 ± 0.04 to 0.65 ± 0.04) for the repeated segment and 3.6% (0.66 ± 0.05 to 0.64 ± 0.05) for the random segment (Fig. 2c).

On day two, participants demonstrated some maintenance of the improvements achieved during the acquisition period on day one, providing evidence for longer-term learning. Trunk tilt variability showed a main effect of block ($F(1.1,10.3)=13.13$; $p=0.004$ (Greenhouse-Geisser)) but no effect of segment type ($F(1,9)=4.81$; $p=0.06$). Post hoc analysis indicated that the block effect was driven by a significant difference between the retention block (average 2.4 ± 0.71) and early training on day one (average 3.6 ± 1.54) and not between late training (average 2.4 ± 0.56) and the retention block. COM phase control also showed a main effect of block ($F(2,18)=39.05$; $p<0.001$) but no effect of segment type ($F(1,9)=3.52$; $p=0.093$) and similar to trunk tilt variability, post hoc analyses indicated that performance during the retention test (average $-8.27 \pm 4.91^\circ$) remained significantly different from behaviours during early training (average $-14.09 \pm 3.71^\circ$). Participants shifted an average of $2.74 \pm 3.37^\circ$ between the last training block and the retention block, which represented 32% of the gains achieved during training on day one. Finally, participants demonstrated longer-term retention of the small COM gain improvements achieved during

the acquisition period. Although COM gain showed a main effect of block ($F(2,18)=4.98$; $p=0.02$) and segment ($F(1,9)=12.21$; $p=0.01$), post hoc analyses revealed that COM gain during retention testing was not significantly different from late training for repeated ($p=0.10$) or random ($p=0.06$) segments.

Looped Sequence (LS) Protocol

Despite the change in protocol, participants trained with a single sequence in the LS protocol also engaged in non-specific learning as evidenced by retention or rapid re-acquisition of improvements observed during training and by transfer task performances which did not differ significantly from the first retention block. During acquisition, trunk tilt variability showed a main effect of block ($F(2,21)=8.76$; $p=0.002$ (Greenhouse-Geisser); Fig. 3a). Post hoc analysis indicated however, that appreciable decreases did not occur continuously throughout training. Rather, participants showed significant improvements in trunk control from block one to block two ($p<0.05$) and no difference in the remaining blocks. Significant shifts in COM phase (Fig. 3b) and significant reductions in COM gain (Fig. 3c) were also observed during acquisition ($F(2.6,26.5)=20.13$; $p<0.0001$; Greenhouse-Geisser and $F(2.3,22.6)=7.23$; $p=0.003$; Greenhouse-Geisser respectively). For COM phase, group performance improved from a mean of $-8.22 \pm 2.47^\circ$ in early training (block one) to $-0.2 \pm 3.68^\circ$ in late training (block nine) while a mean decrease of 7.76% occurred for COM gain (from 0.70 ± 0.04 in early training to 0.65 ± 0.05 in late training).

Similar to results from the ES protocol, participants maintained improvements in trunk stability as evidenced by comparisons between the final block of practice on day one and the first retention block on day two ($t(10)=-0.119$; $p=0.91$). Significant losses in COM phase control ($t(10)=2.835$; $p=0.018$) and COM gain control ($t(10)=-4.571$; $p=0.001$) did occur during the retention interval but performances remained significantly different from those observed during early training ($t(10)=-6.13$; $p<0.0001$ and $t(10)=3.23$; $p=0.004$ respectively). Further examination also indicated that later retention performances (block three) for both COM phase and COM gain were not significantly different from the final block of practice on day one ($t(10)=0.624$; $p=0.547$) and ($t(10)=-1.038$; $p=0.324$) indicating rapid re-acquisition of COM gain and phase control upon re-exposure on day two.

To examine the specificity of learning, a comparison was made between the first retention block and the transfer block to determine whether participants exhibited poorer performance for the transfer block (i.e. lack of transfer). For all measures, performance was not disrupted by the presentation of a new perturbation sequence. Neither trunk tilt variability nor COM phase differed significantly from retention to transfer ($t(10)=-1.55$; $p=0.16$ and $t(10)=-0.82$; $p=0.43$ respectively). A significant difference was observed for COM gain but the change was in favor of a smaller gain during the transfer task ($t(10)=3.31$; $p=0.008$). Together, these findings demonstrate that performance improvements were not driven by sequence-specific learning.

Extended Practice

Older adults given 50% more exposure to platform motion and four times more training with a repeated sequence in the LS protocol did not perform like young adults in the ES protocol (Fig. 4). Between-group comparisons of the repeated middle segment for six blocks of training demonstrated that the ES and LS practice groups of older adults did not differ on measures of trunk tilt variability ($F(1,19)=1.228$; $p=0.282$) or COM gain ($F(1,19)$; $p=0.257$) suggesting that the change in protocol did not affect these outcomes. COM phase lag however, was significantly less for older adults trained using the LS versus ES protocol ($F(1,19)=7.326$; $p=0.014$) and therefore, we did not analyze the effects of additional training for this variable. An age-comparison between young adults and older adults in the LS

protocol revealed greater trunk tilt variability and COM gain for older adults following six blocks of training. Although a main effect of group existed for trunk tilt variability ($F(1,21)=6.227$; $p=0.021$), a main effect of training block also existed ($F(1,1)=11.658$; $p=0.001$; Greenhouse-Geisser), revealing that older adults improved trunk stability at a similar rate to young adults over six blocks of training. A comparison between block six and block nine of the LS protocol however, revealed that older adults did not demonstrate additional improvements in trunk tilt variability with added practice ($p>0.05$). For COM gain, an interaction between age and training block revealed that reductions in COM gain occurred at a slower rate for older adults ($F(2,42)=3.544$; $p=0.04$; Greenhouse-Geisser). Again, post hoc analyses revealed that additional training did not lead to further reductions in COM gain for this group ($p>0.05$).

Discussion

In both protocols examined here, older adults demonstrated the ability to learn adaptive postural responses to continuous, variable amplitude platform motion and, similar to the young adults in Van Ooteghem et al. (2008), performance improvements were not specific to the temporal relationship between perturbation amplitudes. Learning was demonstrated by maintenance of postural improvements across days of testing or in cases where performance declines occurred during the retention interval, by the ability to regain the previously acquired levels of proficiency with less exposure. Such rapid improvements during retention testing have been attributed to CNS priming for updates to the internal representation of stability (Pavol et al. 2002). Evidence for generalized postural motor learning suggests that training-related improvements in balance control could transfer to similar balance tasks.

In the ES protocol, trunk tilt variability was reduced similarly with practice for a repeated sequence versus randomly presented sequences of surface oscillations. There were also no differences in performance between repeated and random segments during retention testing, as would be seen if more effective learning had occurred for the repeated segment. In the LS protocol, non-specific learning was demonstrated by an ability to maintain retention test performance levels when presented with a new perturbation sequence in the transfer task. The lack of sequence-specific learning demonstrates that practice-related improvements in posture control were not due to a CNS ability to predict with cognitive anticipation, what event would occur next, despite the benefits to stability that could have arisen from exploiting perturbation amplitude regularities embedded in the trials.

Previously, we proposed that young participants could achieve the task goal of maintaining balance by developing an internal plan using other regulatory features or rules of the task, including the constant frequency or amplitude boundaries of platform motion (Van Ooteghem et al. 2008). This internal plan hypothesis could suggest that the nervous system is storing newly acquired knowledge about how to control balance under the current conditions and that retention demonstrates retrieval of this knowledge. The suggestion that upright stance is regulated by a limited repertoire of responses however, (Horak and Nashner 1986) might suggest that postural motor learning of a novel balance task defines the CNS process of determining which responses apply to the current situation and then refining those responses with repeated exposure. A key element of this hypothesis is the concept of adaptive central set used to describe central predictive mechanisms based on expectation or experience with a postural task which has typically been illustrated using discrete perturbations (Horak et al. 1989; Horak et al. 1994). For discrete perturbations, postural motor learning would reflect longer-term retention of central set which, under the current continuous perturbation conditions, might be superimposed on feedback mechanisms. Regardless of the mechanism, evidence for general postural motor learning in healthy older adults demonstrates that the nature of learning does not change with age despite age-related

differences in control strategy and the possibility of additional challenge or threat to stability due to sensorimotor decline.

Previous studies exploring the capacity of older adults to learn sequences have predominantly used upper limb tasks such as the serial reaction time (SRT) task, and have reported mixed findings regarding a preserved ability for older adults to engage in sequence learning (e.g. Howard and Howard 1997; Daselaar et al. 2003; Smith et al. 2005). Unlike the current study, these experiments did not include an element of personal risk which might make it disadvantageous to engage in sequence-specific learning, or use externally- evoked or paced stimuli that could make it impossible to do so. In Van Ooteghem et al. (2008), we proposed that specific postural motor learning could overload the processing capacity of the CNS and impair its ability to respond quickly enough to maintain balance. Learned responses with high specificity could also create added risk if they are inappropriate for transfer to a new perturbation environment. Both of these proposals suggest that sequence-specific learning could represent a less desirable type of learning for balance control. It should be noted that our ability to draw definitive conclusions about non-specific postural motor learning remains limited by the fact that we have not tested young adults using the LS protocol. Thus, it remains possible that an age effect contributed to the lack of sequence-specific learning observed in this protocol.

Although our results demonstrate that non-specific learning occurred in older adults, it remains possible that participants learned stimuli of particular relevance interspersed throughout the sequence (e.g. approximate number and/or general location of large excursions). Indeed, some participants developed declarative knowledge of some elements in the training sequence describing for example, that they “knew where the short jerks were and anticipated them”, or that they “felt a short oscillation before large, then short again”. Consistent with this possibility, a sequence-learning study with an arm reaching task demonstrated that response time decreases with training were attributable to general decreases in movement time with anticipatory shifts in onset times for only a few of the targets (less than 5%) in the sequence (Moisello et al. 2009). Developing responses based on a partial set of relevant stimuli (e.g. boundaries or large velocity changes) would enable participants to establish an appropriate gain to withstand the most disruptive perturbations while achieving some cost minimization with training (i.e. information processing, energy expenditure).

A secondary, clinically-relevant goal of this study was to examine whether additional practice for older adults would enable them to perform like young adults. In Van Ooteghem et al. (2009), older adults showed significant improvements in postural stability with training but their performance remained significantly different from young adults. Since significant differences occurred in early training but did not increase with practice (i.e. there was no age $\times$ practice interaction), the differences could not be attributed to deficits in learning. As such, we were interested to know whether older adults could achieve performances comparable to young adults with additional practice. In the current study, participants in the LS protocol not only received 50% greater exposure to variable amplitude platform motion than both young adults (Van Ooteghem et al. 2008) and older adults in the ES protocol, their exposure was also restricted to a single training sequence. Under these conditions, performance improvements did not differ between the two groups of older adults for trunk tilt variability or COM gain. The COM phase lock achieved by older adults in the LS group differed from older adults trained using the ES protocol. Since these group differences existed as early as block one, it is possible that the two groups of older adults were inherently different or that the singular training sequence used in the LS protocol provided older participants with a performance advantage (e.g. less contextual interference) that enabled them to achieve greater temporal shifts in COM control. Comparisons between

young adults and older adults trained using the LS protocol for six blocks of training showed significantly less trunk tilt variability and COM gain for young adults. These findings were not unexpected given that older adults started training with a performance disadvantage. The older adults however, showed no further improvements with additional practice and as a result, their performances remained significantly different from the young adults who underwent six blocks of training. Two possibilities could explain the lack of significant improvement with additional practice including a) that the rate of improvement was slowing or b) that participants were limited by transient performance effects such as fatigue, lack of motivation or difficulty maintaining focus on the task.

In summary, older adults trained using both the ES and LS protocols demonstrated generalized postural motor learning. To eliminate the possibility that an age effect limited sequence-learning under conditions of a single training sequence, we must test young adults using the LS protocol. Regardless of learning type, an important next step is to identify which cues are deemed critical for postural motor learning. Given this information, we can aim to improve balance performance by facilitating the search for these critical features.

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Fig. 1.

a) An overlay of two trials from the embedded sequence protocol (max. range ± 15 cm) illustrating the repeated middle segment embedded between two random segments. b) An example of platform motion for the looped sequence protocol (max. range ± 15 cm). Each trial consisted of three repetitions of a single training sequence

Fig. 2.

Group changes in a) trunk variability, b) COM phase, and c) COM gain for training and retention phases of the embedded sequence protocol. Repeated segment performance is denoted by *white* squares. Random segment performance is denoted by *black* squares. Error bars represent standard error of the mean. Asterisks indicate significance at $p < 0.05$

Fig. 3. Group changes in a) trunk variability, b) COM phase, and c) COM gain for training, retention, and transfer phases of the looped sequence protocol. Error bars represent standard error of the mean. Asterisks indicate significance at $p < 0.05$

Fig. 4. Group changes in a) trunk variability, b) COM phase, and c) COM gain for the repeated segment of the embedded sequence protocol and the training sequence of the (extended) looped sequence protocol. Young adult performance in the embedded sequence protocol is denoted by the *grey* trace, older adult performance in the embedded sequence protocol is denoted by the *black* trace and older adult performance in the looped sequence protocol is denoted by the *dashed* trace. Error bars represent standard error of the mean. Asterisks indicate significance at $p < 0.05$. Young adult data taken from Van Ooteghem et al. (2008)