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Aging affects postural tracking of complex visual motion cues

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Aging affects postural tracking of complex visual motion cues

H. Sotirakis, A. Kyvelidou, L. Mademli, N. Stergiou & V. Hatzitaki

Keywords:

Aging, Gaze, Posture, Complexity, Visuo-motor integration

Abstract

Postural tracking of visual motion cues improves perception–action coupling in aging, yet the nature of the visual cues to be tracked is critical for the efficacy of such a paradigm. We investigated how well healthy older (72.45 ± 4.72 years) and young (22.98 ± 2.9 years) adults can follow with their gaze and posture horizontally moving visual target cues of different degree of complexity. Participants tracked continuously for 120 s the motion of a visual target (dot) that oscillated in three different patterns: a simple periodic (simulated by a sine), a more complex (simulated by the Lorenz attractor that is deterministic displaying mathematical chaos) and an ultra-complex random (simulated by surrogating the Lorenz attractor) pattern. The degree of coupling between performance (posture and gaze) and the target motion was quantified in the spectral coherence, gain, phase and cross-approximate entropy (cross-ApEn) between signals. Sway–target coherence decreased as a function of target complexity and was lower for the older compared to the young participants when tracking the chaotic target. On the other hand, gaze–target coherence was not affected by either target complexity or age. Yet, a lower cross-ApEn value when tracking the chaotic stimulus motion revealed a more synchronous gaze–target relationship for both age groups. Results suggest limitations in online visuo-motor processing of complex motion cues and a less efficient exploitation of the body sway dynamics with age. Complex visual motion cues may provide a suitable training stimulus to improve visuo-motor integration and restore sway variability in older adults.

Introduction

A progressive neural degeneration at both central and peripheral levels due to aging compromises the efficiency of visuo-motor pathways, which negatively affects motor responses to unpredictable environmental challenges such as circumventing an obstacle or another pedestrian while walking in a busy street. Older adults need longer time for planning and executing medio-lateral stepping adjustments during gait (Chapman and Hollands 2010) and show significantly delayed stepping onset latencies when asked to step over unpredictably moving visual targets (Di Fabio et al. 2003; Mazaheri et al. 2015). In order to compensate for visuo-motor processing delays, older adults increase reliance on prediction when faced with the environmental challenges of daily life, a strategy that could increase proneness to falls (Chapman and Hollands 2006). For example, they prematurely transfer their gaze to future stepping targets while locomoting over obstacles which compromises the control of the present ongoing step cycles (Chapman and Hollands 2006, 2007).

On the positive side, short-term visuo-motor adaptation is possible in old age (Baweja et al. 2015; Bock and Girgenrath 2005; Bock 2005) and older adults maintain the capacity to learn novel visuo-postural coordination tasks (Hatzitaki and Konstadakos 2007). This evidence has been exploited for the development of visually guided sway practice protocols to improve visuo-motor integration and enhance balance capabilities in older adults (Hatzitaki et al. 2009; Lajoie 2004; Sihvonen et al. 2004) and stroke patients (Cheng et al. 2004). Visually guided sway practice improves sensory re-weighting for controlling balance (Davis et al. 2010), perception action coupling when avoiding an obstacle (Hatzitaki et al. 2009), and shifts control of posture from a "fall" prone hip to a safer ankle strategy (Gouglidis et al. 2011). However, the effectiveness of visually guided sway practice has also been questioned as there is evidence showing that the earned adaptations do not last (Shumway-Cook et al. 1988), do not provide additional benefits relative to conventional training (i.e., for stroke) (Walker et al. 2000; Cheng et al. 2004) and do not transfer to other sensory-motor tasks (i.e., auditory guided sway) (Radhakrishnan et al. 2010).

One of the reasons for the limited effectiveness and generalization of learning by the visually guided sway practice could be the type of the visual motions provided during these protocols. Due to the repeated and predictable nature of the visual targets being tracked, visuo-motor practice shifts from a closed (feedback) to an open-loop (predictive) type of control after a few repetitions (Kitago and Krakauer 2013). Moreover, postural tracking of a predictable target, such as a regular metronome or a sine visual cue, results in a reduction in the functional degrees of freedom required to control postural sway (Hatzitaki and Konstadakos 2007). As a result, tracking of such targets may not be useful for un-freezing of the available degrees of freedom, to allow for re-optimizing variability and improving adaptive capacity during performance of complex coordinative tasks such as posture and gait (Harrison and Stergiou 2015; Stergiou and Decker 2011; Stergiou et al. 2006). It is known that aging in particular is accompanied by gradual loss of functional degrees of freedom during voluntary sway performance (Tucker et al. 2008), reduced multi-scale complexity of posture dynamics (Manor et al. 2010; Zhou et al. 2013), increased noise in the neuromuscular system (Kurz and Stergiou 2003; Kurz et al. 2010), and a weaker fractal dimension of gait (Duarte and Sternad 2008). Based on this evidence, it is fundamentally important to consider the nature of the visual motions used for tracking during visually guided sway practice, with special care toward the restoration of adaptive capacity and optimal variability in older adults.

An avenue to address these considerations could be the use of complex motions of the targets used in visually guided sway practice. Biological systems as well as daily life environmental stimuli are characterized by organized complexity (Stergiou and Decker 2011; Harrison and Stergiou 2015), which is considered as a desirable setting for the production of functional and adaptable movement. A healthy sensory-motor system exhibits organized complexity which could be characterized by mathematical chaos and is linked with the ability to be highly adaptable (Harrison and Stergiou 2015). Therefore, complex and less predictable visual motions of the targets used in visually guided sway practice could enhance learning by optimizing variability and adaptive capacity. In previous research, we have found that young adults can couple their posture and gaze to a visual target oscillating in a complex manner similarly well as they couple to a periodically moving target (Hatzitaki et al. 2015). However, it is unknown whether this is also possible with older adults, as a recent study has shown that when following an unpredictably moving target in the medio-lateral direction, older adults lost the phase coupling between the center of mass and the target motion at an earlier frequency as compared to young adults (Cofré Lizama et al. 2014). In this study though, the unpredictable target consisted of adding multiple sine waves and was not inherently complex, while the focus of the investigation was on increasing sway frequency.

Therefore, the purpose of our study was to investigate how aging affects the ability to track complex visual motions. We examined the coupling of both posture and gaze to the visual motions of targets moving with various degrees of complexity in the medio-lateral direction. Specifically, we used three different patterns: (1) a periodic pattern that had a pure sine form, (2) a complex pattern that exhibited mathematical chaos and specifically represented the Lorenz attractor (Suzuki et al. 2012) and (3) a highly complex pattern that is generated by a random process by surrogating (Myers 2016) the Lorenz signal. Posture and gaze entrainment to the motion of the target was assessed using both linear, frequency domain and nonlinear, time-dependent coupling metrics. We hypothesized that older adults would demonstrate weaker posture and gaze coupling to the motion of the target when following the more complex patterns as compared to the periodic.

Methods

Participants

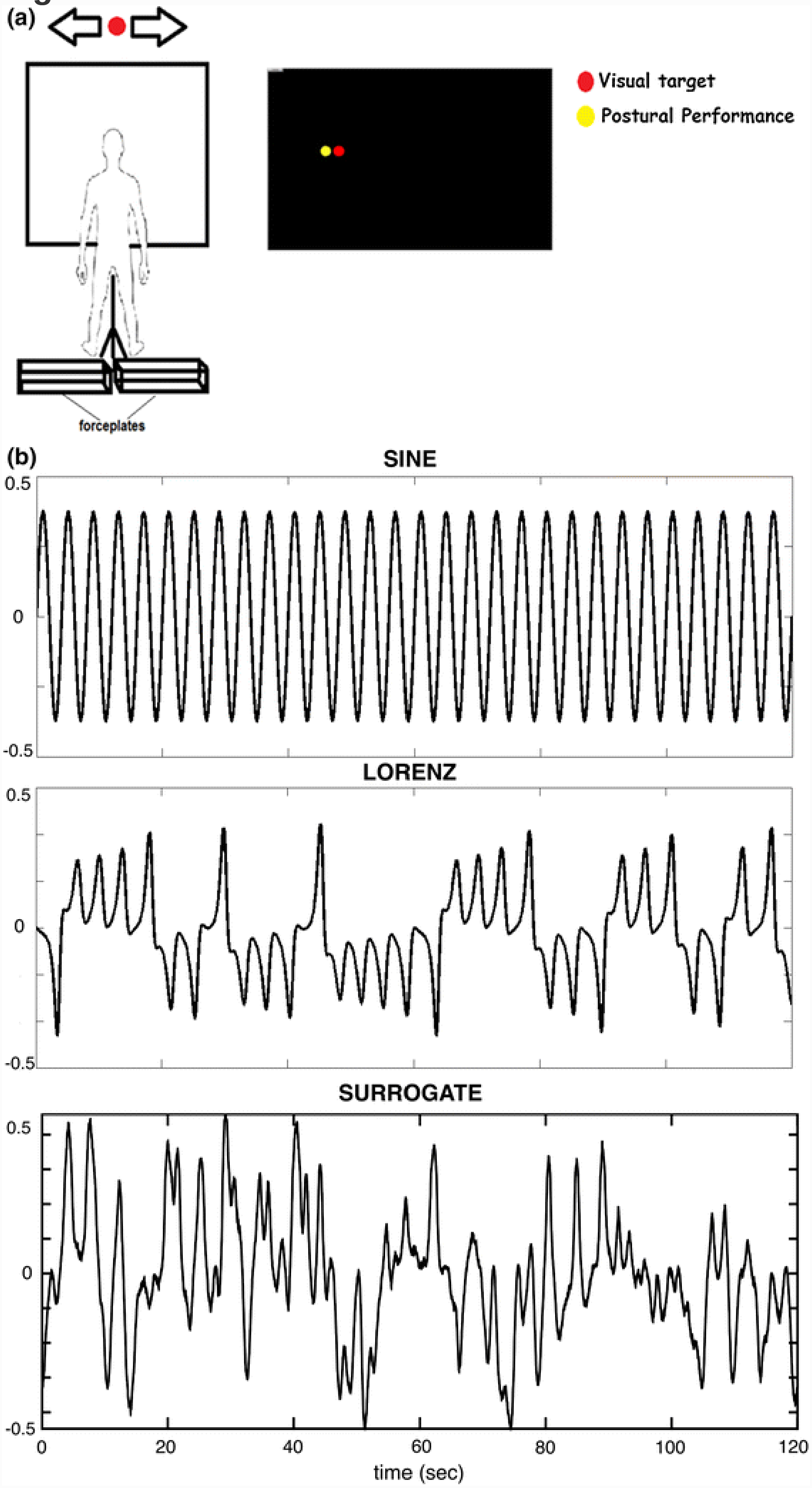
Ten (10) healthy young (22.98 ± 2.95 years, mass: 66.18 ± 11.35 kg, 5 males 6 females) and 10 older adults (72.45 ± 4.72 years, mass: 74.58 ± 4.51 kg, 3 males 8 females) volunteered to participate in this study. Young adults (YA) were recruited from a cohort of university students and older adults (OA) from social recreational community centers for seniors. All participants were free from any neurological or musculoskeletal impairment and had normal or corrected to normal vision. The older adults were screened for cognitive function, using the mini-mental state examination (MMSE; Folstein et al. 1975). All participants scored above (>23) in the MMSE and were included in the experiment. The Time Up and Go test (Podsiadlo and Richardson 1991) was also performed to assess functional mobility of the older adults. All participants performed the TUG test in <11 s indicating sufficient movement functionality to participate in the study. All participants gave their informed consent prior to their inclusion in the study. The experiment was performed with the approval of Aristotle University's ethics committee on human research in accordance with the Declaration of Helsinki.

Apparatus, stimuli and task

Two adjacent force plates (Balance Plate 6501, Bertec, USA) recorded the ground reaction forces at 100 Hz during task performance. The resultant vertical ground reaction force normalized to the participant's body weight was displayed as a yellow dot in real time via a TV Screen (LG 60LA620S-ZA, 1.5 m horizontal × 0.8 m vertical) located in front of the participant at a distance of 1.5 m and at eye level (Fig. 1). The force feedback signal (displayed as a yellow dot) was superimposed on a simulated target signal displayed as a red dot. Target visual signals were constructed using custom MATLAB (version 7.9, Math Works Inc, USA) algorithms, while the data series were accessed and displayed onto the screen using specialized Labview routines (version 8.6, National Instruments Corporation). The position of the stimuli (target, feedback) on the TV monitor was updated at a rate of 50 Hz providing 120 s of continuous target stimulus motion, resulting in 6000 data points for each signal. Eye movements were recorded with the Dikablis eye-tracking system (Dikablis, Ergoneers, 50 Hz) integrated with a Vicon motion capture system (Vicon Motion Systems, Oxford, UK) that enabled calculation of gaze after normalization for head movement. For this purpose, four reflected markers were attached on specific locations on the Dikablis hardware glasses. The Vicon's software development kit (SDK) was used to establish communication between the Vicon system software (Nexus v. 1.8.5) and Labview allowing the synchronous sampling (100 Hz) and digitization of the force, gaze and target motion signals via the Vicon's data acquisition board (MX Giganet).

Three signals of different degree of complexity (Fig. 1b) were used to construct the frequency structure of the visual target motion (red dot): (1) a periodic pattern generated by a pure sine form using the sin function [sine = sin (2_pi_f/fs_t)]. This signal represents simple periodic redundancy, similar to what would be seen from a frictionless clock pendulum. (2) A complex pattern that exhibited mathematical chaos and constructed using the Lorenz attractor (Suzuki et al. 2012). This signal was generated fixing the following parameters: $\sigma = 10$, $\beta = 8/3$ and $r = 28$ and the initial conditions: $x0 = 0.1$, $y0 = 0.1$ and $z0 = 0.1$. The signal characteristics were: h (time resolution) = 0.0040, steps (number of points) = 10,000 (we choose 6000 data points from y-axis [y (4000:10,000)], noise flag = 0. The Lorenz signal as a model closely resembles a double pendulum, which has previously been shown to emulate the dynamics of human posture (Suzuki et al. 2012). (3) A highly complex pattern that is generated by a random process. The Lorenz surrogate was constructed as a random version of the Lorenz signal by using surrogation (Myers 2016). Surrogation is a technique that removes the deterministic structure from the time series, producing an equivalent random data set while maintaining the mean, variance and power spectra of the original signal. The signals' complexity was verified using the Lyapunov exponent (LyE). The LyE values for the three signals used in this study were 0.0016, 0.98392 and 2.4911 for the sine, Lorenz and surrogated Lorenz, respectively. The signals were chosen, as they span the spectrum of signal properties related to the aims of the current investigation. The sine wave had a frequency of 0.244 Hz which is the dominant frequency of medio-lateral self-paced sway as this was estimated by pilot tests. The frequency range for the Lorenz and the surrogated Lorenz signals was confined between 0 and 1 Hz which is an ecologically valid spectrum of frequencies for voluntary medio-lateral sway (Cofré Lizama et al. 2013). Their spectra also revealed a dominant frequency around 0.25 Hz.

Fig. 1



a Experimental protocol. Participants are instructed to follow the moving (*red*) target dot by shifting their body weight (*yellow dot*) in the frontal plane. Inter-malleolar distance was fixed at 10 % of body height **b** the signals used to simulate the three different complexity target motions: sine (*top*), Lorenz (*middle*) and surrogated Lorenz (*bottom*)

Participants were asked to track a moving target, displayed by a red dot by shifting their body weight (represented by a yellow dot) between the two platforms in the medio-lateral (ML) direction (Fig. 1). At the starting position, they placed one foot over each platform distributing their body weight evenly between the platforms while maintaining a normal stance position (inter-malleolar distance adjusted at 10 % of body height). The only instruction was to use the yellow dot in order to follow the movement of the red dot as closely as possible. Participants had to transfer 90 % of their body weight to fit the target's motion amplitude. The experiment required the tracking of three different visual target motions (periodic, chaotic and random), which resulted in three experimental trials that were fully counterbalanced to account for order effects. Each trial lasted 120 s. Familiarization with the tracking task, consisted of a 20-s practice trial, was provided prior to the beginning of testing to avoid the confounding influence of adaptation-learning effects. Posture and gaze data were collected over a single experimental session to avoid effects of learning and/or fatigue.

Data analysis

Ground reaction force and gaze signals were digitally filtered using a low-pass (fourth order, cutoff: 6 Hz) Butterworth digital filter prior to any analysis.

Linear analysis

The relationship between performance (postural sway and gaze) and target motion was quantified using cross-spectral analysis for calculating the coherence, phase and gain between the input (target) and output (performance) signal over a 0–1 Hz frequency range based on the methods of Halliday et al. (1995). Analysis was performed using NeuroSpec 2.0; a freely available archive of MATLAB code intended for statistical signal processing that evaluates time series in equal length segments, computing power spectra and cross-spectra, and returning the mean values with confidence limits. Spectral analysis was performed on 6000 data points that were sampled at a rate of 50 samples/s and by setting the power of the segment length to 10 ($T = 2^{10} = 1024$) returning a segment length of 20.48 s. Each 120-s-long time series was split into 6 non-overlapping windows. Zeroes were added to each segment in order to achieve the desired segment lengths' equality. Coherence, phase and gain values were estimated with a frequency resolution of 0.048828 Hz resulting in an analysis output of 20 values in the frequency band between 0 and 1 Hz.

Analysis involved a) a qualitative comparison of the averaged (pooled across group participants) coherence, phase and gain spectra in the 0–1 Hz frequency range and b) a quantitative analysis of the coherence, gain and phase values at the dominant stimulus frequency (0.244 Hz). Spectral coherence was used as a measure of the degree of correlation between two signals in the frequency domain with values between 0 and 1. Gain revealed the amplitude ratio between the signals by dividing the sway or gaze amplitude by the stimulus amplitude. Phase illustrates the temporal relationship between two signals, expressed in degrees. A gain of 1 and a phase of 0° indicate perfect spatial and temporal coupling, respectively. However, in order to consider gain and phase as reliable measures in our statistical analysis, the two signals must be linearly related. Two signals were considered linearly related when their respective coherence value at the dominant target frequency of 0.244 Hz was significant (over 95 % of confidence limits).

Nonlinear analysis

In order to quantify the degree of co-joined regularity or predictability between the target and performance signals, we calculated the cross-approximate entropy (cross-ApEn) between (a) postural sway and target motion and (b) gaze and target motion. Cross-ApEn has been developed to compare the degree of asynchrony between two time series (Duncan et al. 2013; Wang et al. 2011). Essentially, this algorithm is similar to the approximate entropy algorithm except that a template is chosen from one time series (template time series) and compared with the vectors or segment windows in the other time series (target time series). This algorithm first counts the average recurrence of vectors of m and $m + 1$ pairs of data points across the statistically normalized (mean of zero, variance of 1) time series for the template and target time series that recur within the range of r. Cross-ApEn is the logarithm of the inverse ratio of the recurrence of $m + 1$ pairs of data points with respect to the recurrence of m pairs of data points. The values of m and r were set at 1 and 0.2, respectively. Larger cross-ApEn values indicate greater joint signal asynchrony, while lower cross-ApEn values indicate greater joint signal synchrony.

Statistical analysis

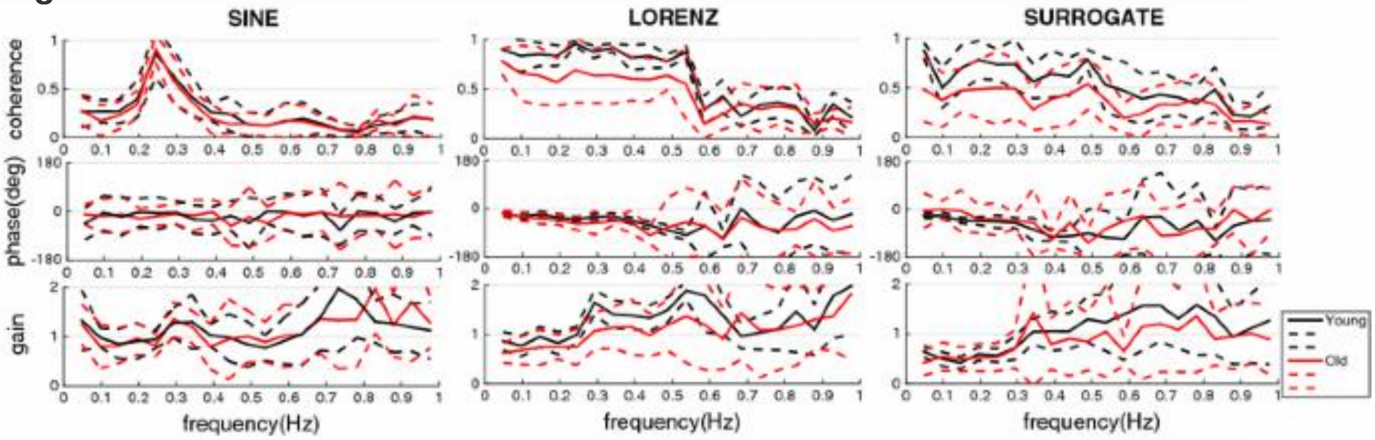
The effect of stimulus complexity and age group on the performance–target coupling measures was evaluated using a 2 (age group; a non-repeated factor) × 3 (stimulus complexity; a repeated factor) mixed repeated-measures ANOVA. Significant interactions between factor levels were further analyzed by performing pairwise (*t* tests) comparisons between the respective factor levels after adjusting *p* values for multiple comparisons. Significance level was set at 0.05, while estimates of effect size are reported using h^2. For the gain and phase metrics, nonparametric analysis was performed due to the limited number of older participants maintaining sway–target linearity (>0.5) across stimulus conditions. Specifically, the Friedman’s two-way ANOVA for related samples was used to compare the performance–target gain and phase across stimuli conditions and the Mann–Whitney *U* test to compare the same metrics between groups. The Wilcoxon signed-rank test was employed for post hoc pairwise comparisons between stimuli levels after adjusting p for multiple comparisons (Bonferroni adjustment).

Results

Sway–target coupling

Sway–target coherence peaked at 0.244 Hz when tracking the sine target, decreased after 0.6 Hz when tracking the chaotic and had the lowest values when tracking the random target motion (Fig. 2a). This was similar between age groups when tracking the sine target but lower for the older participants when tracking the chaotic and the random targets. Sway–target phase was close to 0° for both groups when tracking the sine wave target indicating no sensory-motor delays (Fig. 2b). The phase lag increased for both groups when tracking the more complex (Lorenz, surrogate) stimuli motions, depicting greater latencies as a function of stimulus complexity. The sway–target gain was similar between age groups and close to 1 when tracking the sine and chaotic target motions (Fig. 2c). However, this increased above 1 at stimulus frequencies beyond 0.244 Hz during the tracking of the chaotic target suggesting target overshooting for both age groups. Finally, sway–target gain was lower than 1 for both groups when tracking the random target for stimulus frequencies below 0.3 Hz.

Fig. 2



Averaged (pooled across group participants) sway–target for **a** coherence (*top*), **b** phase (*middle*) and **c** gain (*bottom*) curves during tracking of the sine, Lorenz and surrogate target motion in the 0–1 Hz frequency band. Means (*solid line*) with confidence limits (*dashed line*) are displayed for the old (*red line*, $n = 10$) and young (*black line*, $n = 10$) group participants

Sway–target coherence (Table 1) at the dominant (0.244 Hz) stimulus frequency decreased as a function of stimulus complexity ($F_{2,36} = 25.03$, $p = 0.000$, $h^2 = 0.582$) and was lower for the old compared to the young group ($F_{1,18} = 5.7$, $p = 0.028$, $h^2 = 0.241$). Post hoc within-subjects contrasts further revealed that this decrease was significant between the periodic and the chaotic ($F_{1,18} = 5.93$, $p = 0.025$, $h^2 = 0.248$) as well as between the chaotic and the random ($F_{1,18} = 25.4$, $p = 0.000$, $h^2 = 0.585$) target motions. The interaction between group and stimulus was not significant ($F_{2,36} = 1.78$, $p = 0.182$, $h^2 = 0.090$). However, a marginally significant group by stimulus interaction contrast ($F_{1,18} = 4.13$, $p = 0.057$, $h^2 = 0.187$) suggested that the sway–target coherence decreased between the periodic and chaotic stimulus motions only in the old and not in the young group. Further post hoc between groups comparisons confirmed that the sway–target coherence was significantly lower in the old as compared to the young group, but only when tracking the chaotic target ($p = 0.021$) and not when tracking the periodic and the random target motions.

Due to the reduced number of older participants maintaining sway–target linearity (>0.5) in the more complex stimulus conditions (Table 1), nonparametric analysis was performed for the phase and gain metrics on those participants who maintained sway–target linearity across conditions. The sway–target phase lag increased as a function of stimulus complexity ($X^2_{(2)} = 27.263$, $p = 0.000$). This was significantly longer for the chaotic than the periodic stimulus motion ($Z = 3.823$, $p = 0.000$) while non-significantly different between the chaotic and the random one ($Z = 1.344$, $p = 0.179$). Sway–target phase lag was also longer in the older as compared to young participants (Table 1), although this observation was not confirmed by the statistical comparison (periodic: $U = 60.0$, $p = 0.076$, chaotic: $U = 56.0$ $p = 0.155$, random: $U = 36.0$, $p = 0.072$). Sway–target gain significantly decreased with increasing stimulus complexity ($X^{2}_{(2)} = 17.789$, $p = 0.000$). Specifically, the gain decreased between the chaotic and random stimulus motion ($Z = 3.136$, $p = 0.002$) and was lower in the old as compared to the young group when tracking the periodic target motion ($U = 12.0$, $p = 0.012$).

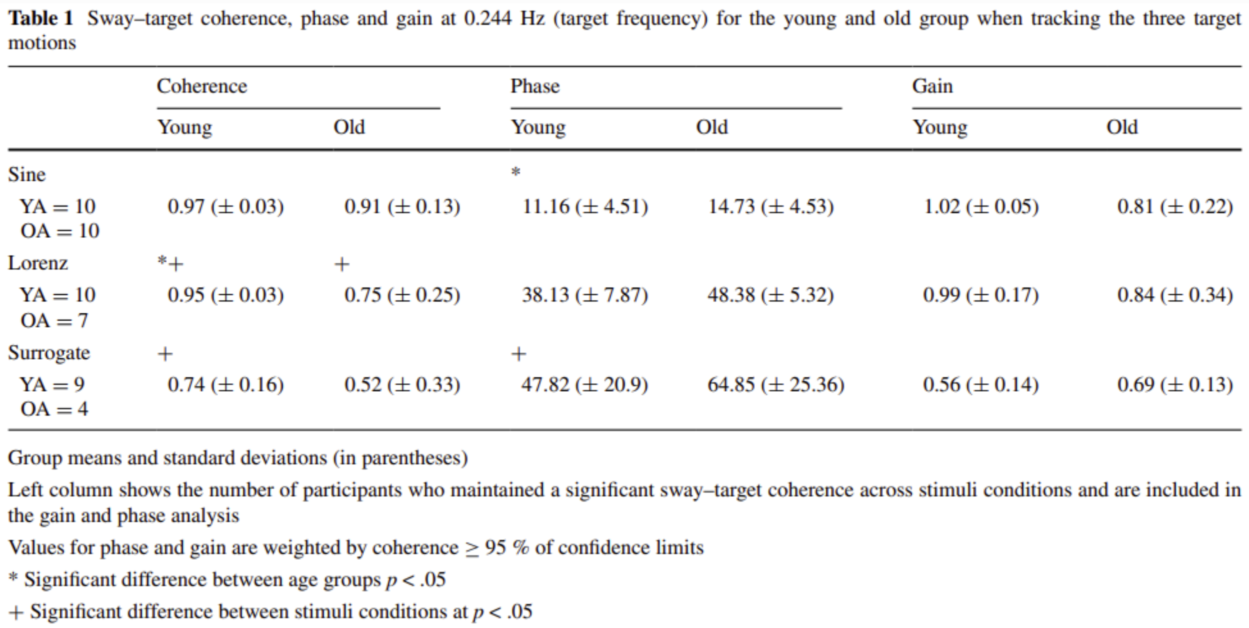


Table 1 Sway–target coherence, phase and gain at 0.244 Hz (target frequency) for the young and old group when tracking the three target motions

	Coherence		Phase		Gain	
	Young	Old	Young	Old	Young	Old
Sine			*			
YA = 10 OA = 10	0.97 (± 0.03)	0.91 (± 0.13)	11.16 (± 4.51)	14.73 (± 4.53)	1.02 (± 0.05)	0.81 (± 0.22)
Lorenz	*+	+				
YA = 10 OA = 7	0.95 (± 0.03)	0.75 (± 0.25)	38.13 (± 7.87)	48.38 (± 5.32)	0.99 (± 0.17)	0.84 (± 0.34)
Surrogate	+		+			
YA = 9 OA = 4	0.74 (± 0.16)	0.52 (± 0.33)	47.82 (± 20.9)	64.85 (± 25.36)	0.56 (± 0.14)	0.69 (± 0.13)

Group means and standard deviations (in parentheses)

Left column shows the number of participants who maintained a significant sway–target coherence across stimuli conditions and are included in the gain and phase analysis

Values for phase and gain are weighted by coherence ≥ 95 % of confidence limits

* Significant difference between age groups $p < .05$

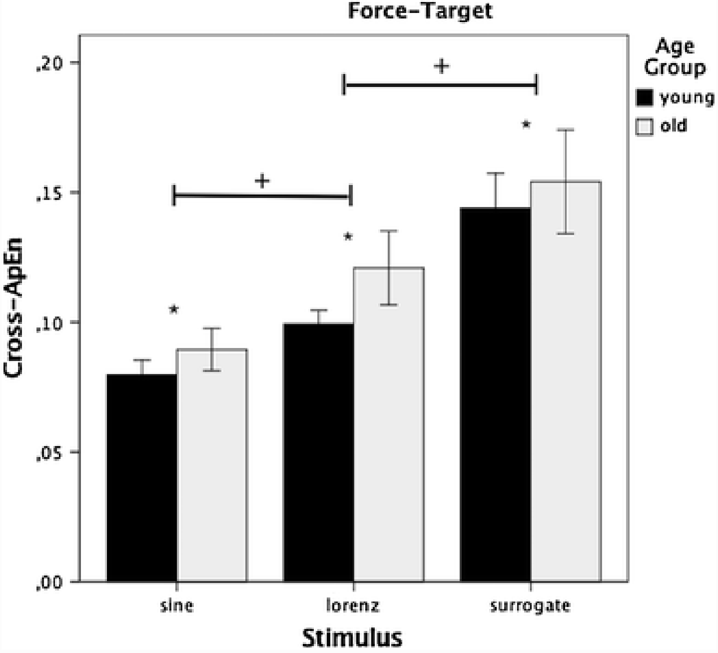
+ Significant difference between stimuli conditions at $p < .05$

In the nonlinear analysis, sway–target cross-ApEn increased as a function of stimulus complexity ($F_{2,36} = 78.26$, $p = 0.000$, $h^{2} = 0.813$). This increase was significant between the periodic and the chaotic ($F_{1,18} = 34.39$, $p = 0.000$, $h^{2} = 0.656$) as well as between the chaotic and the random stimulus motion ($F_{1,18} = 45.11$, $p = 0.000$, $h^{2} = 0.715$) suggesting a less synchronous sway–target coupling with increasing target complexity (Fig. 3). In addition, older adults had a more asynchronous sway–target coupling compared to young participants across all three stimuli conditions ($F_{1,18} = 10.32$, $p = 0.005$, $h^{2} = 0.364$). This was also confirmed by the absence of a group by stimulus complexity interaction effect ($F_{2,36} = 0.638$, $p = 0.534$, $h^{2} = 0.034$).

Gaze–target coupling

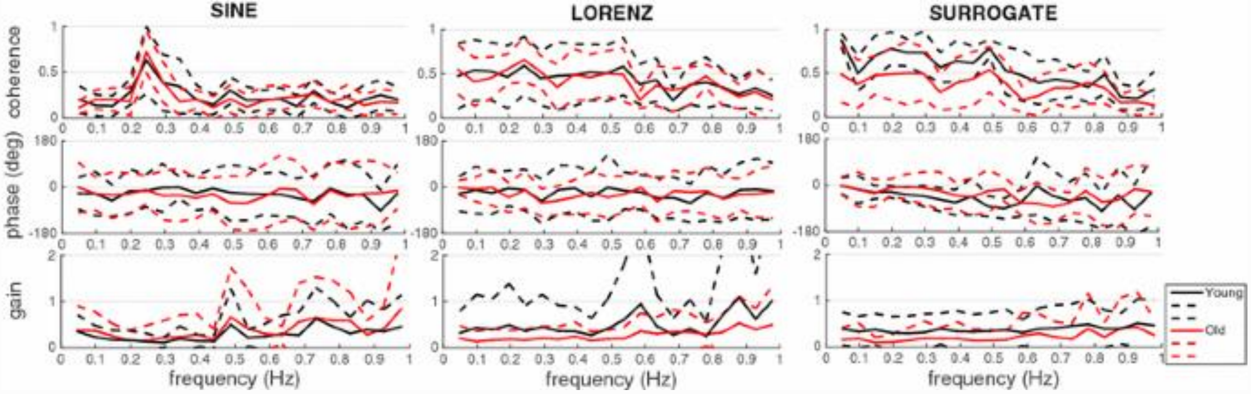
Analyses of the gaze–target coupling were performed on nine young participants due to missing gaze data of one young subject. Gaze–target coherence (Fig. 4a) displayed a peak at the dominant target frequency of 0.244 Hz when tracking the periodic target motion and decreased with increasing frequency when tracking the more complex signals. This was similar between the age groups when tracking the sine and Lorenz target but lower for the older adults when tracking the random target. Gaze–target phase (Fig. 4b) was similar for the two age groups and close to 0° suggesting no sensory-motor delays when tracking the periodic and chaotic stimulus motions. Nevertheless, the phase shift increased when tracking the random target. On the other hand, the gaze–target gain (Fig. 4c) was lower than 1 across all stimuli conditions particularly for the older adults suggesting that participants did not follow the full range of the target motion with their eyes.

Fig. 3



Postural sway–target cross-approximate entropy. Group means and SD are displayed for the young (*black*, *n* = 10) and the old (*gray*, *n* = 10) group. (*asterisk*): significant age effect at *p* < .05, (*cross sign*): significant stimulus complexity effect at *p* < .05

Fig. 4



Averaged (pooled across group participants) gaze–target for **a** coherence (*top*), **b** phase (*middle*) and **c** gain (*bottom*) curves during tracking of the sine, the Lorenz and the surrogate target motion in the 0–1 Hz frequency band. Mean (*solid line*) with confidence limits (*dashed line*) are displayed for the old (*red line*, *n* = 10) and young (*black line*, *n* = 9) group participants

Group means for the gaze–target coupling measures at the dominant stimulus frequency (0.244 Hz) are summarized in Table 2. This did not reveal a significant effect of stimulus ($F_{2,34} = 0.858$, $p = 0.433$) or age group ($F_{1,17} = 1.755$, $p = 0.189$) on the gaze–target coherence and neither a group by stimulus interaction effect ($F_{2,34} = 0.118$, $p = 0.736$).

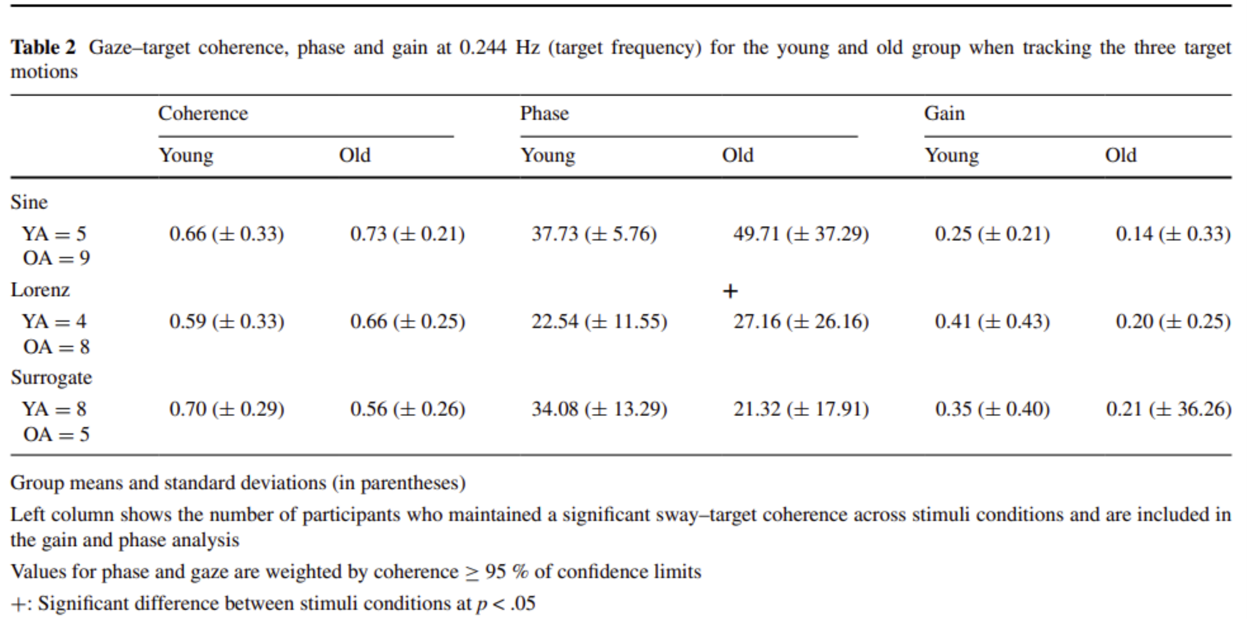


Table 2 Gaze–target coherence, phase and gain at 0.244 Hz (target frequency) for the young and old group when tracking the three target motions

	Coherence		Phase		Gain	
	Young	Old	Young	Old	Young	Old
Sine						
YA = 5 OA = 9	0.66 (± 0.33)	0.73 (± 0.21)	37.73 (± 5.76)	49.71 (± 37.29)	0.25 (± 0.21)	0.14 (± 0.33)
Lorenz				+		
YA = 4 OA = 8	0.59 (± 0.33)	0.66 (± 0.25)	22.54 (± 11.55)	27.16 (± 26.16)	0.41 (± 0.43)	0.20 (± 0.25)
Surrogate						
YA = 8 OA = 5	0.70 (± 0.29)	0.56 (± 0.26)	34.08 (± 13.29)	21.32 (± 17.91)	0.35 (± 0.40)	0.21 (± 36.26)

Group means and standard deviations (in parentheses)

Left column shows the number of participants who maintained a significant sway–target coherence across stimuli conditions and are included in the gain and phase analysis

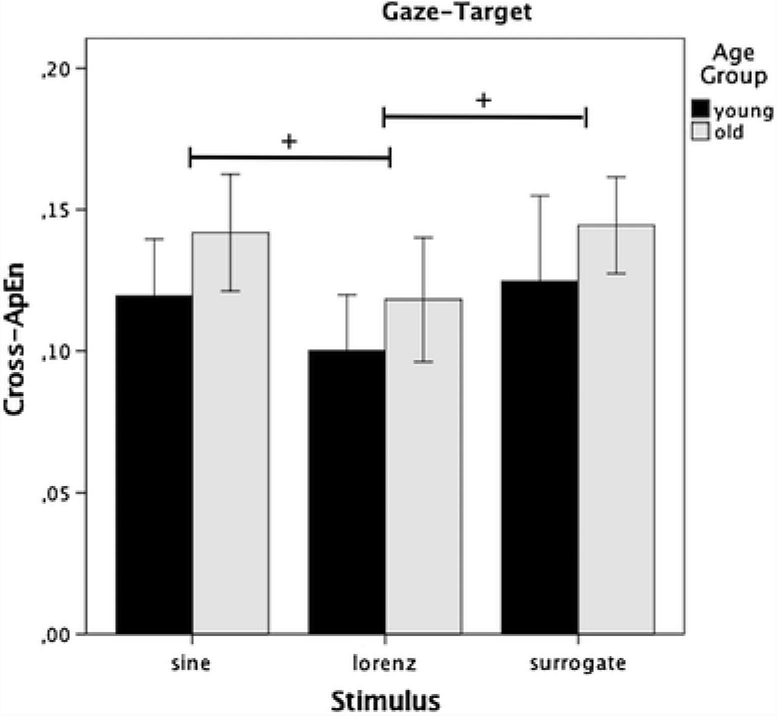
Values for phase and gaze are weighted by coherence ≥ 95 % of confidence limits

+: Significant difference between stimuli conditions at $p < .05$

The number of participants who maintained a linear (>0.5) gaze–target coherence at the dominant frequency (0.244 Hz) decreased in both groups across conditions of increasing stimulus complexity (Table 2). Nonparametric group comparisons of the gaze–target phase and gain for those group participants who maintained gaze–target linearity did not reveal a significant phase (periodic: $U = 24.0$, $p = 0.841$, chaotic: $U = 13.0$, $p = 0.610$, random: $U = 9.0$, $p = 0.107$) or gain (periodic: $U = 8.0$, $p = 0.053$, chaotic: $U = 13.0$, $p = 0.610$, random: $U = 10.0$, $p = 0.143$) difference between age groups. Nevertheless, the gaze–target phase lag significantly decreased for both groups when attending to the chaotic stimulus compared to the other two stimulus conditions ($X^{2}_{(2)} = 6.33$, $p = 0.042$). On the other hand, the gaze–target gain was not affected by conditions of increasing stimulus complexity ($X^{2}_{(2)} = 5.33$, $p = 0.69$).

Analysis of the gaze–target cross-ApEn on the other hand revealed a significant effect of the target's complexity on the gaze–target co-joined regularity ($F_{2,34} = 5.71$, $p = 0.007$, $h^{2} = 0.251$). Particularly, the gaze–target cross-ApEn was significantly lower when attending to the chaotic stimulus motion compared to the periodic ($F_{1,17} = 7.26$, $p = 0.015$, $h^{2} = 0.300$) and the random ($F_{1,17} = 7.46$, $p = 0.014$, $h^{2} = 0.305$) target motion suggesting a more synchronous gaze–target coupling (Fig. 5). This effect was similar in both age groups as suggested by the absence of an age group effect ($F_{1,17} = 3.299$, $p = 0.087$, $h^{2} = 0.163$) or an age by stimulus complexity interaction effect ($F_{2,34} = 0.003$, $p = 0.997$, $h^{2} = 0.000$).

Fig. 5



Gaze–target cross-approximate entropy. Group means and SD are displayed for the young (*black*, $n = 9$) and the old (*gray*, $n = 10$) group. +: significant stimulus complexity effect at $p < .05$

Discussion

In this study, we investigated how young and older adults couple their posture and gaze to visual motion cues of varying degree of complexity when actively tracking horizontal target motions with the whole body. The main finding is that aging diminishes the ability to couple postural sway to complex visual motion cues. On the other hand, gaze tracking of complex cues is not subject to aging influences. Interestingly, gaze is more synchronous to a complex than a periodically and randomly moving target, regardless of age.

Postural tracking

The novel finding of the present study is that the impact of aging on visuo-motor integration during active postural tracking depends on the nature of the visual motions to be tracked. Sway–target coherence was similar between age groups when tracking the periodic target but decreased when older adults tracked the less predictable target motions. In fact, for the older adult group, 3 out of 10 participants were not able to maintain sway–target linearity when tracking the chaotic stimulus motion. This number increased to 6 out of 10 participants when tracking the random stimulus motion. Older adults can employ prediction in order to compensate for age-related visuo-motor processing limitations (Young and Hollands 2012). Yet, prediction is not available when the visual target motion becomes less regular and thus more cognitively challenging. The less coherent sway–target motion when tracking the chaotic visual motion could be due to an age-related loss of complexity in body sway dynamics. With increasing age, the dynamics of standing posture become less complex and loose their fractal structure which is a necessary condition for maintaining adaptability to complex environmental stimuli (Duarte and Sternad 2008; Zhou et al. 2013). This loss of postural complexity in aging compromises postural stability (Manor et al. 2010), while older adults who maintain a non-fractal gait are more likely to experience a fall (Herman et al. 2005).

A weaker sway–target coupling when tracking the complex target motions may originate from older adults’ reduced neuromuscular ability to control and effectively exploit the multiple degrees of freedom available during the voluntary tracking task. The sway–target gain at the dominant stimulus frequency (0.244 Hz) was close to 1 for the young adult participants suggesting perfect amplitude matching when tracking the periodic and chaotic targets. However, this was lower (close to 0.75) for older participants when tracking the chaotic target revealing a reduced ability to reproduce the target amplitude motion. This can be due to the reduced capacity of the ankle muscles to generate the torque at the joint required for shifting the body weight to the extremes of the base of support (90 % of body weight) during voluntary sway (Manchester et al. 1989; Karamanidis et al. 2008). Although the ankle muscles play an important role for controlling sway in the anterior–posterior direction (Winter et al. 1993), tracking of a moving target in the medio-lateral direction requires the coordination of the body’s multiple degrees of freedom in order to convert joint to spatial (i.e., target) coordinates through a single point of force application. Older adults are limited in exploiting the available degrees of freedom in order to couple their postural sway to visual motion cues in the frontal plane (Hatzitaki and Konstadakos 2007). Since tracking of an unpredictable moving target in the frontal plane correlates with daily life gait stability (Cofré Lizama et al. 2015), our results support the idea of an age-related gradual loss of adaptability to the dynamic challenges of the environment.

Age-related delays in visuo-motor processing might also account for the reduced sway–target coupling when tracking the more complex motion cues. Sway–target phase increased as a function of stimulus complexity, and this increase was greater for the older as compared to the young participants. This is in accordance with the results of a previous study showing that older adults lost the CoM-target phasing at a lower frequency compared to young adults when tracking unpredictable targets of increasing frequency (Cofré Lizama et al. 2014). Moreover, a significantly higher cross-ApEn value for the older compared to young participants across all three stimulus conditions suggests that the ability to synchronize posture with visual motion cues diminishes with age. This inability to timely follow the visual stimuli of different temporal complexities with posture could be attributed to two reasons. Firstly, the complexity of standing postural sway is significantly reduced in aged individuals in comparison with healthy young adults, which is also influencing their adaptability to different environmental and task constraints. Thus, it may be harder for the older adults to couple their posture to an external moving stimulus. Secondly, even though there are no differences in gaze–target coupling between the groups, the processing or the weighting of the visual information for controlling posture could be affected by aging. In a study by Baweja et al. (2015), reducing the gain of the visual feedback diminished the age effect on movement variability during tracking a sine target with the hand or the foot. This finding suggest that older adults have greater difficulty in the timely processing of visual feedback information rather than the target's spatiotemporal characteristics for controlling posture. This was confirmed by the absence of a stimulus' complexity by age group interaction on our cross-ApEn results.

Gaze tracking

Interestingly, our results did not reveal an effect of age on gaze–target coupling. Young and older adults tracked the sine and complex target motions with similar coherence (around 0.6 on average) and a phase lag that was shorter when attending to the complex (Lorenz) target. The shorter phase lag, together with the significantly lower cross-ApEn when attending to the complex target, indicates that the chaotic stimulus motion was tracked with greater synchronicity compared to the two other target motions, regardless of age. These findings duplicate the results of a previous study (Hatzitaki et al. 2015) and suggest that the complex target motion imposes a higher demand on attending to the visual target motion as opposed to the sine stimulus motion which is more predictable or the random target motion that is harder to be tracked.

Gaze in this task reflects the eye muscle activity in smoothly pursuing the target since the stimulus motion was sufficiently slow to eliminate the recruitment of eye saccades. Smooth pursuit eye performance declines with age (Sprenger et al. 2011). To compensate for this decline, elderly use anticipation and prediction of the expected (i.e., repetitive) target motion based on prior knowledge. Moreover, it has been shown that the ability to anticipate the impeding target motion onset and predict the target continuation based on previous experience is preserved with age (Sprenger et al. 2011). This observation may explain the absence of an age effect on gaze–target coupling noted in our study. Although this seems reasonable when tracking the predictable target (sine), it does not explain the absence of an age effect when tracking the unpredictable targets. In a study investigating perceptual thresholds of different types of visual motion detection, significant aging effects were noted in the perceptual thresholds of translational motion but only moderate effects in the perception of biological motion (Billino et al. 2008). More interestingly, it was pointed out that the higher motion complexity is not necessarily associated with a greater age-related perceptual deficit. Based on this evidence, it can be argued that both age groups employ similar anticipatory processes when tracking the complex target motion, which results in similar gaze–target coupling.

It is also possible to attribute the absence of an age effect on gaze–target coupling to the less complex nature of the gaze tracking task. Gaze tracking is a simple, two-degree-of-freedom movement compared to postural tracking that is a more complex, multiple degree-of-freedom whole body task. This interpretation is in agreement with previous research reporting substantial age-related gait impairments during the concurrent performance of a secondary task that required visual processing but no age differences in visual performance (Bock and Beurskens 2011). An age-related longer latency between the onset of gaze and postural motion during a gaze re-orientation task

(Cinelli et al. 2008) also supports the idea that posture is a much more complex task and therefore more prone to aging influences when compared to gaze.

Limitations

Some limitations of the present study deserve further consideration in future research. First, our older adults sample consisted of active participants, and thus, different results could be expected for a different sample (e.g., sedentary older adults or fallers). Second, the statistical analysis of our linear measures (coherence, gain, phase) was limited at a single value of the 0–1 Hz frequency band that corresponded to the signals' dominant frequency (0.244 Hz). From a visual inspection of the averaged coherence, phase and gain curves (Fig. 2), it seems reasonable to expect different outcomes if the same spectral metrics were analyzed at a different frequency. For this reason, we plotted and qualitatively discussed the pooled (across participants) coherence, phase and gain curves in the 0–1 Hz frequency band. In addition, we analyzed the cross-ApEn between the performance and target signals which is a nonlinear measure that considers the full spectrum of the signal. Third, the number of older participants who maintained a significant performance–target coherence (i.e., >95 % cl) decreased when tracking the more complex signals. As a result, we analyzed the gain and phase measures using nonparametric statistics. Finally, the low gaze–target gain values reported in our analysis may be due to the limitation of our eye-tracking system in accounting for peripheral vision from single eye recordings.

Conclusions and practical implications

Overall, the present study showed that older adults are less able to adjust their posture to complex visual motion cues suggesting limitations in online visuo-motor processing as well as a less efficient exploitation of the body sway dynamics with age. The need to improve perception–action processes and increase complexity in the aging neuro-motor system suggests the use of complex stimuli in postural tracking exercise protocols. Research on auditory (metronome) guidance of posture and gait has already provided promising results in this direction. Use of nonlinear metronome oscillations has been proved beneficial for restoring the internal natural fractal scaling of Parkinsonian gait (Hove et al. 2012). Variations in the temporal structure of auditory (metronome) stimulation were effective in altering the dynamics of gait in older adults (Kaipust et al. 2013). The benefits of fractalic stimulation have recently been extended to the visual system by showing that entrainment to a fractal visual stimulus can also modulate the complexity of gait dynamics (Rhea et al. 2014). These studies provide promising evidence in support of using complex stimuli to guide sensory-motor performance in order to restore optimal variability and adaptability in the aging motor system. This is expected to improve older adults' capacity to adapt to the fractal structure of environmental stimuli. Although our results seem to support this idea, further work is required to explore the effects of using complex visual motion cues on short- and long-term visuo-postural adaptability and learning. It would be of interest to explore whether practicing active postural tracking of complex visual motion cues can improve perception action in aging and whether such improvement can generalize to daily life function. Also, extending this research in subclinical fall-prone adults or those with history of repetitive falls may provide meaningful insights into fall prediction and prevention research.

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