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1 Visually fixating or tracking another person decreases balance
2 control in young and older females walking in a real-world
3 scenario

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13

14 Highlights

15 1. Balance control was decreased in young and older adults similarly when fixating or tracking
16 another person

17 2. Older adults exhibited lower baseline stability than young adults during free gaze, and when
18 fixating or tracking another person

19 3. Free gaze in an uncluttered environment generated the most optimal balance outcome in young
20 and older adults

21

22 Abstract

23 Balance control during overground walking was assessed in 10 young (23.6 ± 3.4) and 10 older
24 (71.0 ± 5.5 years) healthy females during free gaze, and when fixating or tracking another person in
25 an everyday use waiting room. Balance control was characterised by medial/lateral sacrum
26 acceleration dispersion, and gaze fixations were simultaneously assessed with eye tracking
27 equipment. The results showed decreased balance control when fixating a stationary ($p=0.003$,
28 $g_{av}=0.19$) and tracking a walking ($p=0.027$, $g_{av}=0.16$) person compared to free gaze. The older
29 adults exhibited reduced baseline stability throughout, but the decrease caused by the visual tasks
30 were not more profound than the younger adults. The decreased balance control when fixating on or
31 tracking the observed person was likely due to more challenging conditions for interpreting retinal
32 flow, which facilitated less reliable estimates of self-motion through vision. The older adults may
33 also have adopted a more rigid posture to facilitate visual stability, which attenuated any ageing

34 effect of the visual tasks. The decrease in balance control, the first to be shown in this context, may
35 warrant further investigation in those with ocular or vestibular dysfunction.

36

37 **Keywords:** elderly gait, eye movements, postural control, smooth pursuits, trunk accelerations,
38 walking balance

39

40 1. Introduction

41 Vision helps maintain an upright posture during locomotion [1,2]. This is facilitated by changes in
42 patterns of light intensities caused by relative motion between an observer and their environment,
43 which are sensed at the retina. Lateral trunk lean, for example, would generate a translational flow
44 on the retina in the opposite direction [3]. The central nervous system uses this to estimate shifts in
45 body position and initiate postural adjustments [4]. Eye movements can change the structure of
46 retinal flow, and this has previously been suggested to affect balance control during locomotion.
47 That is, visually tracking a moving target with smooth pursuits led to increased medial/lateral (ML)
48 trunk movement and step-width variability in young and older adults [5]. During such eye
49 movements, although the target of fixation is stabilised on the fovea, the background information
50 invariably shifts on the retina in the direction opposite to the eye rotation [6]. This seems to make it
51 more difficult to estimate self-motion through visual means, which is similar to that shown in
52 standing experiments [7–9].

53

54 During our previous investigation [5], the visual target was projected in 2D at one end of the
55 laboratory. Humans often, however, fixate and track 3D objects located more in the foreground,
56 such as another standing or walking person in the field of view [10]. This would change the
57 structure of retinal flow when compared to a 2D target. Because the person would be closer to the
58 observer relative to the background, there would be defocus blur to regions immediately
59 surrounding the person [10]. Further, the relative distance would generate motion parallax, with the
60 retinal image of the region behind the person shifting in the direction of the observer's movements
61 [11]. Of interest is whether these factors would generate a different balance response in an observer
62 when compared to our previous investigation.

63

64 Previous studies examining parallax and balance control during locomotion have typically used
65 corridor style paradigms [12,13]. These do not create the same defocus blur or parallax which
66 would occur when fixating a single object ahead of the observer, such as another person.

67 Predicting what effect fixating another person would have on balance control during locomotion is
68 thus difficult. However, some evidence can be taken from standing experiments. These typically
69 show improvements to postural control when fixating a single near target in relation to the
70 background. The extra parallax cues are thought to provide ‘richer’ retinal information to make
71 postural adjustments against (for a review see [4]). Therefore, it is feasible that the parallax caused
72 by fixating a standing person (whilst the observer is walking) could maintain or improve balance in
73 the observer when compared to no person being present. On the other hand, if the person being
74 observed walked perpendicular to the observer’s heading direction, a smooth pursuit would be
75 needed to track them. Thus, retinal flow would consist of a combination of radial expansion from
76 forward progression, and horizontal flow from the eye rotation [14]. Similar to our previous
77 experiment [5], this would resemble a curved movement with a shifting focus of expansion [14].
78 Although there are compensatory mechanisms against retinal image motion during smooth pursuits
79 to maintain perceptual stability [6,15], these are imperfect. For instance, there have been
80 documented declines in motion sensitivity [16], and temporal contrast sensitivity to moving stimuli
81 [17]. Ultimately, the altered flow could lead to less accurate visual detection of self-motion, and this
82 could cause a decrease in balance control despite the parallax cues which would be present.

83
84 If tracking a walking person is shown to decrease balance control, it could have important
85 implications in older adults. Older adults have been shown to have a reduced ability to decouple
86 retinal flow caused by external motion from that caused by self-motion, potentially due to
87 somatosensory processing declines [18]. Further, this has been shown to decrease stability during
88 locomotion [19]. Therefore, if older adults are less able to process retinal flow during the smooth
89 pursuit to track a walking person, it could lead to a bigger decrease in stability when compared to
90 young adults. Moreover, although our previous laboratory investigation showed a similar decrease
91 to balance control in young and older adults tracking a 2D target, the older adults were already
92 exhibiting lower baseline stability. This is typical in healthy older populations. Any further decrease
93 to balance control caused by tracking a person, regardless of comparison to young adults, would
94 thus be undesirable.

95
96 Therefore, the present investigation assessed balance control during walking in young and older
97 adults during free gaze, and when visually fixating or tracking a standing or walking person in a
98 real-world environment. Balance was characterised by ML Sacrum acceleration dispersion. It was
99 hypothesised: 1) Visually fixating a standing person would maintain or improve balance control due
100 to more information from parallax; 2) balance would be decreased when the observed person was
101 walking owing to altered retinal flow patterns; 3) the decreased balance caused by tracking the

102 person would be more profound in the older adults, and the older adults would exhibit less baseline
103 stability throughout testing.

104

105 2. Methodology

106 *Participants*

107 Ten young (mean \pm SD: age: 23.6 ± 3.4 years, height: 1.68 ± 5.8 m, mass: 69.0 ± 9.9 kg) and 10
108 older (mean \pm SD: age: 71.0 ± 5.5 years, height: 161.2 ± 5.5 m, mass: 63.9 ± 10.3 kg) healthy
109 females participated in the investigation. The older adults were interviewed by telephone to
110 determine eligibility and adhered to inclusion criteria previously outlined [9]. In brief, they had no
111 known musculoskeletal or neurophysiological conditions which could negatively affect balance
112 control during walking. The participants had an uncorrected visual acuity of $\geq 20/100$ and were able
113 to ambulate in the community without visual correction. The participants were also free from
114 convergence insufficiency. Although this is not a typical problem in older adults [20], it could have
115 affected their ability to focus on the stimuli. The investigation was carried out in accordance with
116 the University of Cumbria's recommendations and guidelines for research involving human
117 subjects, and all procedures, information to the participants, and participant consent forms, were
118 approved by the University of Cumbria Research Committee. All participants gave written informed
119 consent in accordance with the Declaration of Helsinki.

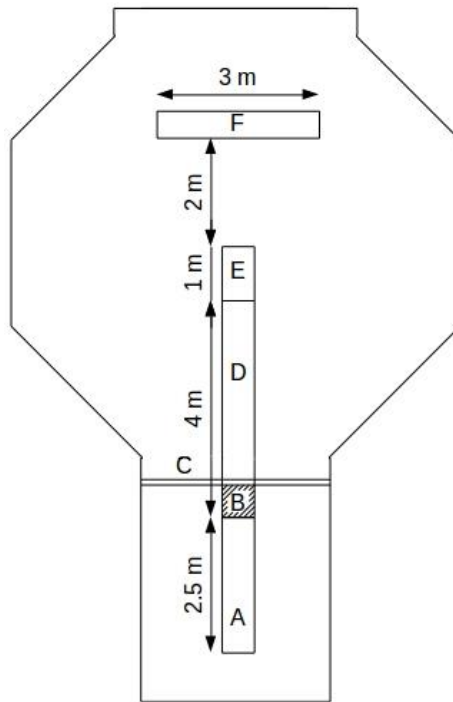
120

121 *Equipment*

122 Testing was carried out on a flat walkway in an everyday use waiting room (Fig. 1). The walkway
123 consisted of a 2.5 m entry area, which has previously been shown as adequate for older adults to
124 reach a steady-state velocity [21], a 4 m data capture area where balance characteristics were
125 assessed, and a 1 m exit area. Sliding doors, controlled by the researcher, concealed the waiting
126 room from the participants when they were at the start of the walkway. A member of the research
127 team (actor) would be absent from or standing or walking within a standardised actor area at the far
128 end of the waiting room (Fig. 2, see experimental protocol). A custom-made contact mat was used
129 to send a signal to a display which informed the actor when to begin walking and in which direction
130 (also see experimental protocol). Four inertial measurement units (IMUs: Opal, APDM, Portland,
131 Oregon) measured accelerations of the centre front head, sacrum, and left and right ankle
132 anatomical land marks of each participant. Participants wore eye tracking glasses (Tobii Glasses 2
133 Eye Tracker, Tobii Technology, Danderyd, Sweden) which have a one-point calibration procedure,
134 and autoparallax and slippage compensation allowing for persistent calibration throughout each
135 trial.

136

137



138

139

140 Figure 1. A schematic diagram of the experimental environment. The walkway into the waiting
141 room consists of entry area (A); contact mat (B); sliding doors (C); data collection area (D); exit
142 area (E); pedestrian area (F). All distances are to scale. Note that the observer walkway was not
143 visually marked out and only verbal instructions were given to instruct the participants to stop
144 walking.

145



146

147 Figure 2. Example of a participant's point of view whilst walking in the waiting room taken from
148 the eye tracking camera. The stationary actor is present in this condition. The red circle on the actor
149 represents a gaze fixation.

150

151 *Experimental protocol*

152 The sliding doors were shut before each trial and then opened signalling the trial to commence. The
153 participants then walked straight into the room at a self-selected pace until verbally instructed to
154 stop when they reached the exit area. Three conditions were implemented: free gaze (FREE),
155 stationary actor (STAT), and walking actor (WALK). For FREE, the waiting room was void of the
156 actor. For STAT, the actor stood stationary in the centre of the participant's field of vision. For
157 WALK, on the first heel strike on entering the data capture area, the contact mat (beginning at the
158 start of the data capture area and ending 30 cm along the walkway) sent a signal to a laptop out of
159 view of the participant which informed the actor to walk 1.5 m horizontally across the participant's
160 field of vision. The direction was random on each trial. During FREE, the participants were given
161 no instructions where to look. During STAT and WALK, they were informed to look at the actor at
162 all times, and if the actor moved, to track them with their eyes only making sure not to rotate or tilt
163 their heads. The 1.5 m threshold corresponded to 12° of visual angle relative to the participants
164 while they were at the start of the data capture area, and 26° at the end. During STAT and WALK,
165 the actor was present on door opening and was thus visible to the participants at the start of the
166 walkway. However, prior to door opening, the participants were blinded to the conditions in the
167 room.

168
169 Five trials for each condition (FREE, STAT and WALK) were completed. The conditions were
170 randomly assorted and segregated into 3 blocks of 5 trials. There was a 30 s rest period between
171 each trial, and a 2-5 min rest period between each block of 5 trials.

172
173 *Data analysis*

174 Raw data from the IMU devices were exported and analysed offline (Scipy, Scientific Computing
175 Tools for Python). Raw data were filtered with a phase-corrected low-pass Butterworth filter (10Hz
176 cutoff). Heel strikes and mid-stance phases were determined using validated methods previously
177 described in detail [22,23]. All data were truncated to the first right heel strike upon entering the
178 data capture area, and the third left stride midstance period. Standard deviation (SD) of linear
179 Sacrum acceleration in the participants' ML direction (aligned to the relevant axis of the IMU) then
180 defined sacrum acceleration dispersion, which characterised balance control.

181
182 Walking speed was calculated as a function of time and total distance covered. Distance covered
183 was defined as the total of 2 stride lengths between the 3 right foot locations at each midstance
184 period. The right foot locations were calculated using the methods of Rebula et al. [23]. In short, the

185 Opal proprietary Kalman filter yields a time varying IMU orientation estimate in the global
186 coordinate system, with an arbitrary home location corresponding to the first midstance period
187 irrespective of positioning of the IMU on the ankle. The orientation time series was used to
188 transform the IMU's acceleration trace into the global reference frame by removing the gravity
189 vector. The acceleration trace was then integrated forward between each known zero velocity
190 instant (defined as each midstance period) using the trapezoidal rule to yield a zero velocity updated
191 global velocity trace. The IMU's trajectory in space was then calculated by integrating (also
192 trapezoidal rule) the corrected velocity trace between each zero velocity instant. Principal
193 component analysis was used to fit a line in 3D between the three midstance locations (minimising
194 the distance between the line and each point) which defined the local heading direction. The
195 distance between each footfall location along the heading direction then defined stride length.

196

197 To ensure the participants followed instructions, SD of head rotations about the yaw axis obtained
198 from Opal proprietary orientation estimates were calculated, in addition to gaze coordinates [5]. In a
199 modification to the previous gaze analysis [5], a pre-trained histogram of orientated gradients
200 combined with a linear support vector machine model (OpenCV, computer vision library) was used
201 to automatically identify the actor and record their coordinates on the exported 2D video frames,
202 which were subsequently compared to those of the gaze coordinates. The centroid inside the
203 bounding box surrounding the actor was used as a tracking point, which corresponds roughly to the
204 centre of mass of the actor. Root mean square (RMS) of gaze subtracted from the actor coordinates
205 then defined RMS gaze error, and Pearson's correlation coefficients between the gaze and actor
206 coordinates defined the strength of relationship between both timeseries.

207

208 *Statistical analysis*

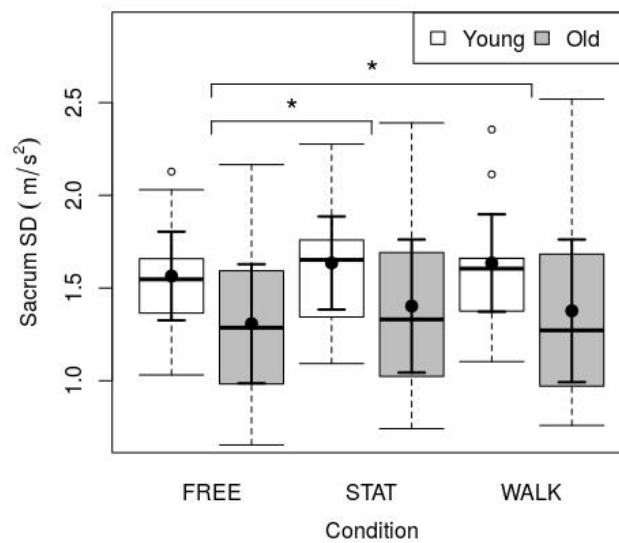
209 The mean/median of the 5 trials for each participant in each condition was used for statistical
210 analysis of the relevant outcome measure depending on normal or non-normal distribution of the
211 raw data. Normality of the aggregated data was then confirmed for Sacrum SD, Walking speed and
212 Gaze error RMS, but not for Head rotation SD or correlation coefficients between the gaze and
213 actor coordinates. Condition ($3 \times$ visual scenes) and age (young and older) were considered as 2
214 independent factors. The effect of these factors on Sacrum SD, and Walking speed, were examined
215 with a 2 way (condition \times age) mixed analysis of variance (ANOVA). The same model was applied
216 to examine RMS gaze error, but with only STAT and WALK considered. Robust mixed ANOVAs
217 based on trimmed means [24] were used to examine Head rotation SD and correlation coefficients
218 between the gaze and actor coordinates. Post-hoc analyses were *t*-tests with Bonferroni corrections.
219 Finally, where significant differences were found ($p \leq 0.05$), Hedges' g_{av} effect sizes were calculated

220 [25]. Common indicative thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8).
221 Statistical analyses were performed with the R software package.

222

223 3. Results

224 Sacrum SD in the ML direction is shown in Fig 3. Sacrum SD showed a main effect of condition
225 ($F_{2,36}=8.585, p<0.001$). Post-hoc comparisons revealed larger Sacrum SD during STAT ($p=0.003,$
226 $g_{av}=0.19$) and WALK ($p=0.027, g_{av}=0.16$) compared to FREE. Sacrum SD showed no main effect
227 of age or interaction effect between condition and age.



228

229

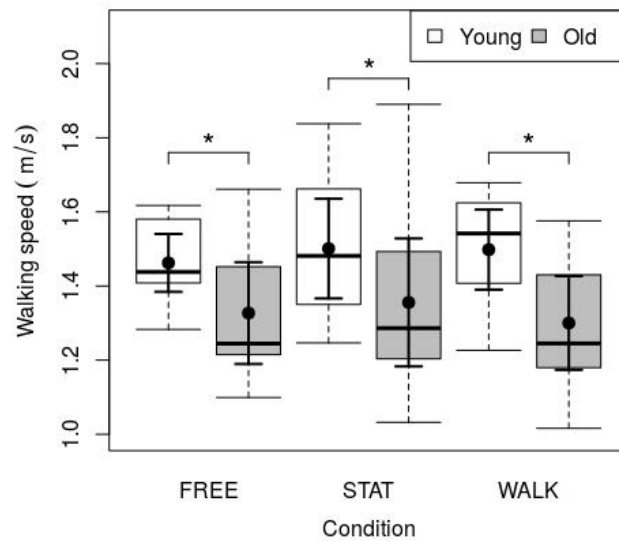
230 Figure 3. Sacrum SD in the ML direction in young ($n=10$) and older ($n=10$) females during different
231 eye movement conditions. FREE: free gaze; STAT: stationary actor; WALK: walking actor. Data are
232 displayed as means and 95% confidence intervals in bold dots and bars, and medians and lower and
233 upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference
234 between conditions.

235

236 Walking speed is shown in Fig 4. Walking speed showed evidence of a main effect of age
237 ($F_{1,18}=4.325, p=0.052$), with a reduction in the older adults compared to the younger adults.

238 Walking speed showed no main effect of condition, or any interaction effect between condition and
239 age.

240



241

242

243 Figure 4. Walking speed in young ($n=10$) and older ($n=10$) females during different eye movement
 244 conditions. FREE: free gaze; STAT: stationary actor; WALK: walking actor. Data are displayed as
 245 means and 95% confidence intervals in bold dots and bars, and medians and lower and upper
 246 quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between
 247 age groups.

248

249 Head rotation SD is shown in Table 1. Head rotation SD showed no main effect of condition or age,
 250 or any interaction effect between condition and age. RMS gaze error and the correlation coefficients
 251 between gaze and actor coordinates are shown in Table 2. RMS gaze error and the correlation
 252 coefficients (all strong) showed no main effects of condition or age, or any interaction effects
 253 between condition and age. This suggests the participants followed instructions and tracked the
 254 actor with their eyes whilst refraining from head rotations.

255

256

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260

261

262 Table 1. Head rotation SD about the yaw axis in young ($n=10$) and older ($n=10$) females during
 263 different eye movement conditions. FREE: free gaze; STAT: stationary actor; WALK: walking actor.
 264 Data are displayed as means \pm SD.
 265

Condition	Head rotation SD ($^{\circ}$)	
	Young	Older
FREE	3.17 \pm 2.10	4.91 \pm 4.26
STAT	2.64 \pm 1.67	3.77 \pm 2.02
WALK	2.82 \pm 1.15	3.69 \pm 1.51

266

267

268 Table 2. RMS gaze error and Correlation coefficients between gaze and actor coordinates in young
 269 ($n=10$) and older ($n=10$) females during different eye movement conditions. STAT: stationary actor;
 270 WALK: walking actor. Data are displayed as means \pm SD.

271

Condition	RMS gaze error (a.u.)		Correlation coefficients (r)	
	Young	Older	Young	Older
STAT	2.10 \pm 0.49	1.87 \pm 0.50	0.92 \pm 0.17	0.96 \pm 0.08
WALK	2.19 \pm 0.50	1.97 \pm 0.60	0.94 \pm 0.05	0.92 \pm 0.11

272

273

274 4. Discussion

275 The present results show a reduction in balance control whilst visually fixating or tracking another
 276 person as opposed to free gaze in young and older adults. In contrast to our first 2 hypotheses, there
 277 was a similar decrease to balance control when the person being observed was standing compared
 278 to walking. There were no differences in gaze errors between conditions or ages, and the
 279 correlations between the gaze and actor coordinates were all strong. It can thus be assumed that the
 280 participants followed instruction and averted their gaze to the actor. There were also no changes in
 281 walking speed between conditions, and so alterations to walking speed could not have altered ML
 282 trunk acceleration. Therefore, it seems to be that the underlying mechanisms responsible for the
 283 decreased balance control had a similar magnitude of effect in both conditions.

284

285 One potential explanation is that the act of constraining vision to the actor inherently altered
286 balance characteristics as opposed to free gaze. That is, it might have hindered the gathering of
287 visuospatial information useful for balance control. Doi et al. [26], for example, demonstrated
288 increased ML trunk acceleration in healthy older adults reading from an earth-fixed display when
289 compared to free gaze [26]. However, they also found a reduction in walking speed, which was
290 thought to be associated with the ‘dual task’ nature of walking and reading. The present results do
291 not show this. Moreover, merely constraining vision to a fixed location ahead of the observer has
292 previously been shown not to alter gait characteristics when compared to free gaze in older adults
293 [27]. Therefore, it is unlikely that the present results can be explained by either simply constraining
294 vision, or by dual task effects.

295
296 From another perspective, gazing real-world biological motion adds a social layer when compared
297 to inanimate stimuli. Varlet et al. [28], for example, showed that 2 participants who were in each
298 other’s field of view exhibited unintentional coupling of variables associated with control of stance
299 when performing a visual tracking task. This phenomenon, termed ‘interpersonal coordination’, has
300 been shown in a variety of conditions [29]. In the present experiment, as the actor walked across the
301 participants’ field of view (corresponding to the participants’ ML plane), any coupling could have
302 contributed to the increase in ML trunk acceleration. However, unintentional coupling would not
303 explain the decreased balance control when the actor was stationary.

304
305 A more likely explanation pertains to a change in the way parallax flow is processed during
306 locomotion compared to standing. That is, we predicted parallax caused by fixating the standing
307 person would maintain or improve balance control, since balance during quiet stance improves
308 when fixating near objects [4]. However, quiet stance is associated with slow and small head
309 movements. During locomotion, the gait cycle would induce bigger and more abrupt movements of
310 the head [30]. In the present experiment, this would have caused the image of the background
311 behind the actor (which would have been subject to defocus blur) to shift up and down and side to
312 side with greater magnitude and more abruptly on the retina. Therefore, it seems that this dynamic
313 retinal flow was more difficult to interpret, and equally so to the flow caused by tracking the
314 walking person.

315
316 With regard to ageing effects, the older adults walked more slowly throughout testing compared to
317 the younger adults. This is typical, and the values fall in line with previous literature [31].
318 Importantly, the older adults exhibited similar ML acceleration dispersion compared to the younger
319 adults despite the reduced walking speed. It is known that ML trunk acceleration is dependent on

320 walking speed [32]. Therefore, the older adults were relatively more unstable than the younger
321 adults. This agrees with our previous findings [5] and supports part of our final hypothesis.

322
323 Despite the lower baseline stability, averting gaze to the actor did not cause a bigger reduction to
324 balance control in the older adults when compared to the young adults, which was unexpected. One
325 possible explanation is that the older adults simply processed retinal flow during the visual tasks as
326 effectively as the young participants. This might not be surprising considering other older
327 populations have been shown to exhibit resistance to visual motion perception ageing effects due to
328 compensatory mechanisms [33]. The present older participants were also healthy and could all
329 ambulate within the community without visual correction. They can thus be considered as a
330 relatively healthy sample of the wider older population.

331
332 An alternative explanation relates to rigidity. In their review, Young and Mark Williams [34]
333 suggest older adults may prioritise visual stability during visual search behaviours by adopting a
334 more rigid posture. This is because older adults can have a reduced ability to initiate stabilising
335 head movements [35]. In the present experiment, averting gaze to the actor might have caused a
336 similar stiffening effect. Hence, the older adults might have been working harder to maintain a rigid
337 posture to facilitate the ocular movements, and this led to attenuated ML trunk acceleration. In a
338 similar vein, an increase in anxiety about performing the visual tasks could have also contributed to
339 a stiffer postural response. For example, Eikema et al. [36] linked anxiety levels to an increase in
340 postural stiffness during a visual target avoidance task. Indeed, increased anxiety has often been
341 shown to generate a more rigid body position in older adults [34]. To shed light on these potential
342 mechanisms, it would be necessary to incorporate more measurement techniques. However, it
343 should be noted that the present experiment attempted to reduce the amount of equipment utilised,
344 thus maximising the real-world element of the research.

345
346 There was no ageing effect for the visual parameters of RMS gaze error and correlation coefficients
347 between gaze and actor coordinates. During locomotion, the accuracy of the visual system has been
348 shown to change for saccadic eye movements but not for smooth pursuits in older adults [37], so
349 this might not be unexpected. However, the eye tracking equipment used in the present
350 investigation is not sensitive to fine grained metrics, such as latencies – it was mainly intended to
351 ensure that the participants were following instructions.

352
353 In conclusion, the present results show a reduction in balance control in young and older adults
354 when fixating or tracking another person as opposed to free gaze. This was likely related to altered

355 retinal flow. The lack of an ageing effect from the visual tasks might indicate the older adults
356 adopted a more rigid posture to facilitate visual stability. However, further research is needed to
357 confirm this notion. Because the older adults were already exhibiting a lower baseline stability, the
358 further decrease caused by gazing the actor was undesirable. The small increase in sacrum
359 acceleration dispersion may also warrant further investigation in those at a greater risk of falling,
360 such as those with ocular or vestibular dysfunction.

361

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366

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