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Posture and gaze tracking of a vertically moving target reveals age-related constraints in visuo-motor coupling

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Posture and gaze tracking of a vertically moving target reveals age-related constraints in visuo-motor coupling

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Abstract

Previously we have demonstrated that the effect of aging on posture and gaze active tracking of a visual target moving in the horizontal direction is dependent on target's complexity. In this study, we asked whether a similar phenomenon is present when tracking a visual target moving with varying complexity in the vertical direction. Ten young (22.98 ± 2.9 years) and 10 older adults (72.45 ± 4.72 years) tracked for 120 s, a visual target moving vertically by shifting their bodyweight in the anterior-posterior direction. Three target motions were tested: a simple periodic (sine wave), a more complex (Lorenz attractor) and an ultra-complex random (Surrogated Lorenz attractor) pattern. Cross-spectral analysis revealed lower sway-target coherence as a function of age, regardless of target motion's complexity. This age effect was significant for the sway-target gain but not for the phase index. Gaze-target analysis revealed age related differences only when tracking the more complex targets. Regardless of age, tracking of the complex target was associated with lower cross Approximate Entropy. It is concluded that tracking of visual targets oscillating in the vertical direction reveals age related constraints that are independent of visual motion's complexity. These constraints are evident in the spatial and not temporal aspects of visuo-motor coupling, which suggests the presence of neuromuscular deficiencies in controlling visually guided postural sway in the anterior-posterior direction.

1. Introduction

Most habitual daily activities, such as gait, standing, jumping or landing, involve a significant amount of sway in both the Medio-Lateral (ML) and Antero-Posterior (AP) direction, while inter-limb load-unload patterns are evident in both directions.

Considering the postural control directional constraints, swaying in the sagittal and frontal directions constitutes two separate control mechanisms [1]. On the one hand, swaying in the AP direction induces in-phase motion between the limbs, while the body oscillates as an inverted pendulum around the ankle joint [2]. Therefore, swaying in the AP direction is foremost controlled by the ankle muscles, that is depicted in the well-known ankle strategy [3]. On the other hand, when swaying in the ML direction, the lower limbs are moving in an inter-limb anti-phase pattern, while the hip joint mostly controls the oscillation [4].

While it is generally accepted that ML sway can discriminate old fallers from non-fallers [5], postural sway in the AP direction needs to be considered as well in order to understand older adults' instability during everyday life activities. Use of the ankle strategy for balancing in the AP direction imposes additional difficulties in older adults, due to a selective, age-related loss of somatosensory afferents and motor units in the distal lower limb muscles [6]. This distal muscle deficiency restricts full range of motion when swaying around the ankle joint. Consequently, older adults shift control to the hip joint during demanding standing postures [7], self-imposed [8] or externally-imposed [9] balance perturbations. This reduced ability to use the ankle musculature to control posture, results in greater instability in the AP than the ML direction [10] and increases proneness to falling [11].

Active postural tracking of visual motion cues is used to study age-related deficits in balance control, perception-action coupling and whole body coordination [12–14]. The same paradigm has also been employed in rehabilitation research to improve static and dynamic balance [13,15] revealing greater benefits for AP than ML postural tracking practice [15]. However, the regularity of the target motions to be tracked, alters the control of posture to a feed-forward mode, very early in practice, leaving limited space for perception based action improvement [16]. In contrast, the unpredictable, complex nature of real life environmental stimuli renders the need for online, feedback based control of postural sway highly important [17]. For this reason, target motions that exhibit patterns of great complexity such as of mathematical chaos and/or random patterns have been employed lately in postural tracking research [13,18]. Tracking of complex targets is a more ecologically valid paradigm [13,18] because this mimics the spatiotemporal characteristics of the real world [17]. Moreover, it was shown that older adults have greater difficulties, as compared to young participants, to couple their posture to complex (i.e. chaotic) target motions, while no age-related differences were evident when tracking periodic (i.e. a sine wave) target motions [13]. However, postural sway in most previous research [12,14] was confined in the ML direction while this was driven by a horizontally moving target resulting in congruent posture-target motions.

In the current study, we explored aging effects on active posture and gaze tracking of complex visual target cues moving in the vertical (up and down) direction. Postural tracking was realized by shifting body weight in the AP direction. The matching directions of sway-target motions were experimentally set based on previous research

[18] and pilot testing indicating the presence of an inherent spatial bias to match forward sway with an upward target motion and vice versa. We hypothesized that aging affects the coupling of gaze and AP postural sway to a visual target oscillating vertically while age-related limitations are a function of target's motion complexity.

2. Methods

2.1. Participants

Ten (10) healthy young adults (YA, 22.98 ± 2.95 yrs) and 10 older adults (OA, 72.45 ± 4.72 yrs), free from any neurological or musculo-skeletal impairment, volunteered to participate in the study. Older adults were screened for cognitive and physical function using the MMSE test (>23 for all participants) and TUG test (<12 s) respectively. Participants were informed about the experimental protocol and gave their informed consent to participate in the study. The experiment was performed with the approval of the institution's ethics committee in accordance with the Declaration of Helsinki.

2.2. Apparatus, stimuli and task

Participants were asked to stand on the midline between two adjacent force-plates (Balance Plates 6501, Bertec USA), adjusting their heels and toes in order to equally distribute body weight between the two platforms recording the vertical ground reaction force (Fig. 1). Inter-malleolar distance was fixed at 10% of body height. Two dots were displayed on a black TV screen (LG 60LA620S-ZA, 60 inches) located 1.5 m in front of the participant at eye level. A red dot simulated the target's motion and a yellow one the participant's bodyweight (vertical force) distribution between the platforms in the AP direction. The target (red) dot's range of motion was set to 90% of the participant's bodyweight. An eye tracking system (Dikablis, Ergoneers, 50 Hz) recorded the 2D gaze coordinates after normalizing for head's motion (Nexus 1.8.5, Vicon Motion Systems, Oxford, UK).

Three signals of different complexity were used to simulate the visual target motion (red dot): a) a periodic generated by a sine wave, b) a chaotic generated by the Lorenz attractor and c) a random generated by surrogating the Lorenz signal (for further details see [13]). The performance (yellow) dot was set to move upwards when the participant was leaning forward and downwards when he/she leaned backwards, considering that when an object is far away, it is intuitively perceived to be higher in the field of view [19]. Participants were asked to track (by weight-shifting between platforms) the red dot as accurately as possible with the yellow one for 120s. A 20 s practice trial was given for familiarization with the target. Experimental conditions were randomised to account for order effects.

2.3. Data analysis

Spectral coherence was used to test the linear relationship between the performance and target signals in the frequency domain. Analysis involved a qualitative description of the group averaged performance-target coherence, phase and gain plots in the 0–1 Hz frequency band and a quantitative comparison of the same parameters at the dominant target frequency (0.244 Hz). Gain was calculated as an amplitude-coupling index while phase illustrated the temporal lag between signals, in degrees. The cross-Approximate Entropy (cross-ApEn) was calculated as an index of co-joint regularity between the target and performance signals in the non-linear space [18].

Prior to statistical analysis, the one-sample Kolomogorov- Smirnov test was used to test for violations of the normality assumption in each dependent measure. The test revealed that at least one dependent measure in each factor level was not normally distributed. For this reason, non-parametric statistics were employed. Specifically, the Friedman's two-way ANOVA for related samples was used to compare the performance-target coupling measures across experimental conditions and the Mann-Whitney U test to compare the same metrics between groups. The Wilcoxon Signed Ranks Test was employed for post hoc pairwise comparisons between levels after adjusting p for multiple comparisons (Bonferroni adjustment).

3. Results

3.1. Sway-target coupling

The group averaged coherence curves revealed lower sway-target coherence for the OA than the YA group in all target conditions (Fig. 2). This difference was statistically confirmed by the coherence value at 0.244 Hz (Table 1) (periodic: U = 15.0, p = 0.005, chaotic: U = 24.0, p = 0.017, random: U = 9.0, p = 0.001). In addition, coherence (at 0.244 Hz) decreased as a function of target motion's complexity (2(2) = 22.571, p = 0.000) between the periodic and the chaotic (Z = 2.277, p = 0.023) and the chaotic and the random target (Z = 3.555, p = 0.000).

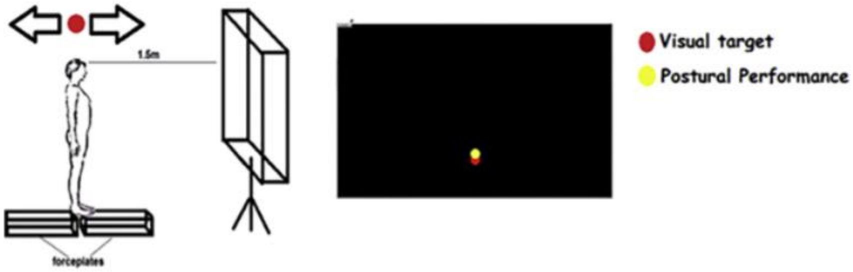

Fig. 1. The experimental tracking task. Participants stood in the midline of the two platforms and were instructed to track the vertically moving target (red dot) by shifting body weight (yellow dot) in the antero-posterior direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

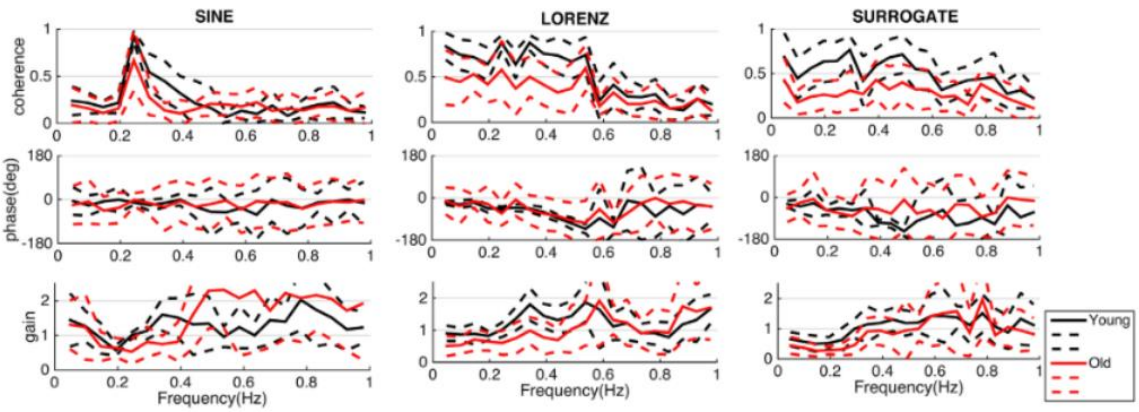

Fig. 2. Group averaged curves of sway-target coherence (top), phase (middle) and gain (bottom) during tracking of the periodic (SINE), chaotic (LORENZ), random (SURROGATE) targets in the 0–1 Hz frequency band. Black solid line represents young adults and the red line the older adults. The respectively colored dashed lines represent the 95% confidence limits. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Sway-target coherence, gain, phase and Cross-ApEn. *: significant difference between groups. +: significant difference between target motions.

	Coherence			Phase			Gain			Cross-ApEn		
	Young		Old	Young		Old	Young		Old	Young		Old
SINE		*						*			*	
Young Old	0.94(±0.54)		0.66(±0.29)	13.60 (±6.23)		20.93(±16.38)	1.00(±0.08)		0.58(±0.32)	0.084(±0.008)		0.130(±0.033)
LORENZ		+*			+			*			+*	
Young Old	0.87(±0.08)		0.59(±0.30)	45.18 (±8.09)		59.12(±26.71)	1.02(±0.23)		0.60(±0.37)	0.105(±0.011)		0.137(±0.035)
SURROG.		+*						+*			+	
Young Old	0.66(±0.22)		0.24(±0.18)	56.87(±12.33)		59.40(±27.52)	0.63(±0.37)		0.32(±0.20)	0.137(±0.012)		0.159(±0.038)

Age did not affect the sway-target phase (Fig. 2). Both age groups maintained a phase close to 0◦ when tracking the periodic target, while the phase lag increased when tracking the chaotic and random targets (2(2) = 28.737, p = 0.000). Yet, the phase lag at 0.244 Hz was significant only between the periodic and chaotic target (Z = 3.920 p = 0.000).

The OA group had lower sway-target gain than the YA group in all conditions (periodic: U = 7.0, p = 0.001, chaotic: U = 21, p = 0.009, random: U = 26, p = 0.023). Sway-target gain decreased in both groups as a function of target's complexity (2(2) = 10.381, p = 0.006), albeit only between the chaotic and random target motions (Z = 0.322, p = 0.0020).

Non-linear analysis revealed higher Cross-ApEn for the OA compared to the YA group when tracking the periodic (U = 1.0, p = 0.000) and the chaotic targets (U = 22.0, p = 0.011, Table 1). Sway-target Cross-ApEn increased as a function of target's complexity (2(2) = 27.364, p = 0.000) (periodic- chaotic: Z = 2.062, p = 0.039,chaotic-random: Z = 4.042, p = 0.000).

3.2. Gaze-target coupling

OAs' gaze was less coherent to the target than YAs' gaze when tracking the chaotic and random target motions (from 0 to 0.6 Hz) but not during periodic target tracking (Fig. 3). This group difference was confirmed by the statistical analysis of the gaze-target coherence at 0.244 Hz (chaotic: U = 24.000, p = 0.017; random: U = 7.000, p = 0.000, Table 2). Coherence at 0.244 Hz was lower when attending to the random than the chaotic target (Z = 2.203, p = 0.28) (Table 2).

The gaze-target phase relationship did not reveal notable phase shifts either as a function of target's complexity or age. The gaze- target gain on the other hand, was lower for the OA than the YA group, in all conditions although group comparisons at 0.244 Hz did not confirm this difference. The gain significantly increased between the periodic and the chaotic target tracking for both age groups (Z = 2.203, p = 0.028) (Table 2).

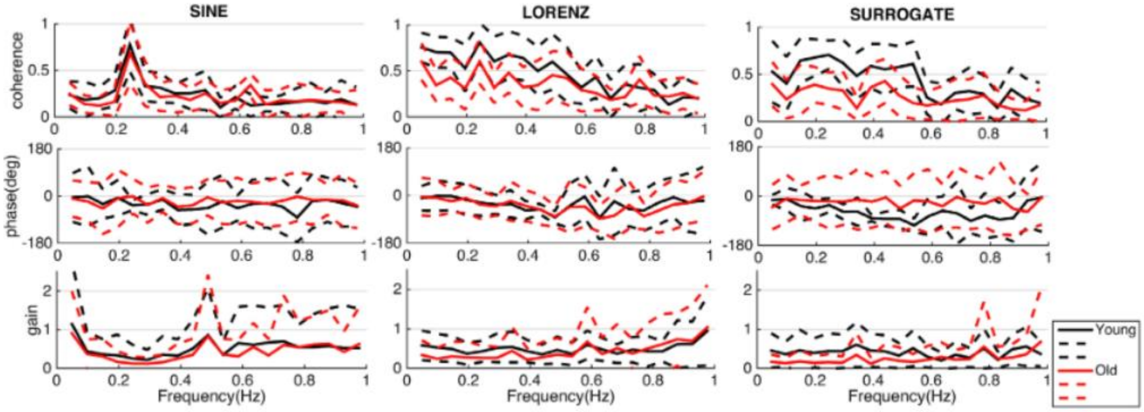

Fig. 3. Group averaged curves of gaze-target coherence (top), phase (middle) and gain (bottom) during tracking of the periodic (SINE), chaotic (LORENZ), random (SURROGATE) targets in the 0–1 Hz frequency band. Black solid line represents young adults and the red line the older adults. The respectively colored dashed lines represent the 95% confidence limits. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Gaze-target coherence, gain, phase and Cross-ApEn. *: significant difference between groups. +: significant difference between target motions.

	Coherence			Phase		Gain			Cross-ApEn		
	Young		Old	Young	Old	Young		Old	Young		Old
SINE											
YoungOld	0.78(±0.29)		0.68(±0.33)	44.60(±24.19)	46.40(±44.70)	0.25(±0.36)		0.12(±0.18)	0.120(±0.023)		0.137(±0.040)
LORENZ		*					+			+	
YoungOld	0.81(±0.22)		0.60(±0.24)	48.60(±25.14)	56.06(±26.54)	0.43(±0.27)		0.26(±0.31)	0.095(±0.013)		0.108(±0.041)
SURROG.		+*								+	
YoungOld	0.71(±0.15)		0.35(±0.17)	36.27(±18.20)	50.61(±37.83)	0.44(±0.45)		0.16(±0.21)	0.112(±0.016)		0.127(±0.032)

The gaze-target cross ApEn was not significantly different between groups although this decreased when tracking the chaotic target (Z = 2.912, p = 0.004) while it increased again when tracking the random target (Z = 2.833, p = 0.005).

4. Discussion

The main finding of the current study is that older adults were less able to couple their AP gaze and postural sway to the vertical motion of a visual target independently of target's complexity. Interestingly, this age related deficiency was evident in the spatial but not the temporal components of visuo-postural coupling.

The lower visuo-postural coupling due to age is in line with our previous study findings reporting age effects on posture and gaze coupling to a horizontally moving target when swaying side-ways (ML direction) [13]. In the ML direction however, the target's complexity was a distinguishing factor between age groups. Specifically, a greater age-related reduction in visuo-postural coupling was noted when tracking the more complex target cues in the ML direction while no age effect was observed in the periodic target tracking. This was explained by older adults' tendency to employ prediction when tracking predictable visual motions in order to compensate for possible age-related slowness in perception-action coupling.

One reason for the reduced sway-target coupling noted irrespectively of the target's complexity could be the extra cognitive load associated with converting the vertical (up-down) target motion to AP (for-aft) sway. Such a spatial conversion however, is ecologically relevant, because humans have the inherent tendency to perceive up as distant-far in the field of view and therefore converge to a target moving downwards by swaying forward [19]. By contrast, down is inherently perceived, as proximal-nearby in space and therefore performers tend to diverge from a target moving upwards by swaying backwards. Nevertheless, all participants naturally (intuitively) selected this spatial directional matching. Moreover, an age-related difficulty in performing this spatial conversion would be reflected in a greater phase lag between the target's motion and performance that was not confirmed by the present results.

A more plausible explanation for the age-related reduction in spatial coupling could be older participants' inability to reach the AP limits of stability during swaying [20]. Neuromuscular [7,11] and sensorimotor [6,21] constraints that are specific to the ankle musculature are reported in the aging literature. These limit the boundaries of stability and impose difficulties in controlling sway in AP direction [22] particularly when a 90% of bodyweight shifting is required. Based on the results of the present study, it is also argued that older adults prioritize the temporal coupling to the target's motion at the cost of reducing sway amplitude. This time prioritization was recently confirmed in Parkinson's disease patients when instructed to rhythmically shift their bodyweight laterally [23].

Sway-target cross-ApEn was higher for the older adults revealing a reduced co-joint regularity as a function of age when tracking both periodic and chaotic targets. The increased cross-ApEn as a function of age is in line with our previous study findings [13] and reveals a decreased ability of older adults to incorporate the visual target's motion complexity into their postural sway patterns. The progressive loss of temporally organized behaviour in standing sway due to aging compromises postural stability and diminishes adaptability to environmental constraints while this is also associated to an increased proneness to falling [24].

Aging affected the gaze-target coherence only when tracking the less predictable targets. The absence of an age effect when tracking the regular target motion suggests that older adults, similarly to young participants, can predict the target's trajectory continuation [25]. However, older adults lose the ability to predict the target's motion with increasing complexity. Such age-related differences were not observed when tracking the horizontally moving target [13] which leads to the hypothesis that tracking of a target moving vertically may be more cognitively challenging for older adults. In addition, the lower cross-ApEn when tracking the chaotic target indicates greater gaze-target synchronicity confirming that the demand for attention to the target increases as a function of complexity for both age groups [13,18].

5. Conclusions

The results of the current research emphasize that the ability to track, with active antero-posterior body sway, vertical motion cues decreases with age independently of visual motion's complexity. The reduced ability to sway to the limits imposed by the target's amplitude, together with absence of temporal delays suggests that neuromuscular rather than central constraints accompanying aging limit the integration of AP sway to vertical motion cues. Considering that this is a component of sensorimotor adaptation having a significant impact in everyday life, the present findings stress the importance of AP sway training when constructing intervention programs for improving perception-action in aging with the goal of fall prevention. It will be of interest to investigate between-directions transfer effects as a result of acquiring novel visuo-motor transformations through practice.

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