LANCASTER UNIVERSITY

The Effects of Eye Movements on Postural Control in Young and Older Adults

Neil M. Thomas, BSc

A thesis submitted for the degree of
Doctor of Philosophy

Word count: 62480

April 2018

Declaration of Authorship

I, Neil M. Thomas, BSc, declare that this thesis entitled, 'The Effects of Eye Movements on Postural Control in Young and Older Adults' and the work presented in it are my own, and has not been submitted in substantially the same form for the award of a higher degree elsewhere, and that the word count does not exceed 80,000 words.

“Sometimes science is more art than science... A lot of people don’t get that”

- Rick Sanchez

Acknowledgements

The experimental work described in this thesis was supported by the Dowager Countess Eleanor Peel Trust.

To Susan, Theo and Tim, thank you for giving me the opportunity of a lifetime.

Thank you to all my family – your support during my PhD has been invaluable.

Abstract

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Eye movements are used day-to-day to acquire visual information. Vision is also used for postural control. There are growing indications eye movements can affect postural control. However, this has not been investigated in older adults, which is surprising given the high incidence of falls in older populations. The present thesis aims to address this.

The first experimental chapter explores the effects of eye movements on balance during standing in young and older adults. The findings show decreased stability during smooth pursuits, whereas saccades maintained stability to that when fixating a static target. The older adults matched the younger groups performance throughout.

The second experimental chapter explores the effects of smooth pursuits and saccades on balance during locomotion in young and older adults. Smooth pursuits were shown to decrease stability, whilst saccades maintained stability compared to fixating a static target. The effects of the eye movements were similar in the older adults. However, the elders exhibited lower baseline stability.

The third experimental chapter explores the effects of tracking a real-world stimulus (another person known as 'pedestrian') on balance control during locomotion. The pedestrian could be standing still or walking. Fixating the stationary and the walking pedestrian decreased stability similarly when compared to free gaze when the pedestrian was not present.

To determine whether these results were transferable to natural gaze rather than instructed gaze, the fourth experimental chapter explores free gaze patterns in a similar real-world environment. Both the young and older adults typically fixated the pedestrian when he was standing still and walking, but began to ignore him once he had walked away from their direction heading. Therefore, experiment 3 behaviour was transferable to natural gaze patterns. The older adults also adopted a more cautious approach by fixating regions on the ground initially, and for longer, before looking to their direction heading.

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Chapter 1

General introduction

There is a well documented high incidence of falls and fall-related injuries amongst older adults (Ambrose et al., 2013). The consequences not only impact on the individuals concerned, socially and psychologically, but place a substantial burden on health care providers the world over. Fragility management is thought to cost the UK National Health Service alone £2.7 billion a year (NICE, 2013). This is further exacerbated by today's ageing population, which is expected to reach over 21.1% by 2050 (UN, 2013). Furthering understanding of the mechanisms associated with increased risk of falls is, therefore, an issue of major contemporary relevance.

1.1 Human balance in context

Maintaining an upright posture during day-to-day activities is a largely automatic affair and may seem easy for most healthy young adults. However, the mechanisms and processes which enable us to achieve this are numerous and complex in nature. This is because the very act of being upright places us in an inherently unstable position. Consider a standing person. The point at which all the matter contained within their body is concentrated, known as the centre of mass (COM), is located high above a relatively small area encompassing the feet. Thus, gravity is always pulling body segments about their supporting pivots (the ankles, knees and hips), and we must make continuous corrections to prevent loss of balance (Winter, 1995). Things become even more challenging during walking, as the COM must be voluntarily shifted forward, which effectively leads to a cyclic series of controlled falls onto the lead foot (Winter, 1995). Add to this changing terrain and complex environments, and balance demands increase significantly (Patla, 1997). Intuitively then, a person must sense how they are moving in relation to the external environment in order to initiate appropriate postural adjustments (Guerraz and Bronstein, 2008). One such sense is vision.

1.2 Vision and balance control

1.2.1 Retinal

Visual estimates of self-motion are typically considered in the context of Gibson's theory of direct perception (Gibson, 1950). Gibson suggested that light reflected off structures in the environment reaching the retina creates an optic array surrounding the observer. When the observer moves, the structure of the array changes, which generates an optic flow field about a point of central observation (Gibson, 1950). Consider a standing person who sways in the lateral direction whilst looking at a fixed point on a wall. The change in patterns of light on the retina (caused by the person's movement) would contain information about the magnitude and direction of motion in relation to the fixed point, and the central nervous system

(CNS) appears to use this to initiate appropriate postural corrections. Evidence for this can be taken from experiments involving moving visual surrounds, e.g. linearly oscillating walls, floors and tunnels (Bronstein, 1986, Dijkstra et al., 1994, Fluckiger and Baumberger, 1988, Lee and Lishman, 1975, Stoffregen, 1985), which have frequently shown a coupling of postural sway with stimulus motion. This is considered to be a consequence of the CNS misinterpreting self-motion for motion of the visual field and initiating incorrect postural responses (Guerraz and Bronstein, 2008).

More recently, retinal detection of self-motion for balance control has been shown to persist during locomotion, with direction specific mediolateral (ML) and anterioposterior (AP) trunk movement and increased step-width variability in response to perturbations of the visual field (Logan et al., 2010, 2014, Franz et al., 2015). Step-width variability is of particular interest as it is linked to control of the bodies COM in the ML plane on a step-to-step basis (Bauby and Kuo, 2000). Such contributions appear to be less dominant in the AP plane – since the magnitude of change to the visual field is far greater than that in the ML plane, estimates of self-motion with respect to the vertical can be more challenging in the AP plane (Warren et al., 1996).

1.2.2 Extraretinal

Another mechanism of visual self-motion detection relates to extraretinal signals. Paulus et al. (1984) found standing balance was improved whilst participants visually fixated on a small stationary light emitting diode in an otherwise dark environment when compared to complete darkness. In these conditions, compensatory eye movements in response to movements of the head during postural sway keep gaze fixated on the target (Kowler, 2011), implying little or no changes to light patterns on the retina. Thus, the eye movements themselves must facilitate estimates of changes in body position relative to the fixation point. Two lines of reasoning have been discussed to explain this behaviour. The first is related to extraocular muscles feeding information about eye position, which can only be interpreted after initiation of eye movements – evidence for this comes from direction specific postural sway in response to stimulation of the extraocular muscles responsible for the eye movements (Guerraz and Bronstein, 2008). The second infers a copy of the motor command to signal eye movements (an efference copy) is used to anticipate displacement of the eyes relative to the fixation point, which suggests that changes in body position can be predicted in a feed-forward manner (Guerraz and Bronstein, 2008).

It is currently not known if the extraretinal component of balance control persists during walking. However, researchers found a minimum threshold of 0.3° of eye movement for 1 cm of translational head movement was useful for extraretinal balance control during standing (Guerraz and Bronstein, 2008). During locomotion, the gait cycle would induce translation head movements meeting this threshold. Thus, it seems logical that extraretinal signals may be of use for balance control during locomotion, at least when fixating an appropriately stable region of the environment.

1.3 Eye movements

The extraretinal signals used for balance control result from gaze controlling eye movements initiated by the vestibulo-ocular reflex (VOR) and smooth pursuit system. These are used to stabilise a fixation and maintain visual consistency by keeping the object of interest on the central region of the retina (the 'fovea'), where visual acuity is highest (Kowler, 2011). In addition to facilitating extraretinal balance control, such eye movements can be considered critical for accurate retinal detection of self-motion, since they provide a stable visual reference frame from which shifts in body position can be estimated. Other kinds of eye movements, however, can change the structure of retinal flow, and have been shown to affect balance control.

1.3.1 Smooth pursuits

Smooth pursuits are used to view moving objects, where a continuous eye rotation keeps the target of interest stabilised on the fovea and thus in clear view (Kowler, 2011). Strictly speaking, smooth eye rotations are needed when tracking fixed objects during self-motion in addition to externally moving objects. For example, fixating a target located on the ground whilst walking. Because this can be considered a 'gaze control' eye movement, herein, smooth pursuits are considered in the context of tracking externally moving objects only (e.g. a passing pedestrian).

Smooth pursuits have been shown to increase postural sway in young adults (Glasauer et al., 2005, Laurens et al., 2010). Participants were asked to track an oscillating target over a feature rich background, and thus, in the presence of retinal flow. Therefore, the retinal flow generated during the smooth pursuit must have been more difficult to interpret for balance control. This can be explained by changes in its structure. During a smooth pursuit, whilst the target of interest is typically stabilised on the fovea, the background information appears to shift in the opposite direction to the target movement, and may be subject to motion blur depending on the speed of the eye rotation (Schulmann et al., 1987). This would likely make the retinal flow more complicated and thus difficult to interpret to estimate changes in body position, which results in less postural stability. Such an effect may be further exacerbated by the retinal flow being prevalent in the periphery of vision, which has been associated more with balance control (Dichgans and Brandt, 1978).

In a second condition, the participants tracked an oscillating target with no background visual information (in an otherwise dark environment), which also increased postural sway. Assuming accurate tracking of the target, retinal flow in these conditions would be minimal. Thus, the reduced stability was likely a consequence of more noisy extraretinal signals.

There are data, however, which suggest that smooth pursuits can improve stability (Rodrigues et al., 2015). Postural sway when tracking a moving target was compared to that when fixating on a stationary target, and there was an increase in stability. The researchers suggested that postural sway was modulated to afford greater accuracy of gaze behaviour, or to stabilise the relationship between body position and visual orientation. The exact reasons for the differences in results across experiments remains unexplained, but might be related to differences with the methodological designs. For example, Rodrigues et al. initiated the visual stimulus on a computer monitor, whereas other studies utilised larger projection screens occupying the full field of vision (Glasauer et al., 2005, Laurens et al., 2010). Therefore, the relatively small displacement of the visual target on the computer screen – which would have generated an equally small smooth pursuit eye rotation – did not affect retinal flow sufficiently to bring about a negative change to balance.

Despite investigations about how humans control their direction heading during smooth pursuits, it is currently not known if and how they affect balance during locomotion with respect to maintaining an upright posture. When considering the nature of retinal flow, however, negative changes to balance are feasible. For example, visually fixating a stationary object straight ahead whilst walking would cause radial flow from forward progression, and this would emanate from the central point of observation, with information at the periphery of vision shifting parallel to the line of motion (Warren and Hannon, 1990). Such flow may be considered useful for balance control since it provides a relatively stable reference frame (assuming accurate gaze control) from which self-motion with respect to the upright can be determined. Conversely, tracking an object in horizontal motion would cause horizontal flow from eye rotation in addition to radial flow from forward progression (Warren and Hannon, 1990). The resulting pattern would resemble a curved movement with a shifting focus of expansion. Similar to during standing, this added complexity may cause difficulty when estimating self-motion, thus decreasing balance control.

It can be expected that the dominant area of change might be in the ML plane, since visual sensitivity to retinal flow is greater there (Warren et al., 1996). Although, since vision does affect the AP plane, changes in this plane caused by smooth pursuits cannot be ruled out, and this may even be specific to the different phases of locomotion. Recent work by Logan et al. (2014) has revealed increased foot dorsiflexion and thigh flexion during the swing phase of gait with an approaching visual scene (sped up optic flow in relation to walking speed). The major implication of this is that the midstance of gait appears to mark a visually sensitive period to AP flow in which the height of the swing limb can be modulated in order to accommodate for hazards or impending collisions. If visual tracking during smooth pursuits reduces the ability to interpret AP flow due to more complicated retinal flow patterns, it could affect swing limb trajectory and thus reduce the efficacy of trip avoidance strategies.

1.3.2 Saccades

Saccadic eye movements are rapid shifts of gaze from one region or target to another, and are commonly utilised to visually explore the environment (Kowler, 2011). In contrast to smooth pursuits, saccades have consistently been shown to maintain or improve stability (Bonnet and Baudry, 2016, Giveans et al., 2011, Legrand et al., 2013, Stoffregen et al., 2006). Maintenance of stability may not be unexpected. Because saccades are essentially a series of fixations separated by short rapid intervals, they facilitate relatively long periods of high visual acuity between successful shifts of gaze. Thus, they can preserve the stable visual field similar to gaze control eye movements. The improved balance control in some situations has been suggested to be a result of the CNS attenuating body movements to better connect pre- and post-saccadic views, thus facilitating more stable gaze shifts. The magnitude of attenuation during saccades is thus likely dependent on factors such as frequency and duration of saccades, with higher frequencies requiring more postural stabilisation to facilitate accurate gaze shifts. Such a response also likely rules out normal saccades and smooth pursuits increasing cognitive load to the point of negative balance control. Thus, the changes to posture caused by smooth pursuits (Guerraz and Bronstein, 2008, Laurens et al., 2010), rather than being due to cognitive load, were likely due to changes in retinal and extraretinal signals. Presumably, saccades with an unnaturally high frequency would reduce stability, since the useful stable visual field (usually preserved with slower frequency saccades) would become difficult to interpret. That is, there would be less time for fixation and more time when vision is down-weighted during gaze shifts.

With regard to locomotion, similar to smooth pursuits, the effects of saccades have not strictly been examined in the context of balance control. However, since it is known saccades maintain longer periods of fixation, the stable reference frame provided by fixations should be preserved during locomotion – ignoring saccades to extreme displacements and/or with unnaturally high frequency.

1.4 Ageing

1.4.1 Processing retinal information for balance control

Advanced age has been shown to cause a decline in detecting self-motion from visual information (Warren et al., 1989), such as a reduced ability to detect direction heading from optic flow and to re-weight visual information during locomotion (Berard et al., 2009). Older adults are also typically more sensitive to visual field perturbations during standing (Borger et al., 1998, Sundermier et al., 1996, Wade et al., 1995) and walking (Franz et al., 2015), with bigger postural sway, and increased ML step placement and COM trajectory variability, respectively. It is thought that the ageing CNS relies on visual information more for balance control, at least in the short term (Jeka et al., 2006, 2010), because of vestibular and mechanical sensory declines (Bugnariu and Fung, 2007, Sundermier et al., 1996, Yeh et al., 2014). Strong evidence for this interpretation comes from older adults displaying increased sensitivity to visual feedback coupled with reduced sensitivity to tendon vibration (Eikema et al., 2013). Thus, if elders rely on vision more and cannot decompose retinal flow as effectively as younger adults, eye movements may exacerbate the increase in postural sway demonstrated in some young subjects tracking a moving target over fixed backgrounds.

1.4.2 Vestibulo-ocular reflex

The VOR is important for stabilising the retinal image thus keeping gaze fixated on regions of interest during movements of the head. Therefore, it is critical for gaining accurate estimates of self-motion based on retinal and extraretinal information. Researchers have often examined age-related declines in the VOR by testing the ability of elders to fixate on stationary targets during movements of the head. Peterka et al. (1990) found a decrease in VOR gain response during full body sinusoidal rotations using electrooculography. Paige (1991) also found age-related declines in VOR gain with high velocity and high amplitude sinusoidal rotations, suggesting a degradation of VOR function. Baloh et al. (2003) investigated changes in VOR response in the elderly during yearly examinations up to 10 years (average age on entry was 78.5 years). They found a deteriorating gain with age which weakly correlated with fall risk. More recent data indicate that substantial declines in VOR function are limited to adults aged 80 years and over, but the functional consequences of such degradations are yet to be discerned (Li et al., 2015). It is possible that since the VOR promotes stabilisation of gaze relative to movements of the head, and eye movement signals are interpreted for balance control in a number of conditions, a decline in VOR function may affect both retinal and extraretinal components of balance control.

1.4.3 Smooth pursuit system

The smooth pursuit system is also a mechanism utilised to keep gaze fixated on moving targets, and it too has been shown to degrade with age, such as reduced accuracy (Moschner and Baloh, 1994, Spooner et al., 1980, Ross et al., 1999), delayed onset latency (Sharpe and Sylvester, 1978, Knox et al., 2005), and a greater number of catch-up saccades to reposition the eye following tracking errors (Ross et al., 1999, Sharpe and Sylvester, 1978). It is possible, therefore, that declines in smooth pursuit function also impact on the extraretinal component of balance control whilst tracking moving objects, by further complicating extraretinal signals due to more noise generated in an inaccurate system.

1.4.4 Saccades

Similar to young adults, saccades have been shown to improve stability in the elderly during standing. Aguiar et al. (2015) compared balance when fixating on a static target with saccadic eye movements at different frequencies and during different stance conditions (no young group), and found increasing stability with faster eye movements. Interestingly they found no change in postural sway between wide and narrow stance (AP axis) in the elders, which contradicts previous results from younger participants who became more unstable during narrow stance (Rodrigues et al., 2013). The authors suggest that they may have adopted a more rigid postural response due to muscle co-contraction, which has previously been shown in elders when performing dual tasks stood with their feet together (Melzer et al., 2001). This may be a mechanism to compensate for natural age-related declines in the balance control system. Alternatively, elders often present with impaired performance during saccadic eye movements, such as reduced onset latency and execution of more saccades to reach a specified fixation point (Moschner and Baloh, 1994). Thus, an exaggerated postural response, i.e. more stability during feet together stance, may have been required to facilitate gaze shifts in a more inaccurate system.

The notion that saccades can improve balance may be of particular interest in the field of gerontology. It has previously been proposed that populations at higher risk of falls attempt to utilise saccades more instead of smooth pursuit eye movements, since the latter were shown to decrease stability (Schulmann et al., 1987). However, it has also been suggested that it is not optimal to foster dependency on visual fixations in patients undergoing vestibular rehabilitation therapy (Han et al., 2011). Since normal saccadic eye movements, usually completed in around 40.6 ms (Abrams et al., 1989), are separated for relatively long periods by stationary fixations, utilising saccades may also not be optimal in training programs. Instead, Han et al. (2011) suggest exposing patients to moving visual scenes in artificial environments, or watching videos of conflicting stimuli while performing head and body movements may be beneficial. If it is shown that smooth pursuits negatively affect balance in older adults, perhaps it is warranted to apply similar interventions in older populations.

1.5 Conclusion and aims

There are growing indications that eye movements can affect balance control in young adults. Of particular interest is that smooth pursuits can cause decreased stability. Yet, despite the high incidence of falls in older populations, this has not been investigated in the elderly. There is a pressing need, therefore, to advance our understanding of the effects of eye movements on balance control, amongst different age groups and across postural tasks. To these ends, a series of experiments were conducted.

- Experiment 1 (Chapter 3): The effects of smooth pursuit and saccadic eye movements on balance control were assessed in young and older adults during standing in the laboratory. It was hypothesised that smooth pursuits would decrease stability, and with a more profound effect in the older adults. In contrast, saccades were hypothesised to maintain or improve stability in both age groups.

- Experiment 2 (Chapter 4): The effects of smooth pursuit and saccadic eye movements on balance control were assessed in young and older adults during locomotion in the laboratory. It was hypothesised that smooth pursuits would decrease stability, and with a more profound effect in the older adults. In contrast, saccades were hypothesised to maintain or improve stability in both age groups.

- Experiment 3 (Chapter 5): Building on the results of the previous investigations, the research was moved into a real-world environment. The effects of visually fixating a real-world pedestrian on balance control were assessed in young and older adults during locomotion. It was hypothesised that visually fixating the pedestrian would lead to decreased stability similarly in both age groups, and with a more profound effect when the pedestrian was walking.

- Experiment 4 (Chapter 6): To put the results of Chapter 5 into context, natural gaze patterns in young and older adults were examined during locomotion in a similar real-world environment.

Chapter 2

General methods

This section details methods used where they remained consistent in each experimental chapter so as to avoid unnecessary repetition, or where a more in depth elaboration is appropriate.

2.1 Ethical procedures and considerations

All investigations were carried out in accordance with the recommendations of the University of Cumbria's ethical principles and guidelines for research involving human subjects, and all procedures, information to the participants, and participant consent forms, were approved by the University of Cumbria Research Committee (see Appendix F). In line with this, all data was purged of identifying material and kept no longer than necessary as per institutional guidelines. Further, the participants had the right to withdraw from the study they participated in up until dissemination of the aggregated findings. Since the work described in Chapter 4 took place in Italy, several discussions with colleagues took place to ensure that the translation of the participant information sheets and consent forms were accurate, whilst also meeting the University of Rome *'Foro Italico's'* ethical requirements.

Prior to recruitment, all of the older participants were interviewed by telephone to determine suitability for testing. Further, to ensure their safety and well-being, in addition to avoiding interference of other factors in the testing, the cognitive abilities of the older participants were assessed with the mini mental status examination (MMSE: see Appendix G). Briefly, this includes a series of information recollection and motor control tasks designed to indicate the participant's cognitive state. All participants achieved a score of $\geq$24 out of 30. This was considered as a minimum acceptable threshold for involvement, and indicated the participants had normal cognition.

Each participant's visual acuity was assessed to ensure they could walk safely in the experimental environments, and for methodological purposes (described in each chapter where appropriate). A Snellen chart was used to achieve this (see Appendix H), which involves reading high contrast letters which get smaller on each subsequent line from a set distance. It provides a fraction, with the first number representing the distance of the text from the observer, and the second representing the distance at which the observer can clearly read the letter. 20/20 vision, for example, is considered normal. I.e. the observer can see at 20 feet what the average eye can see at 20 feet.

Finally, all of the participants adhered to a series of rigorous inclusion criteria. These included, by self-report: (1) No macular degeneration, glaucoma, cataracts or colour blindness; (2) No muscle or bone conditions which could prevent standing or walking for short intervals with regular breaks, including but not limited to, lower limb, hip or spine surgery within the previous year, present or recent injury or pain in any region; (3) No psychological/neurological conditions which could prevent standing or walking for short intervals with regular breaks, including but not limited to, Parkinson's disease, vestibular impairment (dizziness/vertigo), numbness or loss of sensation in the lower limbs, or schizophrenia; (4) No severe motion sickness; (5) No medication which could depress the nervous system or effect balance (benzodiazepines, anti-depressants, anti-seizure, or anti-anxiety); (6) No multiple falls within the previous year; (7) No over-reliance on handrails when climbing the stairs; (8) No assistive walking devices such as a cane, crutches, or a walking frame. These criteria aimed to ensure that the sample of participants were healthy (i.e. free from pathology which could affect balance, gait, or vision; (Ambrose et al., 2013)), and could complete the testing with no discomfort. Some of criteria have also been used in previous vision and balance literature (Logan et al., 2010).

2.2 Eye tracking equipment

The participants wore eye tracking glasses (Tobii Glasses 2 Eye Tracker, Tobii Technology, Danderyd, Sweden). These have a one point calibration procedure, autoparallax compensation and slippage compensation allowing for persistent calibration throughout testing with no loss of data aside from blinking. Gaze data was sampled at 50 Hz and subsequently filtered with the Tobii I-VT fixation filter to yield gaze fixations (window length 20 ms, threshold 30 $^{\circ}/s$). 2D video sequences consisting of the participant's point of view of each visual scene superimposed with their gaze fixations was exported and analysed offline depending on the experimental requirements, which are outlined in the methods of each experimental chapter.

2.3 Custom-made contact mat

A custom-made contact mat was built by the present author and used to control data acquisition, stimulus presentation and experimental timing (Fig. 2.1). This was constructed from strips of conductive tape laid over a flooring tile. Conductive tape was also placed on the heel of the participants. When the participants made or broke contact with the mat (corresponding to heel strike or heel off at gait initiation) the mat sent a signal through a custom USB serial port also built by the present author to a computer running Python code applicable to each experiment. For example, in experiment 1 (Chapter 3), the first heel strike was used to present a visual stimulus. The temporal resolution of this setup (i.e. the time taken to record a heel strike or heel off event) was evaluated by sending data through a serial port and over the closed circuit contact mat to an Arduino micro controller, and back again. In reality, this takes even longer than simply closing or opening the circuit with a heel strike or heel off event, respectively. Notwithstanding this, the time taken was sub-millisecond, which indicates a more than adequate resolution.

2.4 Visual stimuli

Visual stimuli were presented to the participants (Chapters 3 and 4) to initiate eye movements and generate different forms of retinal flow. All stimuli were programmed in Python by the present author using Psychopy stimuli presentation tools (Peirce, 2007). For example, to generate an oscillating visual background, a large-field grating was defined and programmed to update its position as a function of time following a sinusoidal trajectory using a harmonic equation, where $D =$

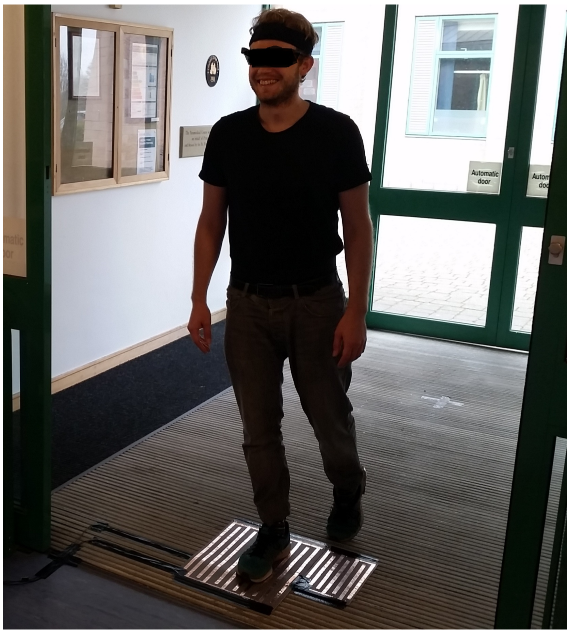


FIGURE 2.1: Example of person walking over the contact mat.

maximum displacement in degrees of visual angle, P = new position of stimulus on each monitor refresh, Hz = intended oscillation frequency, t = time.

$$P = [Dsin(2\pi Hzt)] \tag{2.1}$$

2.5 Data analysis

2.5.1 Software

Two custom software applications were written by the present author to facilitate analysis of data (Chapters 3 and 4). These are open source and freely available to download and use.

The Sway Analysis Toolkit (SwAT) is a simple GUI application allowing users to import and analyse postural sway data recorded with AMTI force platforms

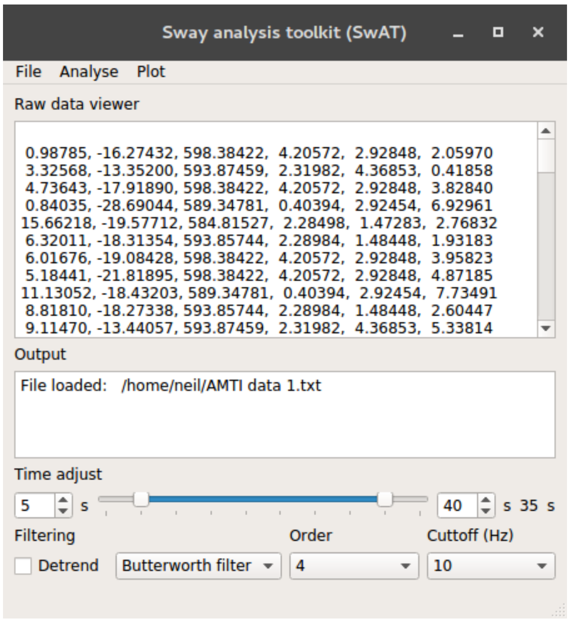


FIGURE 2.2: Graphical user interface of the SWaT, showing imported data matrix and relevant buttons to process data, e.g. filtering and detrend functions.

in .csv format (Fig. 2.2). It is built on C++ with Qt and makes use of Eigen and Biomechanical Toolkit libraries. It is available at https://github.com/N-M-T/SWaT.

Fixation Logger (FLo) is a simple GUI application allowing users to import video sequences superimposed with gaze fixations recorded from eye tracking equipment, and log features frame-by-frame by a single key press (Fig. 2.3). It is built on C++ with Qt, and is available at https://github.com/N-M-T/FLo.

2.5.2 Custom scripts

All other data processing was performed using custom Python (Scipy, scientific computing tools for Python) and R (R project for statistical computing) scripts developed by the present author. The following key calculations were used (the context of each is described in each chapter where applicable):

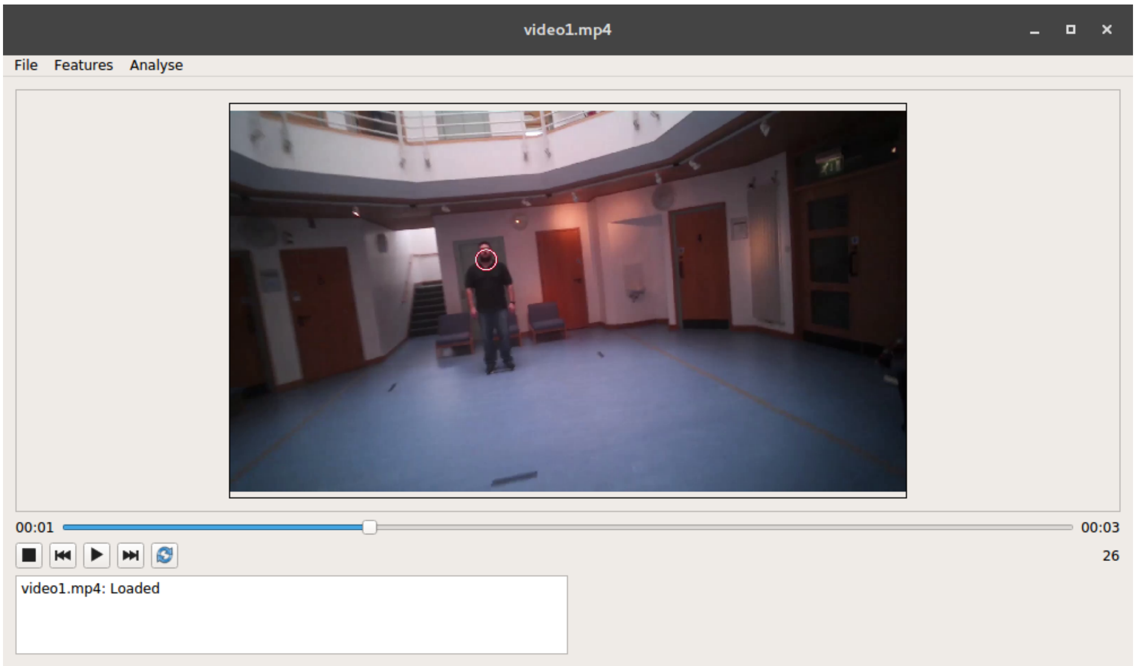


FIGURE 2.3: Graphical user interface of the FLo showing imported eye tracking video sequence.

Root mean square (RMS), where N = number of data points and $n = 1, ..., N$:

$$RMS = \sqrt{\frac{1}{N} \sum n^2} \tag{2.2}$$

Resultant timeseries (RT), where N = number of data points and $n = 1, ..., N$:

$$RT = \sqrt{{n_1}^2 + {n_2}^2} \tag{2.3}$$

Coefficient of variation (CV), where $MEAN$ and SD = mean and standard deviation of each data set, respectively:

$$CV = \frac{SD}{MEAN} 100 \tag{2.4}$$

Hedges' g_{av} effect size as given by Lakens (2013), where N = number of data points and $n = 1, ..., N$, and $MEAN$ and SD = mean and standard deviation of each group, respectively:

$$g_{av} = d_{av}\left(1 - \frac{3}{4(n_1 + n_2) - 9}\right) \tag{2.5}$$

$$d_{av} = \frac{M_{\text{diff}}}{\frac{SD_1 + SD_2}{2}} \tag{2.6}$$

$$M_{\text{diff}} = MEAN_1 - MEAN_2 \tag{2.7}$$

The previous chapter provided an overview of methods used where they remain consistent throughout the thesis, or where further explanation was appropriate. The following chapter explores the effects of smooth pursuits and saccades on balance control during standing in young and older adults.

Chapter 3

Eye movements affect postural control in young and older females

The work presented is this chapter arose from the following publication (see Appendix A):

Thomas, N. M., Bampouras, T. M., Donovan, T. and Dewhurst, S. (2016), ‘Eye Movements Affect Postural Control in Young and Older Females’, *Frontiers in Aging Neuroscience*, 8, 216, DOI 10.3389/fnagi.2016.00216

And was presented at the 21st Annual Congress of the European College of Sport Science, Vienna 2016 (see Appendix E).

3.1 Introduction

Vision is an important sensory cue to familiarise ourselves with the external environment, a prerequisite for which are voluntary or involuntary eye movements, necessary to process information such as recognition, localisation and proprioception (Donaldson, 2000, Irwin, 1991, Lewis et al., 1994). Vision also facilitates stabilisation of upright posture, by enabling detection of self-motion relative to structures in the visual field (Dichgans and Brandt, 1978). There is growing evidence to suggest eye movements interact with this process (Glasauer et al., 2005, Laurens et al., 2010, Schulmann et al., 1987, Rodrigues et al., 2015). However, this has received little attention in the gerontology literature, which is surprising given the prevalence of eye movements in everyday life (Kowler, 2011), their potential link with postural control, and the high incidence of falls and fall related injuries amongst the elderly (Ambrose et al., 2013, Sturnieks et al., 2008). Here, the focus is on the effects of eye movements on postural control during standing in young and older adults.

Visual cues for postural stabilisation have traditionally been associated with deformation of the retinal image. As a person shifts their position in space, changes in the pattern of light intensities about a central point of observation create an optic flow pattern, which is projected onto the retina. This projected image shifts/deforms creating retinal flow according an individuals movements (Gibson, 1950), which the central nervous system (CNS) uses to estimate body position and initiate appropriate postural adjustments (Lestienne et al., 1977, Nashner and Berthoz, 1978, Wapner and Witkin, 1950). Optical changes at the retina can include uniform components, e.g. horizontal movement of the retinal image, parallax (generated by near and far structures in the visual environment), and expansion and contraction, which is indicative of anterior or posterior head motion (Gibson, 1950, Gibson et al., 1955). Evidence demonstrating how retinal flow guides postural adjustments can be taken from investigations involving moving visual surrounds, e.g. linearly oscillating walls, floors and tunnels, which have frequently shown a coupling of postural sway with stimulus motion (Bronstein, 1986, Dijkstra et al., 1994, Fluckiger and Baumberger, 1988, Lee and Lishman, 1975, Stoffregen, 1985). This is believed to result from the CNS misinterpreting externalmotion for self-motion and incorrectly adjusting body orientation (Guerraz and Bronstein, 2008).

There is a close relationship between the ways in which visual and vestibular information about head position are used for postural control (DeAngelis and Angelaki, 2012), and eye movements have been shown to affect posture during standing. Fixating on a small lit target in an otherwise dark room improved stability compared to absolute dark (Paulus et al., 1984). In these conditions, visual and vestibular initiated compensatory eye movements in response to movements of the head keep gaze fixated on the target, implying diminished retinal flow. Therefore, eye movements relative to the target seem to be used to infer body position in space (Guerraz and Bronstein, 2008). Visually tracking moving targets with smooth pursuits, on the other hand, caused increases of postural sway in young adults, in the presence of a static visual field and without (Glasauer et al., 2005, Laurens et al., 2010). This may be related to more challenging conditions for interpreting retinal flow for postural control (Schulmann et al., 1987), or, in part, more complex extraretinal signals (Glasauer et al., 2005). However, there are data which show an opposite effect, indicating posture can be modulated for more accurate gaze behaviour (Rodrigues et al., 2015). This concurs with similar findings during rapid shifts of gaze from one target to another with saccadic eye movements in young (Stoffregen et al., 2006, Rougier and Garin, 2007, Rodrigues et al., 2013) and older (Aguiar et al., 2015) adults, thus suggesting a functional integration of gaze and posture for both smooth pursuits and saccades. These differences remain unexplained. Moreover, little is known about extraretinal control of posture in elders, or how smooth pursuits effect balance in elders.

Older adults have demonstrated declines in visual self-motion perception (Warren et al., 1989), and can become more unstable in the face of moving visual surrounds (Wade et al., 1995, Sundermier et al., 1996, Borger et al., 1998). This might reduce their ability to interpret retinal flow for postural control as effectively as younger adults during eye movements. Declines in vestibulo-ocular reflex (VOR) function with age (Peterka et al., 1990, Paige, 1991, Baloh et al., 2003) may additionally affect the extraretinal component of postural control, since the VOR is one mechanism which serves to stabilise gaze, and eye movement signals appear to be used to infer body position. Further, an inaccurate smooth pursuit system in elders (Sharpe and Sylvester, 1978, Spooner et al., 1980, Moschner and Baloh, 1994) may potentially cause less efficient processing of more complex extraretinal signals whilst visually tracking moving targets, thus exacerbating the increase in postural sway demonstrated by some young adults. Paquette and Fung (2011) indirectly assessed balance during smooth pursuits in older participants, but the authors focus was gaze accuracy, and they cannot clarify if declines in postural control were associated with the gaze outcomes.

Because loss of balance in the elderly can be costly and debilitating (Brunner et al., 2003), there is a pressing need to further understanding of the interplay between eye movements and postural control in this population. Therefore, the present investigation assessed postural sway, increases of which can indicate reduced stability, during visual fixation of stationary targets, smooth pursuits and saccades, in young and older adults. The experiment also implemented combinations of absent, fixed, and horizontally oscillating visual backgrounds to generate different forms of retinal flow, and to isolate the extraretinal factors involved in visual control of balance. The following hypotheses were tested: (1) fixating a stable target would reduce postural sway, (2) fixed backgrounds would have a stabilising effect and oscillating backgrounds a destabilising effect, (3) smooth pursuits would increase postural sway, (4) saccades would decrease postural sway, (5) the older adults would be more unstable throughout, and this would be more profound during smooth pursuits and oscillating backgrounds.

3.2 Methods

3.2.1 Participants

Twelve young (mean $\pm$ SD, age: 26.1 $\pm$ 4.9 years, height: 1.68 $\pm$ 0.06 m, mass: 62.2 $\pm$ 13.7 kg) and 12 older (mean $\pm$ SD: age: 72.8 $\pm$ 6.9 years, height: 1.64 $\pm$ 0.05 m, mass: 63.6 $\pm$ 10.7 kg) females participated in the investigation. An initial cohort of 20 elders was reduced to 12 following the screening protocols detailed in General methods section 2.1.

3.2.2 Equipment

Visual scenes were rear projected (Sanyo PLC-XU74, Tokyo, Japan) onto a 3.2 $\times$ 2.4 m translucent screen. The lower border of the screen was placed at foot level. An AMTI AccuPower portable force platform (AMTI Force and Motion, Watertown, MA, USA) was positioned with its centre 1 m adjacent to the middle of the screen.

Participants wore eye tracking glasses as detailed in General methods section 2.2. The experiment was carried out in a light-controlled room.

3.2.3 Visual scenes

Ten $\times$ 45 s visual scenes were used during testing (see General methods section 2.4). Visual stimuli were programmed in degrees of visual angle to enable standardisation between experiments. Visual stimuli included a red target (circle with a 3° diameter) and a large-field background occupying the full width and height of the screen, which was made up of black and white vertical stripes each with a width of 3°. Participants had an uncorrected visual acuity $\geq$20/100 measured on the day of testing. Discrimination of spatial patterns separated by a visual angle of 50/60th of 1° is possible even at lower visual acuities (Paquette and Fung, 2011). Therefore, stimuli utilised in the present investigation were visible at all times, and this was always confirmed with the participants.

The target could be fixed (F), moving smoothly (P) or moving with saccadic motion (S). When fixed, the target would remain in the centre of the screen at natural gaze height (see below). When moving smoothly, the target would displace from the centre of the screen to 6° in the vertical, horizontal or diagonal direction before returning to the centre of the screen with a frequency of 0.33 Hz. For saccadic movement, the same protocol was implemented; however, the target would disappear from the centre of the screen and reappear at the 6° threshold, and vice versa. Target direction was programmed to be random on each oscillation. The large-field background could be absent (N), fixed (F) or oscillating horizontally to 6° from the centre position in each left and right direction at 0.33 Hz (O). To simulate a condition of darkness (D), a black screen was projected absent of any stimuli. Letter codes used to identify visual conditions are presented in Table 3.1. Six degrees of visual angle was chosen to prevent head rotations which could affect measures of postural sway, since gaze shifts of less than 15° are commonly are achieved without rotations of the head (Hallet, 1986), and this method has previously been effective in minimising head movements (Glasauer et al., 2005, Stoffregen et al., 2006, 2007).

Table 3.1: Letter codes denoting combinations of large-field background and target state used to identify visual conditions. The first letters refer to the state of the background and second refer to the state of the visual target. Adapted from Laurens et al. (2010).

	Target		
Large-field background	Fixed	Smooth pursuit	Saccadic
None	NF	NP	NS
Fixed	FF	FP	FS
Oscillating	OF	OP	OS
No large-field background or target: Dark (D)			

A novel approach was used regarding the height at which the visual targets were presented, as opposed to eye level. Older adults have been shown to adopt forward trunk lean, which may be related to factors such as backward disequilibrium (Manckoundia et al., 2007) or poor balance and fear of falling (Sato and Maitland, 2008). Previous research has also shown focusing gaze at different heights affects measures of postural sway, e.g. 25° up or down from eye level decreased sway velocity and amplitude (Ustinova and Perkins, 2011). Consequently, if the targets were presented at eye level it may have forced the older participants to adopt an unnatural body lean and/or gaze height in order to maintain gaze on the target, which could have affected the results. Therefore, prior to testing, all participants were instructed to stand as still as possible with their feet together (no footwear) in the middle of the force platform (position marked with a cross for accurate relocation between trials) with their hands by their sides. They were then told to look ahead as comfortably as possible at a visual scene consisting of horizontal green lines which took up the full horizontal width of the screen, and covered 2° in the vertical direction – each was separated by a gap of 2°. After 30 s, gaze fixation settled at a specific line or in between lines. This was considered to be natural gaze height. The participants were subsequently instructed to adopt the same stance position throughout testing, which was reiterated before each trial.

3.2.4 Experimental protocol

Two practice trials of 45 s duration separated by 10-20 s were granted following determination of natural gaze height to familiarise the participants with measurement of postural sway. Following a break of 2-5 minutes, testing commenced. The participants, relocated on the cross and in the same stance as before, were instructed to fixate their gaze on the red target. If the target moved, they should follow it with their eyes only, making sure not to rotate or tilt their head. During the dark condition, they were told to keep looking ahead. The 10 visual scenes were displayed to each participant in a random order, which was different for each participant. After the 3rd and 7th scene, the participants were granted a 3-5 minute break where they sat down. In between the remaining scenes there was a 10-20 s break where participants remained standing. A member of the research team was present behind each participant during testing in case of loss of balance. The eye tracking glasses were calibrated to each participant before determining natural gaze height after the practice trials, and subsequently after each 3-5 minute break.

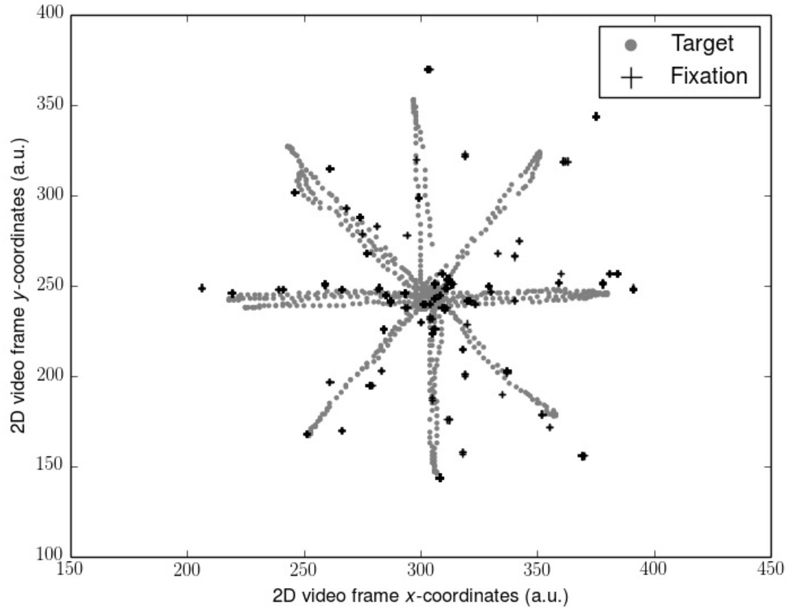
3.2.5 Force platform data

Force platform data were sampled at 100 Hz for 45 s during each trial and analysed offline (see General methods section 2.5.1). Since the investigation was not concerned with how quickly the participants adapted to new stimuli, or end anticipation effects, the first and final 5 s were discarded leaving 35 s of data for analysis. This was because elders have been shown to have similar adaptation rates to young adults regarding sudden changes in visual stimulus motion during an initial 5 s period (Jeka et al., 2010). Mediolateral (ML) and anteriorposterior (AP) centre of pressure (COP) coordinate timeseries (x and y, respectively) were then computed and passed through a 4th order zero-lag Butterworth filter with a cut-off frequency of 10 Hz. This choice of cut-off was determined with residual analysis of the raw data (Winter, 2009).

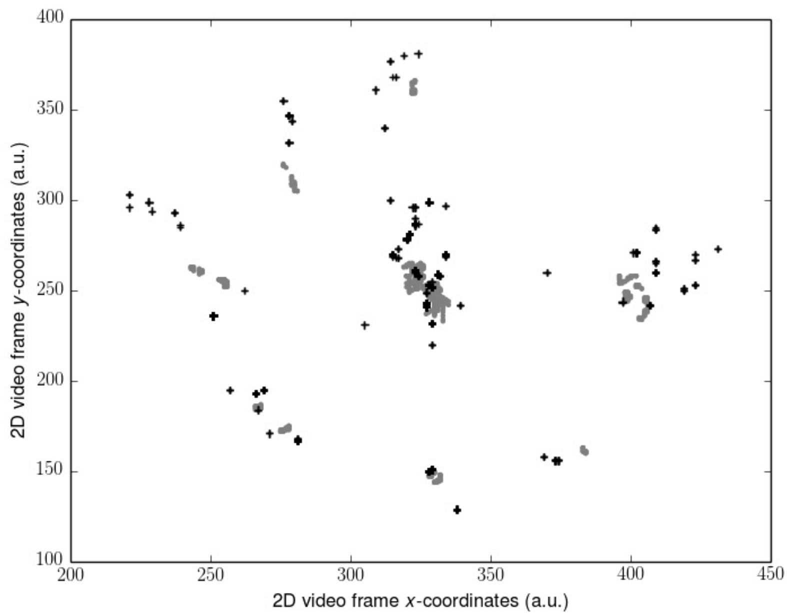
To characterise the size of the path travelled by the COP over the surface of support on both axes, we calculated the root mean square (RMS) of each de-trended timeseries (see General methods section 2.5.2). Rocchi et al. (2004) recommended RMS to characterise COP coordinate timeseries following principle component analysis. Further, repeated RMS measures of postural sway have been shown to be reliable in young and older populations (Lin et al., 2008).

3.2.6 Gaze fixations

Following export of the gaze data as detailed in General methods section 2.2, the position of the target and the position of each gaze fixation as x and y coordinates on the 2D video frame (Fig. 3.1) was determined using a motion tracking algorithm (OpenCV Python libraries). Each video sequence was optically filtered by adapting hue, saturation, brightness and contrast, and luma space level settings in order to improve the accuracy of the tracking algorithm. The resultant coordinate timeseries was then calculated as detailed in General methods section 2.5.2.



(A)



(B)

FIGURE 3.1: Representation of target trajectory and gaze fixations from 1 participant, A: during smooth pursuits, B: during saccades. Coordinates along each axis were taken from the 2D video scene relative to the observer and represent arbitrary units (a.u.). Note that the target position is not stable due to the postural sway of the observer. Also note the errors of the fixations compared to the target locations.

The first and final 5 s of each timeseries were removed in accordance with the force platform data. Where no gaze data were sampled due to blinking, the target coordinate at the corresponding time point was converted to zero. Errors of gaze relative to the target were then assessed by computing the RMS of gaze subtracted from the target position throughout each video sequence (RMS-gaze error). Reliability of the tracking procedure was assessed by re-tracking the target and fixation position during scene OP from the young participants and computing the coefficient of variation (CV: see General methods section 2.5.2) between the gaze error outcome measures from each. Scene OP was chosen as it presented with the most challenging optical conditions for motion tracking. The CV between tests (0.47%) indicated excellent reliability. No gaze data were collected for the dark (D) condition.

3.2.7 Statistical analysis

Age (young and older) and condition (10 × visual scenes) were considered as two independent factors. The effects of these two factors on the postural sway outcome variables RMS-x and RMS-y were examined with a two-way (age × condition) mixed analysis of variance (ANOVA). The effects of the same independent factors minus the dark condition on RMS-gaze error were also examined with a two-way mixed ANOVA. Post-hoc analyses (t-tests or Wilcoxon signed-rank tests) with Benjamini-Hochberg corrections were used where applicable. Where significant differences were found between conditions ($p<0.05$), Hedges' g_{av} effect sizes were calculated (see General methods section 2.5.2). Common indicative effect thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8). Statistical results were interpreted in the context of strength of evidence against the null hypotheses, which was determined by the magnitude of the p values (smaller values indicate stronger evidence) and effect sizes. Statistical analyses were performed with the R software package.

3.3 Results

3.3.1 Postural sway

RMS of the COP coordinate timeseries on the ML (x) and AP (y) axes for young and older females are presented in Table 3.2 and Fig. 3.2. Significant p values for the ML plane are also presented in Table 3.3.

TABLE 3.2: RMS of COP coordinate timeseries on the, A: ML (x) axis, B: AP (y) axis, in young (n = 12) and older (n = 12) females during different visual scene conditions. D: dark, N: none, F: fixed, O: oscillating, P: pursuit, S: saccadic. Data are presented as mean ± SD

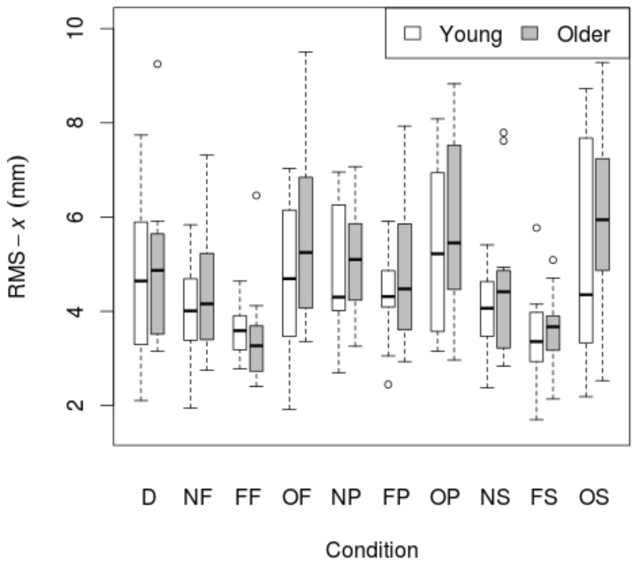
(A)

	RMS-x (mm)	
Condition	Young	Older
D	4.95 ± 1.68	4.70 ± 1.73
NF	4.43 ± 1.39	3.99 ± 1.11
FF	3.44 ± 1.08	3.58 ± 0.55
OF	5.69 ± 1.89	4.72 ± 1.64
NP	5.06 ± 1.21	4.85 ± 1.43
FP	4.82 ± 1.56	4.33 ± 0.92
OP	5.81 ± 1.96	5.36 ± 1.76
NS	4.59 ± 1.62	4.01 ± 0.85
FS	3.63 ± 0.79	3.46 ± 1.03
OS	6.32 ± 2.31	5.09 ± 2.28

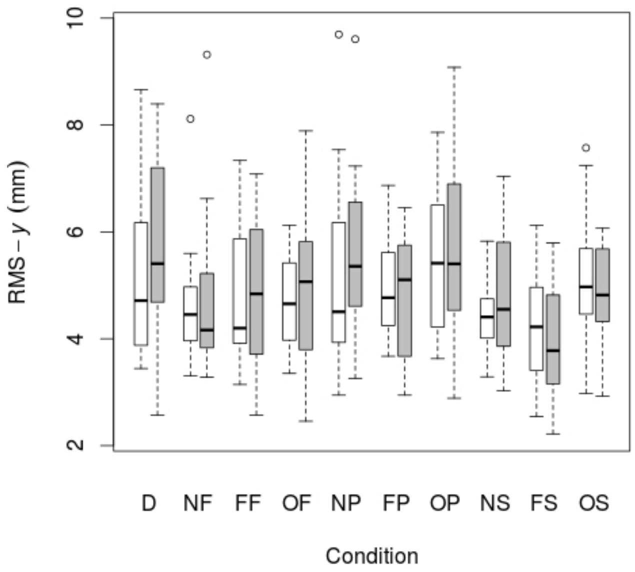
(B)

	RMS-y (mm)	
Condition	Young	Older
D	5.66 ± 1.78	5.22 ± 1.75
NF	4.79 ± 1.70	4.67 ± 1.27
FF	5.18 ± 2.39	4.78 ± 1.30
OF	4.99 ± 1.52	4.68 ± 0.95
NP	5.89 ± 2.15	5.14 ± 2.00
FP	4.78 ± 1.23	4.94 ± 0.89
OP	5.66 ± 1.84	5.44 ± 1.42
NS	4.80 ± 1.29	4.41 ± 0.73
FS	3.97 ± 1.11	4.26 ± 1.12
OS	4.89 ± 0.94	5.13 ± 1.30

ML (x) movement: There was no main effect of age on RMS-x. There was a significant main effect of condition on RMS-x ($F_{9,198}$=17.769, p<0.001). This was confirmed with a robust mixed ANOVA (p<0.001). Post-hoc comparisons revealed: (1) A reduction of postural sway with a fixed target in dark (NF) compared to dark



(A)



(B)

FIGURE 3.2: RMS of COP coordinate timeseries on the A: ML (x) axis, B: AP (y) axis, in young ($n = 12$) and older ($n = 12$) females during different visual scene conditions. D: dark, N: none, F: fixed, O: oscillating, P: pursuit, S: saccadic. Data are presented as medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately).

alone (D) (p=0.032, 12.75%, g_{av}=0.40); (2) A reduction of postural sway with a fixed background and a fixed target (FF) compared to dark alone (D) (p<0.001, 27.18%, g_{av}=0.96), compared to a fixed target in dark (NF) (p=0.005, 16.54%, g_{av}=0.63), and a reduction of postural sway with a fixed background and saccades (FS) compared to saccades in dark (NS) (p=0.001, 17.68%, g_{av}= 0.66); (3) An increase in postural sway with an oscillating background and a fixed target (OF) compared to a fixed background and a fixed target (FF) (p<0.001, 48.20%, g_{av}=1.16), an oscillating background and smooth pursuits (OP) compared to a fixed background and smooth pursuits (FP) (p=0.001, 22.03%, g_{av}=0.62), and an oscillating background and saccades (OS) compared to a fixed background and saccades (FS) (p<0.001, 60.91%, g_{av}=1.18); (4) An increase in postural sway with smooth pursuits in dark (NP) compared to a fixed target in dark (NF) (p=0.038, 17.85%, g_{av}=0.57), and smooth pursuits with a fixed background (FP) compared to a fixed target with a fixed background (FF) (p<0.001, 30.36%, g_{av}=0.95); (5) Saccades did not significantly alter sway compared to a fixed target in any condition; There was no interaction effect between age and condition on RMS-x.

TABLE 3.3: Significant p values for RMS of COP coordinate timeseries on the ML (x) axis in young ($n = 12$) and older ($n = 12$) females during different visual scene conditions. D: dark, N: none, F: fixed, O: oscillating, P: pursuit, S: saccadic.

Condition	D	NF	FF	OF	NP	FP	OP	NS	FS	HH
NF	0.032									
FF	< 0.001	0.005								
OF			<0.001							
NP		0.038								
FP			<0.001							
OP						0.001				
NS										
FS								0.001		
HH										
OS									<0.001	

AP (y) movement: There was no main effect of age on RMS-y. There was a significant effect of condition on RMS-y ($F_{9,198}$=4.372, p=0.020). This was confirmed with a robust mixed ANOVA (p<0.001). Post-hoc comparisons revealed: (1) No change in postural sway with a fixed target; (2) No change in postural sway with fixed backgrounds; (3) An increase in postural sway with an oscillating background and saccades (OS) compared to a fixed background and saccades (FS) (p=0.008, 21.77%, g_{av}=0.78), but no other changes in postural sway with oscillating backgrounds; (4) No change in postural sway with smooth pursuits; (5) No change in postural sway with saccades. There was no interaction effect between age and condition on RMS-y.

3.3.2 Gaze error

There was no significant effect of age on RMS-gaze error. There was a significant effect of condition on RMS-gaze error ($F_{8,186}$=17.629, p<0.001). This was confirmed with a robust mixed ANOVA (p<0.001). Post-hoc comparisons revealed: (1) No change in gaze error with fixed or oscillating backgrounds; (2) An increase in gaze error with smooth pursuits in dark (NP) compared to a fixed target in dark (NF) (p<0.001, 74.37% g_{av}=1.13), smooth pursuits with a fixed background (FP) compared to a fixed target with a fixed background (FF) (p=0.007, 57.4% g_{av}=0.67), and smooth pursuits with an oscillating background (OP) compared to a fixed target with an oscillating background (OF) (p=0.001, 38.61%, g_{av}=0.64); (3) An increase in gaze error with saccades in dark (NS) compared to smooth pursuits in dark (NP) (p=0.001, 34.22%, g_{av}=0.98), saccades with a fixed background (FS) compared to smooth pursuits with a fixed background (FP) (p=0.016, 23.22%, g_{av}=0.55), and saccades with an oscillating background (OS) compared to smooth pursuits with an oscillating background (OP) (p=0.001, 38.63%, g_{av}=0.87); There was no interaction effect between age and condition on RMS-gaze error.

3.4 Discussion

The present experiment aimed to assess the effects of eye movements on balance in young and older adults. A novel approach was taken by assessing postural sway during three primary occulomotor behaviours with different forms of retinal flow, whilst simultaneously assessing gaze accuracy. Alterations of posture with different visual conditions were found predominantly on the ML (x) axis, with fixed stimuli having a stabilising effect, and oscillating backgrounds and smooth pursuits having a destabilising effect. There were no differences between age groups for any of the posture and gaze measures.

3.4.1 Visual fixation of the stationary target

In support of extraretinal postural control, or the ability of the CNS to interpret eye movement signals to gain positional information (Guerraz and Bronstein, 2008), there was a decrease of postural sway when visually fixating a stationary target in dark. Two lines of reasoning have been discussed to explain this phenomenon: the inflow and outflow hypotheses. The former suggests that proprioceptors located in the extraocular muscles provide information about the magnitude of eye movements, which can be interpreted for estimates of body shifts during postural sway. This can only occur after eye movements have been initiated. The latter suggests such information can be gained from a copy of the motor command used to signal eye movements, or neural outflow used by the CNS to maintain visual consistency, and thus the magnitude of the eye movements may be anticipated in a feed-forward manner.

Since there were no changes to postural sway with age in these conditions, it seems likely the older participants were able to perceive head motion relative to the target as effectively as the young group. There were also no changes in gaze errors with age, which indicates a similar reduction of retinal flow for both young and older adults. Therefore, the extraretinal factors involved in the control of posture might have been preserved. Because maintaining gaze on a fixed target requires compensatory eye movements, initiated in part by the VOR, the present findings also suggest that the elders had no substantial VOR deficits, which lends support to a recent study indicating such declines are limited to individuals aged 80 years and over (Li et al., 2015). Therefore, our suggestion that age-related declines in VOR may affect extraretinal postural control seems not to have occurred in the present participants. Future research should seek to examine extraretinal postural control mechanisms in populations with known VOR deficits.

3.4.2 Fixed and oscillating backgrounds

The addition of fixed backgrounds attenuated postural sway during all eye movements apart from smooth pursuits (discussed below). This reflects integration of the static visual field and thus retinal flow into the postural control system, which allowed for more accurate visual estimates of body position (Glasauer et al., 2005, Laurens et al., 2010). The magnitude of gaze errors did not change, suggesting the participants were not distracted from the visual target.

Oscillating backgrounds generating horizontally translational retinal flow absent of parallax cues had a destabilising effect during all eye movements. Previous work examined coupling of postural sway to stimulus motion with frequency response ratios (Logan et al., 2010). Strong coupling typically occurs at frequencies below 0.2 Hz, which is believed to be a result of the CNS misinterpreting external motion for self-motion and initiating incorrect postural responses. At higher frequencies (>0.3 Hz), coupling is largely diminished (Guerraz and Bronstein, 2008). This is logical, considering if coupling were to remain, loss of balance might ensue. Since oscillation of the background in the present investigation was 0.33 Hz, and the participants did not lose their balance, it is likely there was a weak or no coupling of postural sway with the background, probably through distinguishing between retinal flow caused by self-motion, and retinal flow caused by external motion (DeAngelis and Angelaki, 2012). Vestibular and proprioceptive signals may be of particular importance in such a process, since they provide independent sources of information about head and body position. Notwithstanding this, there were still increases in postural sway. This may be attributed to more challenging integration of the non-static retinal flow. In effect, it was likely harder to make visual estimates of body position against the dynamic background visual field. Interestingly, this occurred even with the stationary fixed target in the centre of the field of vision, which supports the theory that the central area of the retina at which the fixed target would have been located is associated more with object recognition, and the peripheral visual field in which the oscillating background would be located is more dominant in control of posture in moving visual fields (Piponnier et al., 2009). In this respect, it seems the effect of the retinal flow was stronger than potential extraretinal factors which might have been at play. There were no differences in gaze errors when oscillating backgrounds were added, suggesting again that the participants were not distracted from the target.

There were no differences between age groups for static or oscillating backgrounds.

This was surprising as older individuals typically exhibit bigger postural sway when standing in both stable visual information rich environments, such as a lit room (Prieto et al., 1996) and with oscillating visual fields (Wade et al., 1995, Sundermier et al., 1996). In the present investigation, the data was additionally normalized to body height and body mass which have been shown to be determinants of postural sway in females during feet together stance (Kim et al., 2010), but there were still no changes. This suggests that the older participants integrated all of the visual information for postural control as effectively as the young group, including determining body shifts from static and dynamic visual fields, and solving the external motion from self-motion separation issue. We also found no differences in gaze errors between age groups with the addition of fixed or oscillating background information. Previous findings have suggested that elders may be more distracted by background motion, possibly related to a reduction in GABA-mediated inhibition, and this may have consequences for discriminating motion of moving objects from their backgrounds (Tadin and Blake, 2005). The present results do not support this idea.

3.4.3 Smooth pursuits

Smooth pursuits increased postural sway in the absence of retinal flow. It was suggested above that eye movement signals were used to infer body position during fixation of the stable target with no background information (extraretinal postural control). An increase in task complexity during smooth pursuits may complicate such extraretinal signals, which in turn may have caused the increase in postural sway.

Tracking a moving target over a fixed background also increased postural sway, yet it was predicted that the static visual field would have a stabilising effect. One can argue that preserving stability of a given visual field on the retina is important for accurate measurement of postural shifts (Schulmann et al., 1987). During smooth pursuits, however, the image of the visual target may appear stable on the fovea (Thier and Ilg, 2005), but the background visual field shifts on the retina in the opposite direction to the target movement and might be subject to motion blur (Schulmann et al., 1987). This may lead to more challenging conditions for estimation of body position. This supports the notion that smooth pursuits are good at maintaining the image of an object on the fovea, serving a central analytic function, but they are not efficient regarding spatial orientation (Schulmann et al., 1987).

In previous studies, the addition of a fixed background reduced the effect of moving targets on postural sway (Glasauer et al., 2005, Laurens et al., 2010). The differences between these and the present findings could be related to the nature of the stimulus movement. In the previous investigations, stimulus trajectory consisted of either horizontal or vertical oscillations, which may have been easy to predict. In the present experiment, target movement was random in the vertical, horizontal and diagonal directions during each condition, which reflects more unpredictable movements, more complex movement of the background visual information, and more complex extraretinal signals. Thus, integration of retinal flow into the postural control system might have been more challenging, and this reduced the effect of an otherwise stabilising visual anchor.

The present findings contrast with Rodrigues et al. (2015) who found a reduction of postural sway during smooth pursuits. A potential cause lies with more challenging foot placement strategies used in the present investigation and in Glasauer et al.

(2005) and Laurens et al. (2010). Rodrigues et al. (2015) suggested postural sway was attenuated to gain more accurate gaze control during normal stance. When standing with feet together, or on foam/semi tandem stance in the previous experiments, such attenuation did not occur. It seems likely, therefore, that stance position dictates the outcome of postural response during smooth pursuits in the presence of stable visual background information. As Rodrigues et al. (2015) did not assess smooth pursuit movements independent of background visual information, it cannot be inferred whether stance would have any impact in such conditions.

Surprisingly, there were no differences between age groups for balance during smooth pursuits in any condition. It is thus possible that the older participants processed the potentially more complex extraretinal signals and dynamic retinal flow for postural control as effectively as the young group. There were also no differences between age groups for gaze errors. This contradicts previous results showing age-related declines in smooth pursuit accuracy (Knox et al., 2005). It may be the Tobii I-VT fixation filter used to process the raw gaze data, being a velocity-threshold identifier, was not sufficiently accurate to discern small changes between the age groups. This would require finer grained gaze data analysis such as that previously used (Paquette and Fung, 2011). With that said, a recent study found no difference between smooth pursuit parameters of young and older adults tracking targets in an ecologically valid environment (Dowiasch et al., 2015). It cannot ultimately be said for sure which previous results would appropriately describe the present participants. However, the previous suggestion that a decline in the accuracy of the smooth pursuit system with age may affect extraretinal control of balance is incorrect, at least in the present participants.

3.4.4 Saccades

There were no changes in postural sway during saccades compared to fixating a stable target in the absence of a visual background. Since in both conditions, the target was the predominant source of visual information, one must assume a similarity in the way it was used for postural control. This may be explained by the frequency of the target movement (0.33 Hz). Each saccadic shift of the target was completed at the projector refresh rate in the order of sub 20 ms. Consequently, the target remained at the centre position, or at 6° of visual angle at any given trajectory, for close to 1.5 s on each half oscillation. Since a saccadic shift of the human eye also with a displacement of 6° can be completed in around 40.6 ms (Abrams et al., 1989), gaze would have been fixated on a static target for relatively long periods during the saccadic trials aside from corrective saccades due to gaze errors. This suggests that similar to fixating a static target in dark, extraretinal factors were involved in postural control. Future investigations should examine such extraretinal contributions during saccades with a range of movement frequencies.

The addition of a fixed background did attenuate postural sway further. As saccades aim to depict the visual environment as stable, e.g. to connect pre- and post-saccadic views, and gaze would have been fixated in the same position for relatively long periods, the CNS might gain better estimates of head position from the background visual field in this condition (Schulmann et al., 1987), which seems to have occurred in the present experiment regardless of changes in eye orientation.

The present findings do not align with previous data showing improvements in postural stability during saccades (Rodrigues et al., 2015, Aguiar et al., 2015). Stance position was the same as in both of these studies and thus can be excluded as a causal factor. In these previous investigations, the authors suggested that postural sway was modulated to afford more accurate gaze shifts, since they found more sway attenuation at higher frequency saccades (1.1 Hz compared to 0.5 Hz). The frequency of saccades in the present investigation was lower at 0.33 Hz, and may not have required the same magnitude of postural sway attenuation.

There were no differences in postural sway or gaze errors between age groups during saccades. Therefore, the older participants may have been visually fixated on the target for similar times as the young group, which suggests a similar amount of positional information was successfully interpreted. This could have been through extraretinal mechanisms, or from retinal flow. Although it is possible that the present results failed to detect small effects of age on saccadic accuracy, such as longer onset latencies, or more saccades to reach the target (Paquette and Fung, 2011), this certainly had no effect on the postural outcomes.

Another possible explanation as to why there were no differences for postural sway with age during saccades and smooth pursuits relates to postural rigidity. Melzer et al. (2001) showed that when performing a dual task whilst stood with their feet together, elders reduced their postural sway by increasing muscle activity in the *tibialis anterior* and *soleus* muscles. This coactivation about the ankle was thought to be a consequence of a threat to postural stability. Other findings from older adults also point toward increases in muscle coactivation during standing, which may be a mechanism to compensate for natural age-related declines in the postural control system (Nagai et al., 2011). Such a mechanism has indeed been suggested to occur during saccadic eye movements (Aguiar et al., 2015). In the present investigation, the older participants may have been more challenged in terms of central integration of visual cues for postural control, and subsequently adopted a more rigid postural response through muscle coactivation, but this was not detected through measures of postural sway alone. Simultaneous assessment of muscle activity would be needed to confirm or reject this idea.

The present findings demonstrate the effects of eye movements on postural control in young and older females. In younger males and females, similar effects have previously been demonstrated (Glasauer et al., 2005, Laurens et al., 2010). In older males, it can be hypothesised that the present findings would be transferable, since a previous study which manipulated visual parameters in elders was unable to detect significant gender differences in postural sway during quiet stance (Wolfson et al., 1994).

3.4.5 Axis effects

The only change in posture on the AP axis was found with the addition of an oscillating background, whilst all other changes were found on the ML axis. This indicates more stability on the AP axis compared to the ML axis overall, which likely results from a reduced base of support on the ML axis during feet together stance compared to normal stance. With that said, AP translations of the visual background were not implemented during the eye movements to generate expansion and contraction retinal flow patterns. Such conditions may have caused greater instability on AP axis during eye movements – similar to changes in postural sway previously shown by Jeka et al. (2008). This is a recommendation for future experiments.

3.4.6 Method consideration

With regard to previous studies investigating postural sway during eye movements, the participants were instructed to focus on the visual stimuli, but not directly examined as to whether they did so. The present results suggest that such instruction is appropriate and participants are able to remain fixated on the target, aside from natural gaze errors. Therefore, it can be suggested this set-up should continue being used for assessment of postural sway and eye movements during quiet stance.

3.5 Conclusion

The present investigation supports growing evidence that eye movements interact with the postural control system in humans, which could have important implications for practitioners and researchers working with a variety of populations. Extraretinal components have been shown to contribute to postural control in a number of laboratory conditions. Thus, if extraretinal postural control is impeded in individuals with substantial declines in VOR and/or visual proprioceptive function, discerning the relative contribution of extraretinal and retinal mechanisms to postural control in an ecologically valid environment and during different eye movements would be an important step in developing a targeted training intervention. Moreover, since the present investigation and other studies found increases of postural sway during smooth pursuits in more challenging stance positions, stability whilst tracking moving targets may also be affected during locomotion or perturbed stance. This could place populations less able to correct postural disturbances, including elders, at a greater risk of falls. Should such individuals be instructed to refrain from observing moving objects, thus suppressing visual tracking, and only utilise static fixations and saccades which maintain or improve stability to scan their environment? Or perhaps training programs should focus on improving postural control during smooth pursuit eye movements in a variety of conditions. Some of these points were first raised by Schulmann et al. (1987). Further research is still needed, and should also take account of extraretinal factors. With that said, in the present context, the older participants were able to match the younger group's postural and visual responses. This may be said on the cognitive level (sensory integration of visual cues to the postural control system), and on the physical functioning level (musculoskeletal responses to maintain upright stabilty). How this translates to more dynamic situations such as locomotion now remains the topic of interest.

The previous chapter showed that smooth pursuit eye movements can negatively affect postural control in young and older adults during standing, whilst saccades maintained stability. To expand on this research, the following chapter explores the effects of smooth pursuits and saccades on balance control during locomotion in young and older adults.

Chapter 4

Smooth pursuits decrease balance control during locomotion in young and older healthy females

The work presented is this chapter arose from the following publication (see Appendix B):

Thomas, N. M., Dewhurst, S., Bampouras, T. M., Donovan, T., Macaluso, A. and Vannozzi, G. (2017), 'Smooth pursuits decrease balance control during locomotion in young and older healthy females', *Experimental Brain Research*, 9, 235, DOI 10.1007/s00221-017-4996-2

4.1 Introduction

Vision provides important information for balance control during locomotion. Experiments manipulating the visual field of young adult treadmill walkers, for example, have resulted in forward and backward trunk lean (Logan et al., 2010) and increased mediolateral (ML) trunk movement and step-width variability (Warren et al., 1996, McAndrew et al., 2010). Step-width variability is of particular interest as it is linked to control of the bodies centre of mass (COM) on a step-to-step basis and is important for maintaining balance (Bauby and Kuo, 2000). These findings were thought to result from the central nervous system (CNS) detecting changes to the visual field and adjusting posture (albeit in error) accordingly.

Visual sensing of the external environment and self-motion within it occurs at the retina. In a 3D world, patterns of light reflected off structures reaching the retina create an optic array. If the observer moves, it changes the structure of the array about a point of central observation (Gibson, 1950). Such changes in patterns of light which flow across the retina are thought to be interpreted to estimate body position in relation to the external environment (Warren et al., 1996, Logan et al., 2014). However, eye movements can change the structure of the array, and flow patterns on the retina can be a combination of those caused by self-motion in addition to those caused by eye movements (Lappe and Hoffmann, 2000). The CNS must, therefore, solve a source separation issue between the two when judging self-motion (DeAngelis and Angelaki, 2012).

Despite investigations about how humans control their direction heading during eye movements (Royden et al., 1994), studies manipulating visual flow and assessing balance during walking have not considered eye movements. If changes to flow caused by eye movements affect how humans interpret retinal, it may in turn affect balance control.

The nature of changes to balance control would likely depend on the type of eye movement. For instance, visually fixating a stationary object straight ahead would cause radial flow from forward progression, and this would emanate from the central point of observation (Lappe and Hoffmann, 2000). Such flow may be considered useful for balance control since it provides a stable reference frame (assuming a healthy vestibulo-ocular reflex) from which self-motion with respect to the vertical can be determined. Conversely, tracking an object in horizontal motion would cause horizontal flow from eye rotation in addition to radial flow from forward progression. The resulting pattern would resemble a curved movement with a shifting focus of expansion (Lappe and Hoffmann, 2000). Moreover, although the object of fixation would appear stabilised on the fovea, the background information would become blurred (Schulmann et al., 1987). This added complexity may cause difficulty when estimating self-motion, thus decreasing balance control. Saccades are another kind of eye movement used during walking. These are rapid shifts of gaze from one region to another (Kowler, 2011). However, because saccades are a series of fixations separated by rapid intervals, unless the saccades were to an extreme displacement and/or with unnaturally high frequency, the stable reference frame provided by stationary fixations should be preserved during saccadic eye movements.

Of interest when considering the above are older adults. Elders can be more sensitive to mediolateral (ML) perturbations of the visual field during walking resulting in greater reduction of trunk stabilisation and increased step-width variability when compared to younger adults (Franz et al., 2015). Further, it is thought the ageing CNS relies on vision more for balance control because of vestibular and musculoskeletal sensory declines (Yeh et al., 2014). Therefore, because elders cannot decompose retinal flow as effectively as young adults, and can be more reliant on visual information, any decrease in balance control caused by smooth pursuits may be more profound in this age group. Chapter 3 did show a comparable increase in postural sway during smooth pursuits between young and older adults during standing. However, because the biomechanical constraints and nature of visual flow during walking are so different to standing, further investigation is warranted.

Therefore, the present investigation assessed balance control during fixation of a fixed target, smooth pursuits and saccades in healthy young and older adults walking overground. It was hypothesised that: (1) smooth pursuits would increase ML trunk movement and step-width variability compared to a fixed target, (2) saccades would maintain balance compared to a fixed target, (3) the reduced balance during smooth pursuits would be more profound in the older adults.

4.2 Methods

4.2.1 Participants

Ten young (mean ± SD: 22.9 ± 1.5 years; 1.7 ± 0.06 m; 59.5 ± 7.2 kg) and ten older (mean ± SD: 72.1 ± 8.2 years; 1.6 ± 0.03 m; 57.3 ± 5.6 kg) healthy females participated in the investigation. All participants adhered to inclusion criteria detailed in General methods section 2.1. All participants had an uncorrected visual acuity (without glasses or contact lenses) ≥20/100 and were able to ambulate in the community without visual correction.

4.2.2 Equipment

Visual scenes were projected (Sanyo PLC-XU74, Tokyo, Japan) onto a 3.2 × 2.4 m screen on the wall of the laboratory. A 7 × camera Vicon system (MX3, Oxford, UK, sampling frequency 100 Hz) recorded three-dimensional positions of eight passive reflective markers located at the left and right front and back head, C7, sacrum, and left and right heel anatomical landmarks of each participant. A custom-made contact mat was used to initiate visual stimulus movement (see General methods section 2.3 and Experimental protocol section 4.2.4). Participants wore eye tracking glasses as detailed in General methods section 2.2.

4.2.3 Visual stimuli

The visual stimulus (see General methods section 2.4) was a light blue circle displayed over a black background. Each participant could see the target at all times during testing. Three experimental conditions were implemented: fixed target (FIX), smooth pursuit (PUR) and saccade (SAC). For FIX, the target remained in the centre of the screen at eye level. During PUR, the target displaced from the centre of the screen in the horizontal direction to a defined threshold of visual angle (described below) before returning to the centre of the screen with a frequency of 0.33 Hz (Laurens et al., 2010). The target moved randomly left or right on each oscillation, which had no bearing or relation to the participants side dominance. This choice reflects spontaneous tracking movements occurring in everyday activities (Kowler, 2011). For SAC, the same protocol was implemented. However, the target disappeared from the centre of the screen and reappeared at the defined threshold stimulating a saccadic eye movement, and then disappeared and reappeared back at the centre.

Visual stimuli were programmed in degrees of visual angle to enable standardisation between experiments. It was considered to update the size and displacement of the visual target relative to each participant as they progressed along the walkway. This would have maintained a constant degree of visual angle for the size of the target, and visual angle change for the displacement of the target. However, this would have made the target appear to move away from the participants as they progressed forward. In everyday life, objects do not typically reduce in size as an observer approaches. Likewise, objects moving across a person's field of vision, such as a passing pedestrian, often maintain a linear heading. The magnitude of the tracking movement is such a case is thus always dependent on how far the observer is from the visual target. It was decided, therefore, not provide real-time adjustments. As such, the size of the visual target relative to each participant corresponded to 1° at the start of the data capture area, and 2° at the end. The displacement of the target (left or right) in the horizontal direction corresponded to 6° at the start of the data capture area and 12° at the end.

4.2.4 Experimental protocol

Five trials for each condition (FIX, PUR and SAC) were completed. The conditions were sorted randomly and segregated into 3 blocks of 5 trials. Each block was separated by 2 min of rest. The participants walked overground on a flat level walkway in the laboratory for 7.5 m. The walkway consisted of a 2.5 m entry area to achieve a steady-state velocity, which has previously been recommended for older adults (Lindemann et al., 2008), a 4 m data capture area where balance control was assessed, and a 1 m exit area (Fig. 4.1). At least 2.5 strides of data were collected from each participant during each trail which totalled at least 12.5 strides for each participant in each condition. FIX was presented at the beginning of the entry

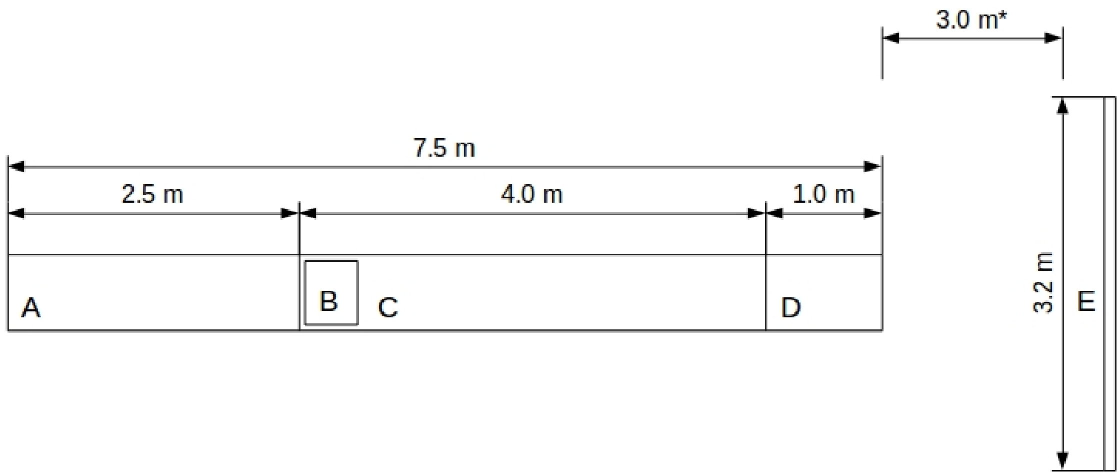


FIGURE 4.1: Walkway consisting of A: entry area, B: contact mat, C: data collection area, D: exit area, and E: projection screen. *Distance between walkway and projection screen is not to scale.

area before the participants set off during all trials. On the first heel strike on entering the data capture area, which was arranged to be in the first 30 cm, visual target movement or no movement depending on the condition was initiated by the custom-made contact mat.

Participants were instructed to fixate their gaze on the visual target at all times. If it moved, they should follow it with their eyes only making sure not to rotate or tilt their head. Gaze shifts of less than 15° are commonly achieved without rotation of the head (Hallet, 1986), and eye movements up to 35° have been performed whilst minimising head movements (Paquette and Fung, 2011). This accommodates the maximum target displacement of 12° in the present investigation. Head rotations during testing were assessed to ensure any changes in the outcome measures were not a result of head movements corresponding to the direction of the visual target movement.

4.2.5 Method considerations

The visual stimuli and experimental set-up aimed to replicate as closely as possible eye movements used in everyday life and their changes to retinal flow whilst standardising eye movement velocity and displacement. Using a virtual reality environment with 3D cues, which would generate similar retinal flow patterns as to walking through a room, was considered. However, this would require treadmill walking, which for reasons discussed below, was not appropriate. Instead, the 2D visual target was projected at the wall of the laboratory, and as such there would have been visual flow generated from the rest of the room as the participants walked forward, e.g. from the walls running adjacent to the walkway. With regard to the target, this just provided a visual fixation point — during a smooth pursuit it is the background visual information (the rest of the room in the present experiment) that becomes more difficult to interpret, and this is what has previously been suggested to affect standing balance control (Laurens et al., 2010, Thomas et al., 2016). The object of fixation is, therefore, not of particular concern.

With regard to locating the target at eye level and in the centre of the visual field, although humans have been shown to fixate on points at which they will step around a second or so before stepping on them (Patla and Vickers, 2003), walking humans also locate their gaze centrally along the horizontal and vertical relative to the direction heading. In other words, toward a heading point (Higuchi, 2013). Moreover, they can fixate on fixed and moving objects. One study, for example, found that of 133 pedestrians, a walker fixated 83% of them at least once whilst navigating a university campus (Foulsham et al., 2011). This coupled with a previously documented visual attentional bias towards people's faces and eyes (Birmingham et al., 2008) suggests that gaze can be allocated at eye level in front of the observer, and often on moving targets, which is in line with the present stimuli.

Finally, the number of recommended strides for assessing gait variability has ranged between 5 and 8 to the order of hundreds whilst dual tasking in older adults (Owings and Grabiner, 2004, Hollman et al., 2010). Additionally, separating data collection into a series of stop-start walks as in the present experiment can increase lower-limb variability when compared to one continuous walk (Paterson et al., 2009). However, measuring gait for long duration walking would typically require a treadmill, which has been shown to significantly alter gait (Dingwell et al., 2001). Further, replicating normal retinal flow patterns on a treadmill would require virtual reality. In addition to the limited availability of such a set up, virtual reality has also been shown to alter gait compared to normal conditions, and may even cause instability in healthy subjects (Hollman et al., 2007). The present investigation, therefore, placed emphasis on repeated short overground walks. First, this more closely replicates everyday walking (Orendurff et al., 2008) in a more familiar way for elders (Schellenbach et al., 2010). Second, it was important to assess immediate effects of visual stimulus onset. In everyday life, eye movements can be initiated spontaneously, and objects of interest may not be observed for many continuous strides. This was important considering the CNS can re-weight its use of vision over longer time frames (Allison et al., 2006) and short-term effects may have gone unnoticed during longer walks.

4.2.6 Data analysis

Raw marker data were extracted using the Biomechanical Toolkit Python bindings (Barre and Armand, 2014) and analysed offline (see General methods section 2.5.2).

Marker trajectories were low-pass filtered using a fourth order zero-phase Butterworth filter with a cutoff frequency of 10 Hz. Heel strike events were determined based on the position of the heel marker in relation to the Sacrum marker (Zeni et al., 2008). In short, the y coordinate of the Sacrum marker at each time frame was subtracted from the y coordinate of each heel marker at the corresponding time frame, and peaks in the resulting time series representing heel strikes determined. This method has been shown to estimate overground heel strike events to within 0.0021 s of gold standard force platform measurements (Zeni et al., 2008).

4.2.7 Trunk movement

Movement of the lower and upper trunk in the ML direction was quantified as the root mean square (RMS: see General methods section 2.5.2) of the ML component of the C7 and Sacrum markers. Trunk lean was defined as the inclination angle of the trunk with respect to the vertical axis, which was calculated from the inverse tangent of the distance between the C7 and Sacrum markers in the ML axis divided by the same distance in the vertical axis. RMS of the resulting time series was then computed. The present experiment focused on the ML axis for trunk kinematics as this is sensitive to the visual component of balance control (Warren et al., 1996, McAndrew et al., 2010).

4.2.8 Lower limbs

Step-width was defined as the ML distance between heel markers at heel strike. Mean and coefficient of variation (CV: see General methods section 2.5.2) was then calculated for step-width across successive steps (Brach et al., 2005, McAndrew et al., 2010, Franz et al., 2015).

4.2.9 Head rotations

The four head markers were used to construct a head segment. Then, rotation matrices were calculated between consecutive frames and converted to Euler angles expressed in degrees of yaw rotation about the vertical. This corresponds to the direction of the visual target movement. RMS of the head rotation time series was then computed.

4.2.10 Gaze fixations

Where participants were looking in relation to the target was assessed to ensure the protocol was completed accurately. Following export of data as detailed in General methods section 2.2, the position of the target and the position of each gaze fixation as x and y coordinates on the 2D video frame was determined using a motion tracking algorithm (OpenCV Python libraries). The resultant coordinate timeseries was then calculated (see General methods section 2.5.2).

Data before stimulus onset and at the end of the data collection area was removed in accordance with the motion capture data. Where no gaze data were sampled to due blinking, the target coordinate at the corresponding time frame was removed (Thomas et al., 2016). Pearson correlation coefficients were then calculated between the coordinate time series of the target and that of the gaze fixations, and finally RMS of gaze subtracted from the target position (RMS gaze error) throughout each video sequence.

Reliability of the tracking procedure used to determine the coordinates of the target and the gaze fixations was assessed by re-tracking all of the video sequences and computing the CV between gaze error RMS results. A CV of 0% indicated perfect reliability throughout.

4.2.11 Statistical analysis

The mean or median of the 5 trials for each participant in each condition was used for statistical analysis of the relevant outcome measures depending on a normal or non-normal distribution of the raw data. Condition (3 $\times$ visual scenes) and age (young and older) were considered as two independent factors. The effect of these two factors on C7 and sacrum RMS, trunk lean RMS, step-width mean and CV, head rotation RMS, correlation coefficients between the target coordinates and gaze fixation coordinates, and RMS gaze error, were examined with a two way (condition $\times$ age) mixed analysis of variance (ANOVA). Post-hoc analyses included t tests or Wilcoxon signed-rank tests with Bonferroni corrections. Where significant differences were found ($p \leq 0.05$), Hedges' g_{av} effect sizes were calculated (see General methods section 2.5.2). Common indicative thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8). Statistical results were interpreted in the context of strength of evidence against the null hypotheses, which was determined by the magnitude of the p values (smaller values indicate stronger evidence), magnitude of effect sizes, and 95% confidence intervals. Statistical analyses were performed with the R software package.

4.3 Results

4.3.1 Trunk movement

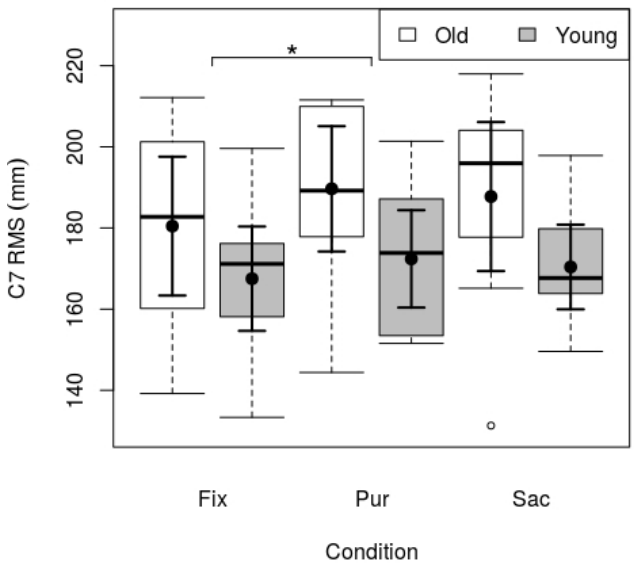
C7 and Sacrum RMS along the ML direction are shown in Fig. 4.2. C7 RMS showed a main effect of condition ($F_{2,36}$=4.71, p=0.015). Post-hoc comparisons revealed larger C7 RMS during PUR compared to FIX (p=0.012, g_{av}=0.32), but no change for SAC compared to FIX. C7 RMS showed no main effect of age or interaction effect between condition and age.

Sacrum RMS showed a main effect of condition ($F_{2,36}$=5.06, p=0.011). post-hoc comparisons revealed larger Sacrum RMS during PUR compared to FIX (p=0.009, g_{av}=0.27), but no change for SAC compared to FIX. Sacrum RMS showed a main effect of age ($F_{1,18}$=5.05, p=0.037), with larger Sacrum RMS in the older group. Sacrum RMS showed no interaction effect between condition and age.

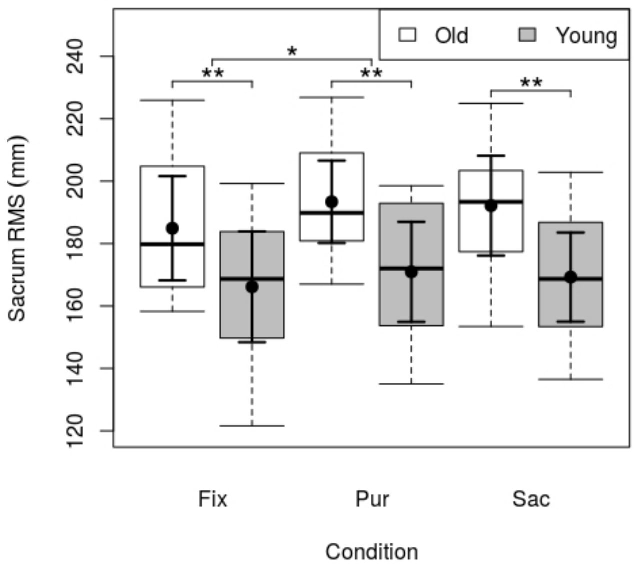
Trunk lean RMS showed no main effect of condition or age, or any interaction effect between condition and age.

4.3.2 Lower limbs

Mean step-width showed no main effect of condition or age, or any interaction effect between condition and age. Step-width CV (Fig. 4.3.) showed a main effect of condition ($F_{2,36}$=4.75, p=0.049). post-hoc comparisons revealed larger step-width CV during PUR compared to FIX (p=0.052, g_{av}=0.39), but no change for SAC compared to FIX. Step-width CV showed a main effect of age ($F_{1,18}$=5.08, p=0.037), with larger step-width CV in the older group. Step-width CV showed no interaction effect between condition and age.



(A)



(B)

FIGURE 4.2: A: C7, B: SACRUM RMS in the ML direction in young ($n = 10$) and older ($n = 10$) participants during different eye movements. FIX: fixed target, PUR: smooth pursuit, SAC: Saccade. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between conditions.**Significant difference between age groups.

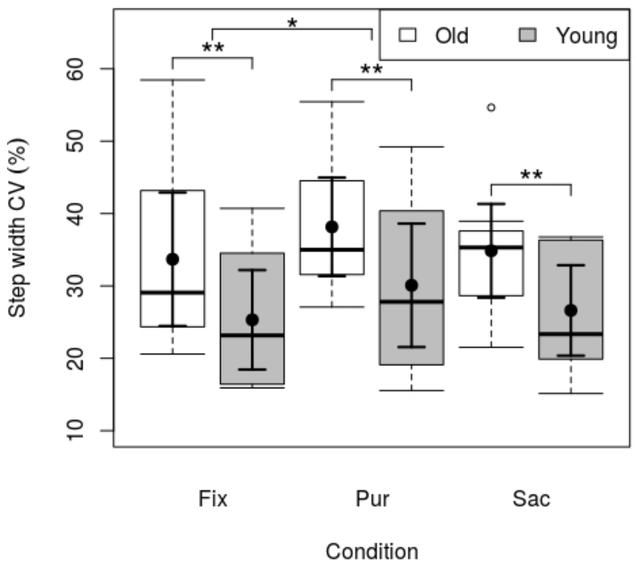


FIGURE 4.3: Step-width CV in young (n = 10) and older (n = 10) participants during different eye movement conditions. FIX: fixed target, PUR, smooth pursuit, SAC: saccade. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between conditions. **Significant difference between age groups.

4.3.3 Head rotation

Head rotation showed no main effect of condition or age, or any interaction effect between condition and age. This suggests that all participants refrained from using head rotations in the direction of target movement.

4.3.4 Gaze variables

The correlation coefficients between the coordinate time series of the target and the gaze fixations, and gaze error RMS showed no main effect of condition or age, or any interaction effect between condition and age. The correlation coefficients between the target coordinates and gaze fixation coordinates were strong (r>0.8) in all conditions for all participants. These results indicate all of the participants followed instructions and completed the visual tasks aside from natural gaze errors.

4.4 Discussion

The present investigation assessed dynamic balance control during fixation of a fixed target and smooth pursuit and saccadic eye movements in young and older healthy females steady state walking. Smooth pursuits increased ML trunk movement and step-width variability compared to the fixed target similarly in both age groups, whilst there were no changes for saccades compared to the fixed target. The elders demonstrated less baseline stability in all conditions.

The present results support the hypothesis that visually tracking a moving target with smooth pursuits decreases balance control during walking. This was likely related to changes in retinal flow caused by the eye movements. Processing of retinal flow for self-motion during eye movements is thought to occur in the medial superior temporal (MST) (Duffy and Wurtz, 1991) and ventral intraparietal (VIP) areas of the visual cortex (Schaafsma and Duysens, 1996). These regions have been linked to judging direction heading from retinal flow (Zhang et al., 2004), and compensation for changes in the focus of expansion during smooth pursuits (Page and Duffy, 1999). In the present experiment, the added complexity to retinal flow caused by smooth pursuits would likely lead to increased processing demands within the MST and VIP areas, and this may have reduced visual sensitivity to self-motion.

Another factor which may have contributed to decreased balance during smooth pursuits is more complex extraretinal signals. Extraretinal signals have been shown to improve balance in standing humans, where small eye movements used to maintain gaze fixations during postural sway (initiated by the vestibulo-ocular reflex) provide information about body position relative to the fixation point (Guerraz and Bronstein, 2008). During locomotion, fixation of a fixed target would produce similar signals. For example, researchers found a minimum threshold of 0.3° of eye movement for 1 cm of translational head movement was useful during standing (Guerraz and Bronstein, 2008). During locomotion, the gait cycle would induce translation head movements meeting this threshold (Borg et al., 2015). It is thus likely that the extraretinal component of balance control persists during walking, and if so, it is also likely that during a smooth pursuit, the eye rotation required to keep gaze fixated on the moving target would surpass any extraretinal signals useful for balance control. This was also thought to occur during standing in previous experiments (Laurens et al., 2010, Thomas et al., 2016).

Supporting the second hypothesis, there were no changes to balance during saccades compared to the fixed target. Because saccades are a series of fixations separated by rapid eye movements, and the target movement during the saccades was completed in sub 20 ms and each saccade in 40–50 ms (Abrams et al., 1989), gaze was fixated on a fixed target for the majority of the saccadic eye movement trials. Such conditions likely preserved the stable reference frame similar to the fixed target. It is also probable, therefore, that any element of extraretinal postural stabilisation was also preserved. Even though the final displacement of the eye rotation during saccades was the same as during smooth pursuit, the nature of eye rotation and neural control to reach that displacement are different (Kowler, 2011). In effect, the continuing rotation during smooth pursuits complicates extraretinal balance signals, whilst the short rapid shifts of saccades preserve longer periods of fixation pre- and post-saccade, and thus useful extraretinal signals.

Contrary to the third hypothesis, the negative change to balance during smooth pursuits was not more profound in the older adults. This is interesting since elders have previously been shown to have difficulties in interpreting retinal flow for self-motion (Berard et al., 2009). However, comparing the present results with others is difficult since there have been no studies considering eye movements and balance in walking elders. One explanation is there was only a small effect (trunk: g_{av}=0.32; lower limbs: g_{av}=0.39) of smooth pursuits on balance in both age groups. The changes to retinal flow, therefore, may not have been profound enough to 'challenge' the ageing CNS enough to bring about a greater change. This would indicate that healthy elders are able to process retinal flow for balance purposes during smooth pursuits as effectively as younger adults. However, the older adults demonstrated reduced balance throughout testing, with greater Sacrum displacement and step-width variability in all conditions. Thus, the elders were already at a disadvantage, which was probably due to a combination of musculoskeletal and sensory deficits which are considered normal in healthy ageing (Ambrose et al., 2013). Any further decrease to balance such as that shown in the present experiment is, therefore, certainly undesirable, particularly considering that greater baseline instability indicates a higher risk of falls (Ambrose et al., 2013).

4.5 Conclusion

The present investigation showed that smooth pursuits decrease balance control in young and older adults. Although the change was not more profound in the older group, elders are typically already at a postural disadvantage. Thus, further negative changes are undesirable. However, because the present results were obtained in a laboratory, further investigation is needed in a real-world environment older adults are likely to use. This may offer a more direct application of the results.

The previous chapter showed that smooth pursuit eye movements can negatively affect postural control in young and older adults during locomotion in the laboratory, whilst saccades maintained stability. To expand on this research, the following chapter explores the effects of smooth pursuits and saccades on balance control in young and older adults during locomotion in a real-world environment.

Chapter 5

Visually fixating an indoor pedestrian decreases balance control in young and older healthy females walking in a real-world environment

The work presented is this chapter arose from the following publication (see Appendix C):

Thomas, N. M., Dewhurst, S., Donovan, T. and Bampouras, T. (2017), 'Visually fixating an indoor pedestrian decreases balance control in young and older healthy females walking in a real-world environment', *Neuroscience Letters*, in review (Submitted June 2017)

5.1 Introduction

Vision helps maintain an upright posture during locomotion (Warren et al., 1996, Logan et al., 2010). This is facilitated by changes in patterns of light intensities caused by relative motion between an observer and their environment, which are sensed at the retina (Gibson, 1950). Lateral trunk lean, for example, would generate a translational flow on the retina in the opposite direction (Guerraz and Bronstein, 2008). The central nervous system uses this to estimate shifts in body position and initiate postural adjustments.

Eye movements can affect how retinal information is used for balance control. Visually tracking a moving target with smooth pursuits increased mediolateral (ML) trunk movement and step-width variability during walking in young and older females similarly – factors which reflect decreased stability (Chapter 4). During such eye movements, although the target of fixation is stabilised on the fovea, the background information can be prone to blurring (Schulmann et al., 1987). This, in turn, may make it more difficult to estimate self-motion through visual means. Previous investigation about eye movements and balance employed targets projected in 2D (Laurens et al., 2010, Glasauer et al., 2005). This mimics viewing of a background scene, where focusing on the target requires similar convergence to other locations surrounding the target (Mays, 1984). Humans often, however, fixate stationary and moving objects located more in the foreground, such as stationary and walking pedestrians (Foulsham et al., 2011). This requires more convergence to bring focus to the object, which in turn causes background blurring (Sprague et al., 2016). If the blur makes it more difficult to determine self-motion with visual information, it may result in decreased balance control even when the object is stationary. Presumably, such an effect will be more profound when the object is moving due to more dynamic blurring. However, whilst a recent study assessed standing balance during fixation of near and far light targets (Matheron et al., 2016), the authors did not consider fixation of the background alone. Further, walking balance whilst tracking fixed or moving objects more in the foreground has not previously been examined.

These considerations may have important implications in older adults. Elders typically demonstrate less 'baseline' stability and a reduced ability to correct loss of balance during walking (Ambrose et al., 2013), and this may place them at an even greater risk of falls during such visual fixation tasks. Assessing elders walking balance whilst fixating static and moving objects more in the foreground may, therefore, further understanding of risk factors of falls in elders. Moreover, conducting the experiment in a realistic setting will offer a more direct application of the results.

The present investigation, therefore, assessed dynamic balance in young and older adults during free gaze, and when visually tracking a standing or walking indoor pedestrian in a real-world environment. It was hypothesised: 1) visually fixating the standing and walking pedestrian would decrease balance control compared to free gaze in young and older participants similarly, 2) there would be a more profound effect whilst tracking the walking pedestrian, 3) the elders would exhibit less baseline stability throughout.

5.2 Methods

5.2.1 Participants

Ten young (mean ± SD: age: 23.6 ± 3.4 years, height: 1.68 ± 0.06 m, mass: 69.0 ± 9.9 kg) and 10 older (mean ± SD: age: 71.0 ± 5.5 years, height: 1.61 ± 0.06 m, mass: 63.9 ± 10.3 kg) healthy females participated in the investigation. All participants adhered to inclusion criteria detailed in General methods section 2.1. All participants had an uncorrected visual acuity (without glasses or contact lenses) ≥20/100 and were able to ambulate in the community without visual correction.

5.2.2 Equipment

Testing was carried out on a flat walkway into a waiting room (Fig. 5.1). The walkway consisted of a 2.5 m entry area to achieve a steady-state velocity, which has previously been recommended for older adults (Lindemann et al., 2008), a 4 m data capture area where dynamic balance characteristics were assessed, and a 1 m exit area. Sliding doors concealed the waiting room from the participants when they were at the start of the walkway. A member of the research team (pedestrian) would be absent from or standing or walking within a standardised pedestrian area at the far end of the waiting room (Fig. 5.2: see Experimental protocol section 5.2.3). A custom-made contact mat (see General methods section 2.3) was used to send a signal to a laptop informing the pedestrian when to begin walking and in which direction (see Experimental protocol section 5.2.3). Four inertial measurement units (IMUs: Opal, APDM, Portland, Oregon) measured accelerations of the centre front head, sacrum, and left and right ankle anatomical land marks of each participant. Participants wore eye tracking glasses as detailed in General methods section 2.2.

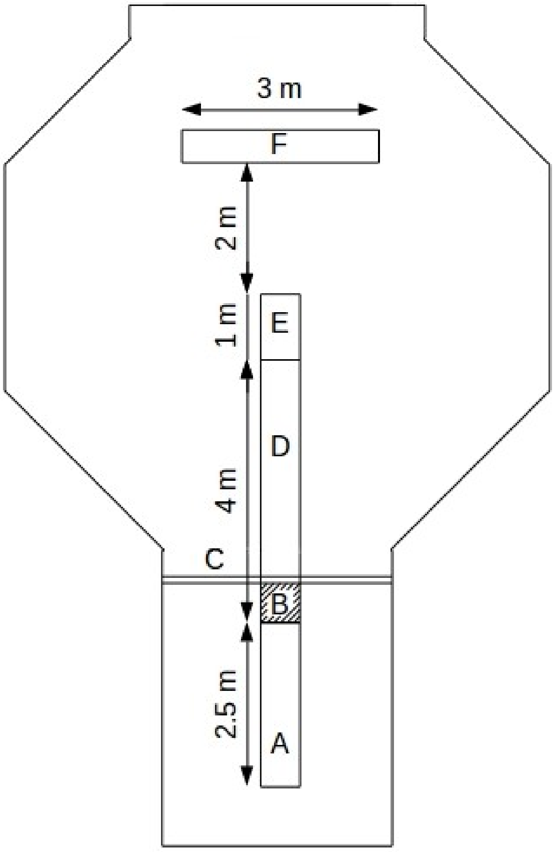


FIGURE 5.1: A schematic diagram of the experimental environment. The walkway into the waiting room consists of A: entry area, B: contact mat, C: sliding doors, D: data collection area, E: exit area, F: pedestrian area. All distances are to scale.

FIGURE 5.2: Example of a participant's point of view whilst walking into the waiting room taken from the eye tracking camera. The stationary pedestrian is present in this condition. The circle on the pedestrian represents a gaze fixation.

5.2.3 Experimental protocol

The sliding doors were shut before each trial and then opened signalling the trial to commence. The participants then walked straight into the room at a self-selected pace along the length of the walkway towards the exit area. Three conditions were implemented: free gaze (FREE), stationary pedestrian (STAT) and walking pedestrian (WALK). For FREE, the waiting room was void of the pedestrian. For STAT, the pedestrian stood upright and stationary in the centre of the pedestrian area facing the participant (perpendicular to the walkway; see Fig. 5.2). For WALK, on the first heel strike on entering the data capture area, the contact mat (beginning at the start of the data capture area and ending 30 cm along the walkway) sent a signal to a laptop out of view of the participant which informed the pedestrian to begin walking and in which direction. The direction (left or right) was random on each trial. The pedestrian walked for 1.5 m across the pedestrian area (beginning with the lead foot which corresponded to the direction of travel) before standing still whilst facing the same direction as in the start position (again perpendicular to the walkway). During FREE, the participants were given no instructions where to look. During STAT and WALK, they were informed to look at the pedestrian at all times, and if the pedestrian moved, to track them with their eyes only making sure not to rotate or tilt their heads. The 1.5 m threshold corresponded to 12° of visual angle relative to the participants while they were at the start of the data capture area, and 26° at the end. During STAT and WALK, the pedestrian was present on door opening and was thus visible to the participants at the start of the walkway. However, prior to door opening, the participants were blinded to the conditions in the room.

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

5.2.4 Data analysis

Raw data from the IMU devices (sampled at 120 Hz) were exported and analysed offline (see General methods section 2.5.2). Raw data were filtered with a zero-lag low-pass Butterworth filter (20Hz cuttoff). Heel strikes and mid-stance phases were determined using the methods of Rebula et al. (2013) and Bötzel et al. (2016). Mid-stance periods were defined as zero velocity instants, where the accelerometer reading is close to gravitational, and the gyroscope reading small. Thresholds used were 0.8 m/s^{-2} (relative to gravity) and 1.7 $radians/s^{-1}$, respectively. Unusually short stationary or swing periods ($<$0.133 s and $<$0.2 s, respectively) were excluded as erroneously detected phases, e.g. quick foot slips during stance. Heel strikes were defined as the lowest point of the first trough after each peak in the gyroscope pitch axis readings (aligned with the ML axis of each participant), which was determined using custom peak detection algorithms. All data were subsequently truncated to the first right heel strike upon entering the data capture area, and the third left stride mid-stance period. The sacrum acceleration readings in the IMU reference frame were then transformed to the global reference frame by subtracting the gravity vector from the acceleration readings. The gravity vector was obtained from Opal proprietary orientation estimates. Standard deviation (SD) of Sacrum acceleration in the global ML direction then defined sacrum acceleration dispersion (Huisinga et al., 2013), which characterised balance control.

To ensure the participants followed instructions, SD of head rotations about the yaw axis obtained from Opal proprietary orientation estimates were calculated, in addition to gaze fixations. Following export of the gaze data as detailed in General methods section 2.2, a pre-trained histogram of orientated gradients combined with a linear support vector machine model (OpenCV, Python libraries) was used to automatically identify the pedestrian and record their coordinates on the exported 2D video frames. These were subsequently compared to the coordinates of the participants' gaze fixations, which were determined using a motion tracking algorithm (openCV Python libraries). The centroid inside the bounding box surrounding the pedestrian was used as a tracking point, which corresponds roughly to the centre of mass of the pedestrian. Root mean square (RMS: see General methods section 2.5.2) of gaze subtracted from the pedestrian coordinates then defined RMS gaze error, and Pearson's correlation coefficients between the gaze and pedestrian coordinates defined the strength of relationship between both timeseries.

These measures of absolute error (and correlation) between the centroid of the bounding box and the fixation locations have some limitations. For example, they do not differentiate between fixations on the pedestrian and fixations on the background wall, nor do they contain information about fine grained metrics such as catch-up saccades or onset latencies. Instead, a low error (or high correlation) merely suggests more accurate ocular following of the pedestrian. This was deemed as a sufficient indication of whether the participants were following instructions.

5.2.5 Statistical analysis

The mean/median of the 5 trials for each participant in each condition was used for statistical analysis of the relevant outcome measure depending on normal or non-normal distribution of the raw data. Condition (3 × visual scenes) and age (young and older) were considered as 2 independent factors. The effects of these factors on Head rotation and Sacrum SD were examined with a 2 way (condition × age) mixed analysis of variance (ANOVA). The same model was applied to the correlation coefficients between pedestrian and gaze fixation coordinates and RMS gaze error, but with only STAT and WALK considered. Post-hoc analyses were *t*-tests with Bonferroni corrections. Finally, where significant differences were found ($p<0.05$), Hedges' g_{av} effect sizes were calculated (see General methods section 2.5.2). Common indicative thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8). Statistical results were interpreted in the context of strength of evidence against the null hypotheses, which was determined by the magnitude of the *p* values (smaller values indicate stronger evidence), magnitude of effect sizes, and 95% confidence intervals. Statistical analyses were performed with the R software package.

5.3 Results

Sacrum SD in the ML direction is shown in Fig. 5.3. Sacrum SD showed a main effect of condition ($F_{2,36}=11.81$, $p<0.001$). Post-hoc comparisons revealed larger Sacrum SD during STAT ($p=0.006$, $g_{av}=0.21$) and WALK ($p=0.001$, $g_{av}=0.23$) compared to FREE. Sacrum SD showed no main effect of age or interaction effect between condition and age.

Head rotation SD showed no main effect of condition or age, or any interaction effect between condition and age. The correlation coefficients (all above 0.7) between the pedestrian and gaze fixation coordinates and RMS gaze error showed no main effects of condition or age, or any interaction effects between condition and age. This

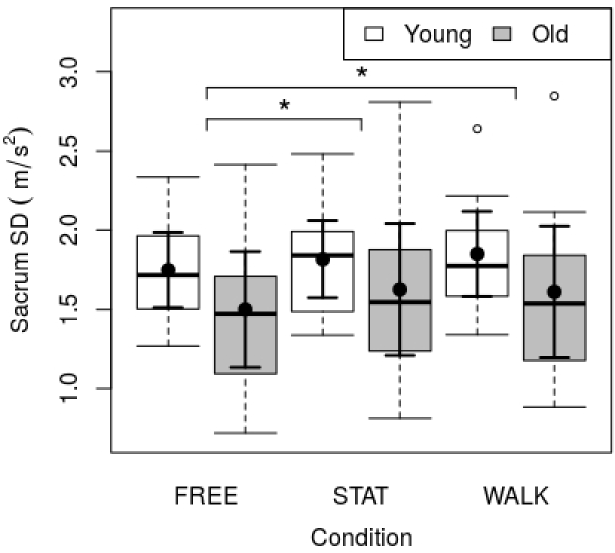


FIGURE 5.3: Sacrum RMS in the ML direction in young (n = 10) and older (n = 10) females during different eye movement conditions. FREE: free gaze, STAT: stationary pedestrian, WALK: walking pedestrian. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between conditions.

suggests the participants followed instructions and tracked the pedestrian with their eyes whilst refraining from using head rotations.

5.4 Discussion

The present investigation assessed balance control during walking in young and older adults visually fixating an indoor pedestrian. Increases in Sacrum acceleration dispersion were found on the ML axis when the pedestrian was standing still and walking. There were, however, no differences between age groups.

In support of the first hypothesis, there was an increase in sacrum acceleration dispersion whilst visually fixating the stationary and walking pedestrian as opposed to free gaze in both young and older participants. This is the first experiment to show such an effect, and in a real-world environment. The result is likely a consequence of more complicated or blurred background retinal information generated by fixation of the pedestrian, which made it more difficult to determine translational trunk movements through visual information alone. In contrast to the second hypothesis, there was a similar increase in sacrum acceleration dispersion during fixation of the stationary pedestrian compared to the walking pedestrian. Since there were no differences in gaze errors between conditions or ages, and the correlations coefficients between the pedestrian and the fixation coordinates were all strong, it can be assumed that the participants fixated the pedestrian satisfactorily in each condition. Thus, it seems that the amount of blur induced by fixation of the stationary pedestrian was sufficient to decrease balance control to the same level as when the pedestrian was walking, even with the dynamic blurring which would have occurred when tracking the walking pedestrian. This may be a consequence of the gait cycle inducing various oscillatory components of retinal flow from the background information which would be blurred due to fixation of the nearer object, even when the object was stationary. In effect, background blur would have been dynamic when fixating both the stationary and the walking pedestrian.

The fact there were no differences between fixation of the stationary and the walking pedestrian raises a question as to why there was a decrease in balance control during smooth pursuits compared to fixation of a fixed target in Chapter 4. This may be attributed to the location of the target with respect to the background. For example, during the free gaze condition in the present experiment, there were no objects located in the foreground to observe, and thus, visual fixation of any point in the room required similar convergence to locations immediately surrounding that point. This actually reflects both the fixation and saccadic conditions in Chapter 4, where the target was projected onto a flat screen. Fixating the pedestrian in the present experiment better reflected the smooth pursuit condition of Chapter 4, since that was the only condition which would have caused blurring. This is why there was a similar increase with smooth pursuits compared to stationary fixation in Chapter 4 (g_{av}=0.27), and with fixation of the stationary pedestrian compared to free gaze in the present experiment (g_{av}=0.21).

In contrast to the third hypothesis, there was no difference in baseline sacrum acceleration dispersion in the elders compared to the younger adults. Therefore, it appears they were able to match the younger participant's performance throughout – processing the visual information and completing the eye movement tasks. The elderly participants were healthy and could all ambulate within the community without visual correction, and other older populations have been shown to exhibit resistance to visual motion perception ageing effects due to compensatory mechanisms (Billino et al., 2008). Therefore, detrimental performance of visual tasks similar to those in the present experiment may not be a necessary consequence of ageing. With that said, the small increase in sacrum acceleration dispersion during both fixations tasks may warrant further investigation in those at greater risk of falling – particularly in those with vestibular/ocular dysfunction.

5.5 Conclusion

The present experiment showed that visually fixating another pedestrian can decrease balance control in young and older adults during locomotion. The findings may be useful to those working with elders. It may not be unusual, for example, for older adults to walk into waiting room environments and fixate on other people. Since this can negatively affect balance control, a quiet room void of people would be more optimal for reducing fall-risk in those who are less stable. Professionals may consider this for interventions as well as designing and maintaining areas high fall-risk older adults are likely to use. Future research should seek to examine if older adults adopt similar gaze fixation behaviour (i.e. fixating other people) during free viewing in a similar real-world environment, which would help put the present results into context.

The previous chapter showed that visually fixating a standing and walking indoor pedestrian can negatively affect postural control in young and older adults during locomotion. To put these findings into context, the following chapter explores natural gaze behaviour in young and older adults during locomotion in a similar real-world environment.

Chapter 6

Visual sampling during locomotion in a real-world environment: effects of ageing and pre-planning, and considerations for reducing fall risk

The work presented is this chapter arose from the following publication (see Appendix D):

Thomas, N. M., Dewhurst, S., Donovan, T. and Bampouras, T. (2017), 'Visual sampling during locomotion in a real-world environment: effects of ageing and pre-planning, and considerations for reducing fall risk', *Frontiers in Aging Neuroscience*, in review (Submitted October 2017)

6.1 Introduction

Vision plays several important roles for successful locomotion. It enables pre-planning for upcoming movements, such as a route to an intended destination (Patla, 1997), or a foot-placement location (Patla and Vickers, 2003). It facilitates online postural adaptations, for example, modifying swing limb trajectory to accommodate for changing terrain (Hollands et al., 1995), and it provides a useful means to estimate self-motion, which is important for control of balance (Logan et al., 2010) and direction heading (Warren et al., 2001).

Visual sensing of the world and self-motion within it occurs at the retina, where patterns of light reflected off structures in the environment are detected (Kowler, 2011). The centre of the retina – the 'fovea' – is the region with the highest visual acuity, and during locomotion, this is typically directed 'overtly' to various regions of the environment to extract information relevant to task demands. These can include predictive footfall locations around one or two steps ahead (Paquette and Vallis, 2010), potential hazards and obstacles (Chapman and Hollands, 2006), and often toward a direction heading (Higuchi, 2013). In addition, attention can be directed 'covertly' to features in the periphery of vision, such as trip hazards, without the need for reorientations of gaze (Marigold and Patla, 2008). Visual self-motion detection is facilitated, in part, by 'retinal flow'. This refers to a change in patterns of light intensities at the retina caused by relative motion between an observer and their environment, about a point of central observation. Forward motion, for example, would generate an expanding flow emanating from the centre of vision (Gibson, 1950). The central nervous system (CNS) can use this to estimate shifts in body position and initiate postural adjustments (Guerraz and Bronstein, 2008).

Chapters 4 and 5 demonstrated a unique interplay between the region/object of foveal fixation and visually derived estimates of self-motion. When young and older participants visually tracked an oscillating computer generated target, and a standing or walking actor in a real-world environment, they exhibited increased medio-lateral trunk movement and step-width variability – factors which reflect decreased stability. It was suggested the visual tasks generated more retinal blur surrounding the foveal region. This would have been caused by the smooth pursuit eye movement to track the moving target and the walking actor, which would also complicate retinal flow due to the rotational eye movement, or by greater convergence to focus on the stationary actor when compared to the background. This likely made it more difficult to determine translational trunk movements with vision, thus reducing the accuracy of visual postural corrections. The findings had important implications for elders' balance control in that any negative change to balance is undesirable in older populations (Ambrose et al., 2013). In these studies, the participants were instructed where to look, which was necessary to isolate the effects of the visual tasks. What is not known is whether young or older adults would adopt similar detrimental gaze behaviour during free viewing. Further investigation of natural gaze behaviour in a similar real-world environment, will elucidate to whether the decreased balance is transferable to natural gaze patterns. Another reason to assess older adults natural gaze behaviour in such a context is that there are actually very limited data obtained from walking elders in real-world environments. Previous laboratory-based investigations have revealed older adults to look lower in the visual field, and to rely on foveal vision more to acquire relevant information (Itoh and Fukuda, 2002). This has been linked to reduced visuospatial memory, slowed visual information processing, and fear and anxiety about falling (Uiga et al., 2015, Young et al., 2012). It is not known, however, if these results are reflected in real-world conditions, since gaze behaviour has been shown to differ between the laboratory and the real world (Dowiasch et al., 2015, Foulsham et al., 2011, Zeuwts et al., 2016). Further investigation is thus needed to bridge the gap between the laboratory and the real world.

Another factor which has been relatively little explored in the real world is the role of visual pre-planning. If participants are allowed to pre-scan the environment prior to gait initiation, it would presumably allow more time to understand visuospatial relationships. Therefore, gaze behaviour might differ to that when instructed to walk straight away with no prior view. This may also be more profound in older adults because of their typically slowed visual information processing (Uiga et al., 2015). However, it is currently not known if given the opportunity, elders take longer to pre-scan the environment or change their gaze behaviour as opposed to being instructed to walk straight away. Laboratory-based studies which have explored gaze behaviour in elders during locomotion, for example, have instructed the participants to look straight ahead until they set off walking, after which they are free to look where they want (Di Fabio et al., 2001), or have had their view of the walkway obstructed completely prior to trial commencement (Zietz and Hollands, 2009). In the present experiment, it would be beneficial to implement pre-planning and no planning conditions. This will not only address concerns of internal and external validity (i.e. constraining participants to either condition may affect their natural gaze behaviour, or at the very least only tell half of the story), but will further understanding of the role of visual pre-planning on gaze characteristics.

Investigations of gaze during locomotion typically utilise metrics such as frequency and duration of fixations at specific regions of interest (ROI) (Foulsham et al., 2011). Although this can provide useful information about where participants were looking and for how long, it cannot objectively describe the sequence of events, particular with multiple participants. A possible approach to address this, which is used in other areas of vision research including facial recognition (Boccignone, 2015) and driving (Underwood et al., 2005), is Markov sequence analysis. This considers each visual scan path (i.e. sequence of fixations at each ROI) as a deliberate sequential process which unfolds over time, and can provide an objective overview of how likely the participants were to fixate a certain ROI first, and how likely they were to transfer their gaze between ROIs (Boccignone, 2015). Another advantage of this method is that multiple scan paths can be modelled together, which is useful when comparing data from two groups, e.g. young and older adults (Coutrot et al., 2017). Such an approach, although not previously implemented during locomotion, will provide a richer understanding of natural gaze behaviour.

To these ends, the present investigation assessed gaze behaviour during free-viewing in young and older adults walking into a real-world waiting room environment with the option to plan before entry, or walking straight in. Reflecting the conditions of Chapter 6, the participants were presented with another standing or walking pedestrian (herein known as 'actor'), or a room absent of the actor. The aims were to: 1) determine if young and older adults fixate the actor, which can equate to an increased fall risk, 2) examine age-related changes to visual behaviour observed in previous laboratory contexts in the real world, 3) uncover potential differences in strategies when given the option to pre-plan a route into the room, 4) probe visual behaviour in a novel way by implementing Markov sequence analysis.

6.2 Methods

6.2.1 Participants

Eleven young (mean ± SD: age: 23.4 ± 3.2 years, height: 1.71 ± 0.07 m, mass: 70.8 ± 10.3 kg) and 11 older (mean ± SD: age: 70.9 ± 5.2 years, height: 1.62 ± 0.05 m, mass: 63.7 ± 9.8 kg) healthy females participated in the investigation. All participants adhered to inclusion criteria detailed in General methods section 2.1. All participants had an uncorrected visual acuity (without glasses or contact lenses) ≥20/100 and were able to ambulate in the community without visual correction.

6.2.2 Experimental environment

Testing was carried out on flat ground in a waiting room (Fig. 6.1). A custom-made contact mat (see General methods section 2.3) was used to record set-off times of each participant (see Experimental protocol 6.2.3). The entrance to the waiting room was a well-lit hallway, which was separated from the room by opaque sliding doors. Reflecting the conditions of Chapter 5, the actor followed standardised pseudo-random behaviour patterns inside the waiting room, e.g. standing still or walking a pre-defined trajectory (see Experimental protocol 6.2.3). This reflects what might occur in a typical waiting room, such as a doctor greeting a patient. Participants wore eye tracking glasses as detailed in General methods section 2.2.

6.2.3 Experimental protocol

The participants stood at the start position on the contact mat, which was located behind the sliding doors (Fig. 6.1). The sliding doors were shut before each trial

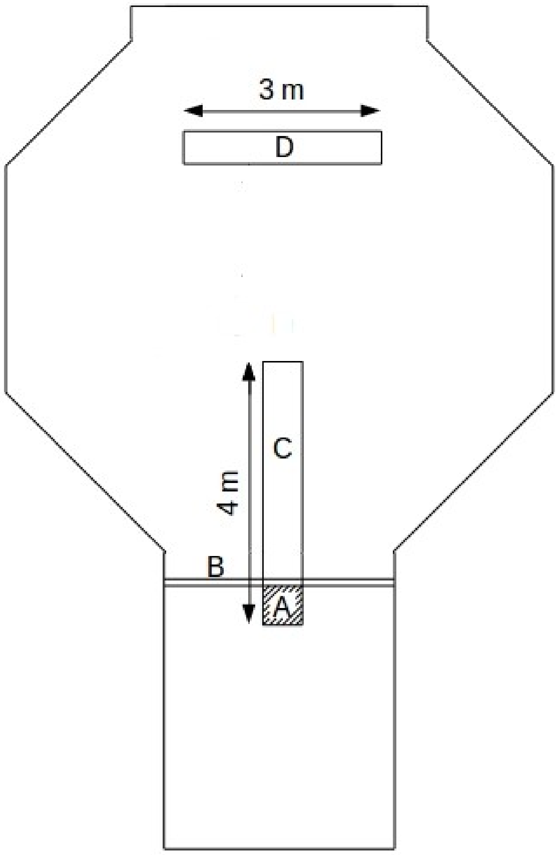


Figure 6.1: A schematic diagram of the experimental environment. A: participants' starting position; B: sliding doors; C: walkway; and D: actor area. All distances are to scale. Note that the walkway outlines were not visible to the participants, and only verbal cues were used to terminate the participants' gait.

so the participants could not see into the waiting room. The doors then opened signalling the trial to commence. Following this, the participants walked into the room at a self-selected pace until verbally informed to stop when they reached a 4 m threshold only known to the researcher. Two planning conditions were implemented: PLAN and No PLAN. For PLAN, the participants were instructed before the trial started to enter the room when they felt comfortable doing so after the doors had opened. For No PLAN, they were instructed before the trial started to enter the room as soon as the doors had opened. The time from the start of the door opening to first heel off (gait initiation) was recorded with the contact mat. Three conditions were implemented inside the waiting room: stationary actor (STAT), walking actor

(WALK) and empty room (ABSENT). For STAT, the actor stood upright and stationary in the centre of the actor area facing the participant (perpendicular to the walkway). For WALK, The actor walked for 1.5 m across the actor area (beginning with the lead foot which corresponded to the direction of travel) before standing still whilst facing the same direction as in the start position (again perpendicular to the walkway). The direction (left or right) was random on each trial. The actor set off walking as soon as the doors had opened during STAT and WALK. For ABSENT, the actor was absent from the waiting room.

One trial for each visual and planning condition was implemented, which totalled 6 trials per participant. The trials were performed randomly with around 30 s of rest between them. No instructions or cues as to where to look were given to the participants.

6.2.4 Data analysis

Following export of data as detailed in General methods section 2.2, gaze fixations were analysed in custom-made software (see General methods section 2.5.1). Five ROIs within the room typically fixated by the participants were identified by watching several videos from the young and older participants. These included the background wall closely surrounding the actor, the actor, the near and far path (near was defined as <4 m at the start of the walkway) and regions in the surrounding visual area, such as the ceiling and walls running adjacent to the room (Fig. 6.2). A fixation was considered to be on a region of interest if the region was visible at any point within the Tobii circle (Fig. 6.2). The duration spent fixating each ROI was then expressed as a percentage of total fixation time.

(A) (B)

FIGURE 6.2: A participant's point of view whilst walking into the room with the actor. The red digitised lines represent the area encompassing the path and background wall. The red Tobii circle represents a gaze fixation. Note that the boundary used to separate the near and far path (A) did not progress with the participant during analysis. However, due to the relatively short nature of the walk, the participants typically averted their gaze to the actor or background shortly after setting off. If analysing longer duration walks, it would be necessary to move the boundary with the participant as they progressed forward. Also note that during analysis, the researcher used real-world markers to determine the boundaries. In other words, digitisation was not employed during the analysis.

6.2.5 Statistical analysis

To examine the effects of ageing on fixation behaviour, a 2-way robust mixed analysis of variance (ANOVA) was implemented, with age (Young $\times$ Older) and ROI ($\times 5$) considered as between and within factors, respectively. The same model was applied to examine the effects of planning on fixation behaviour, and again to assess the effects of planning on set-off times, with planning (PLAN $\times$ NO PLAN) considered as a within factor. Post-hoc analyses were Wilcoxon signed-rank tests with Bonferroni corrections. Separate analyses were conducted for each room condition (STAT, WALK and ABSENT) with only 4 ROIs considered in ABSENT due to no actor being present. Statistical results were interpreted in the context of strength of evidence against the null hypotheses, which was determined by the magnitude of the p values (smaller values indicate stronger evidence), magnitude of effect sizes, and

95% confidence intervals. Statistical analyses were performed with the R software package.

6.2.6 Markov sequence modelling

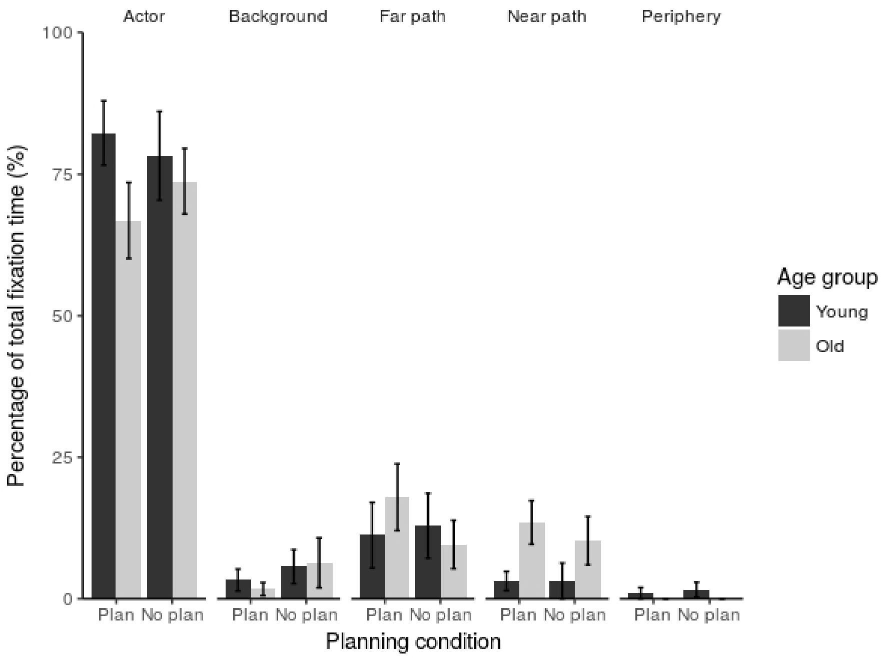
When considering visual scanpaths as Markov processes, fixation locations must be defined as a 'states' in some context (Boccignone, 2015). Previous studies have taken a data-driven approach to learning states using methods such as the 'Variational Bayesian Framework for Gaussian mixture models' (Coutrot et al., 2017). This can be beneficial for optimising the number of states where pre-defined regions of interest are less clear, e.g. when examining faces. In the present investigation, individual differences in head movement and walking speed, and a lower resolution of the visual scene (participant walking through a room as opposed to a single close-up image of a face) negate the applicability of such methods. Instead, each ROI identified from the video sequences was defined as a state, which provides a reasonable compromise between a priori definitions, e.g. dividing a face into equal portions, and objective learning.

Probability distributions over the initial ROI fixations (reflecting where the participants looked first) and probabilities of transfers between ROIs (reflecting a saccade) were calculated from the young and older adults scan paths using the seqHMM package in R. This resulted in one transfer probability matrix and one set of initial probabilities for each age group (young and old). Then, all of the observed probabilities (initial fixation and transfer probabilities) were compared to a Gaussian distribution with a binomial test (Underwood et al., 2005). The Gaussian distribution would indicate a random probability of initial fixation or shifting gaze to any ROI to be 20% during STAT and WALK (as there are five ROIs in this condition) and 25% during ABSENT (as there are four ROIs in this condition). Anything significantly different from this indicates a deliberate initial fixation or shift of gaze as opposed to a stratified random sampling process. Probabilities which were significant but very small (<5%) were not presented since they represent infrequent fixations (Underwood et al., 2005).

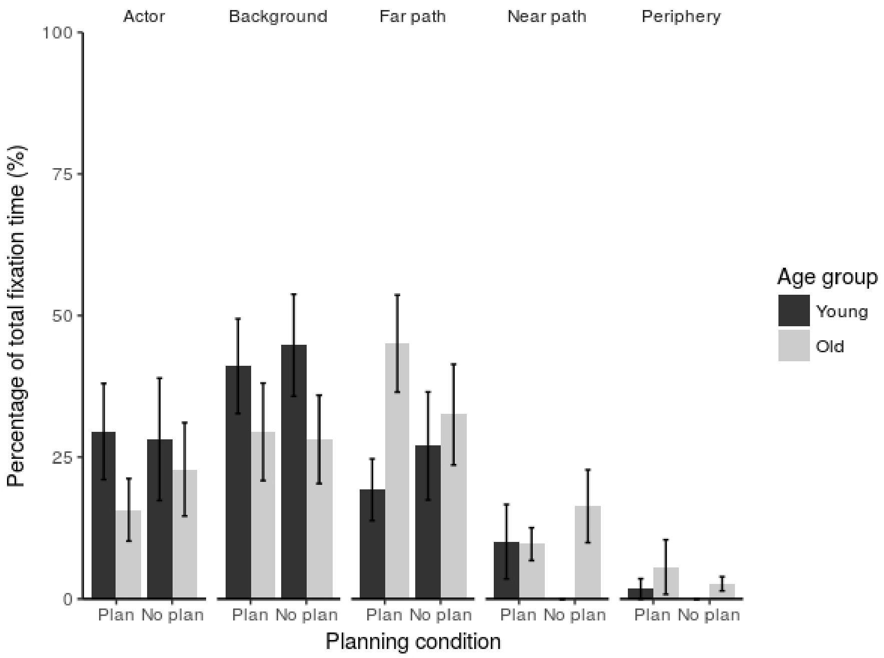
In order to assess differences between young and older adults gaze sequence data, the probabilities from each group (young and older) in each condition (STAT, WALK and ABSENT) were compared with the methods of Kullback et al. (1962) using the markovchain package in R. This approach statistically verifies whether two sequences belong to the same unknown discrete model. If they do not, they can be considered as describing significantly different processes.

6.3 Results

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during STAT is presented in Fig. 6.3. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{4,80}$=94.45, p<0.001) and a significant interaction effect between age and ROI ($F_{4,80}$=2.84, p=0.045). Post-hoc analyses revealed more time spent looking at the actor than the background (p<0.001), far path (p<0.001), near path (p<0.001) and periphery (p<0.001). More time spent looking at the background than the periphery (p=0.033), more time spent looking at the far path than the periphery (p<0.001) and the near path than the periphery (p=0.008). Examination of the interaction plot showed the young adults tended to look more at the actor than the elders, whilst the elders tended to look more at the near path than the young adults.



(A)



(B)

FIGURE 6.3: The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during A: STAT, and B: WALK (± SD) in young (n = 11) and older (n = 11) females. Significant differences are reported in the main text of the results section.

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during WALK is presented in Fig. 6.3. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{4,80}$=16.63, p<0.001) and a significant interaction effect between age and ROI ($F_{4,80}$= 4.34, p=0.008). In contrast to STAT, gaze was more evenly distributed across the ROIs. Post-hoc analyses revealed more time spent looking at the actor than the periphery (p<0.001). More time spent looking at the background than the near path (p<0.001) and the periphery (p<0.001), and more time spent looking at the far path than the near path (p<0.001) and the periphery (p<0.001). Analysis of the interaction plot showed that the young adults tended to look more at the background than the elders, whilst the elders looked more at the far path than the young adults. The young adults also tended to look more at the actor than the elders, whilst the elders looked more at the near path than the young adults.

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during ABSENT is presented in Fig. 6.4. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{3,60}$=29.96, p<0.001) and a significant interaction effect between age and ROI ($F_{3,60}$=7.14, p<0.001). Post-hoc analyses revealed more time spent looking at the background than the near path (p<0.001) and the periphery (p<0.001), and more time spent looking at the far path than the near path (p<0.001) and the periphery (p<0.001). Examination of the interaction plot showed the young adults tended to look more at the background than the elders, whilst the elders tended to look more at the far path than the young adults.

Participant set-off times for PLAN and NO PLAN during STAT, WALK and ABSENT are presented in Fig. 6.5. There were significant effects of planning condition for STAT ($F_{1,20}$=15.69, p=0.003), WALK ($F_{1,20}$=8.42, p=0.019) and ABSENT

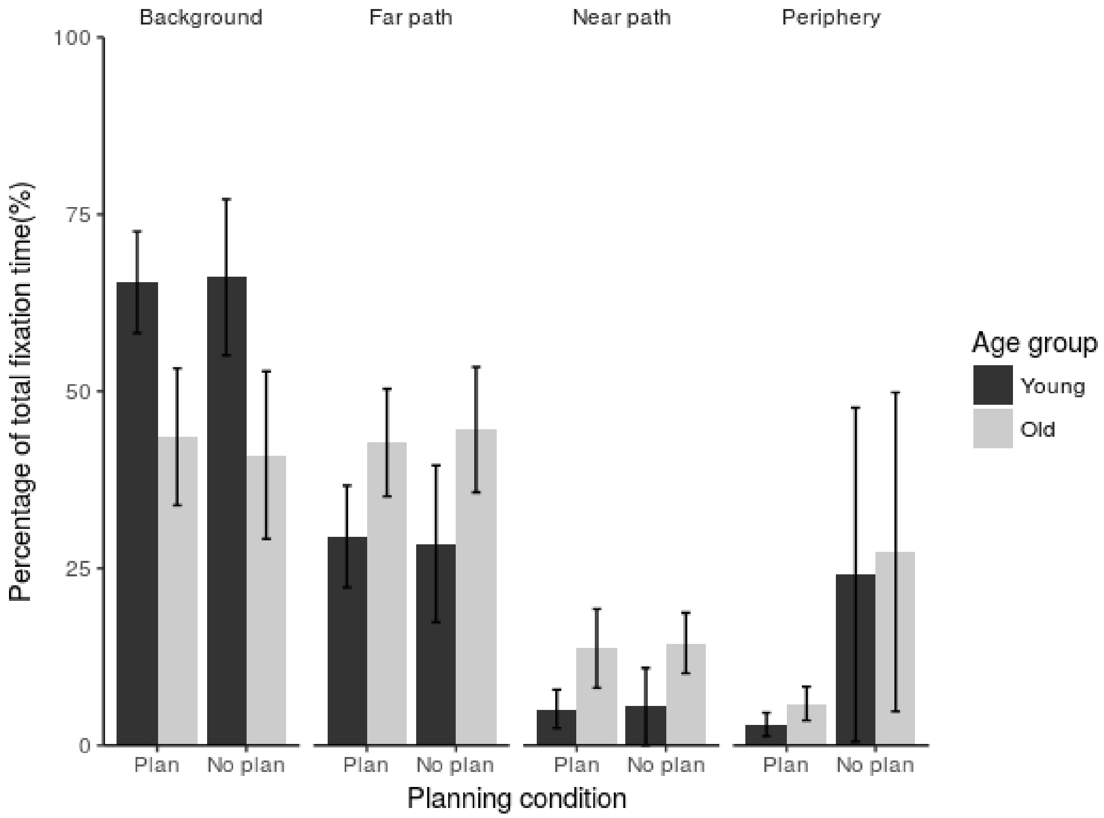
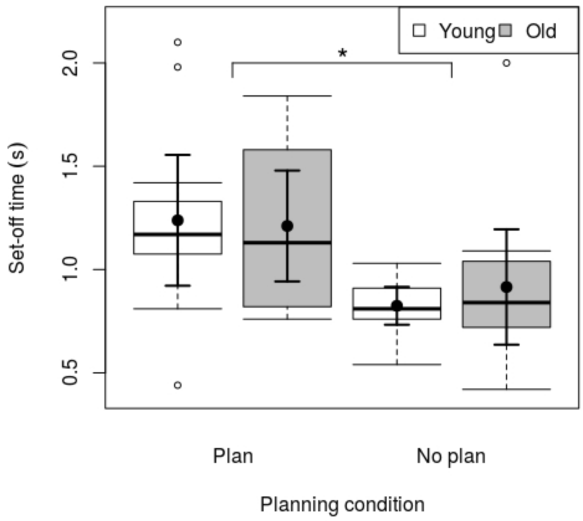


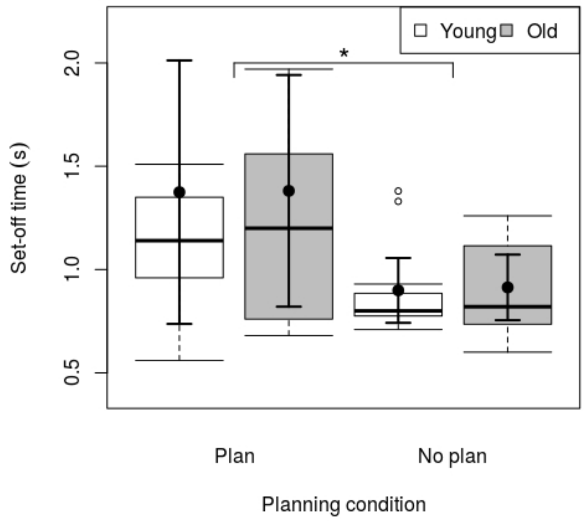
Figure 6.4: The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during ABSENT (± SD) in young (n = 11) and older (n = 11) females. Significant differences are reported in the main text of the results section.

($F_{1,20}$=19.57, p=0.010), with longer set-off times during PLAN compared to NO PLAN. There were no main effects of age, or any interaction effects between planning condition and age for any of the three conditions.

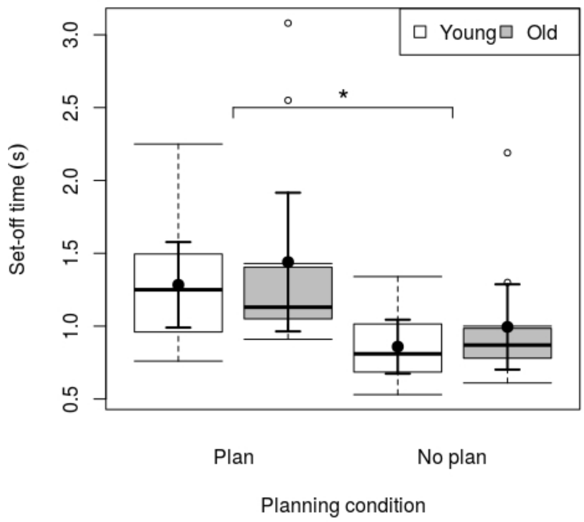
Markov sequence analyses were directed at age groups as opposed to planning conditions since this is where the time-integrated analysis highlighted significant differences. Sequence analyses were calculated for some of the planning data, but as expected, the probabilities were relatively homogeneous across planning conditions. Most infrequent probabilities under the 5% threshold were also very low in all of the conditions, e.g. <0.1%.



(A)



(B)



(C)

FIGURE 6.5: Participant set-off times for PLAN and NO PLAN during A: STAT, B: WALK, C: ABSENT, in young (n = 11) and older (n = 11) females. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between conditions.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during STAT are presented in Fig. 6.6. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the actor first. In contrast, the older adults were more likely to fixate the near path first. The young adults showed significant transfers from the far path, the background and the periphery to the actor, and from the near path to the far path. The older adults showed significant transfers from the near path and the background to the actor, and from the near path to the far path.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during WALK are presented in Fig. 6.6. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the actor first. In contrast, the older adults were more likely to fixate the near path or the actor first. The young adults showed significant transfers from the far path, the actor and the near path to the background, from the near path to the far path, and from the periphery to the background. The older adults showed significant transfers from the near path to the far path, and from the periphery to the background, the far path, and the actor.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during ABSENT are presented in Fig. 6.6. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the far path and the background first. In contrast, the older adults were more likely to fixate the near path first. The young adults showed significant transfers from the far path, the near path and the periphery to the background. The older adults showed significant transfers from the near path and the periphery to the far path.

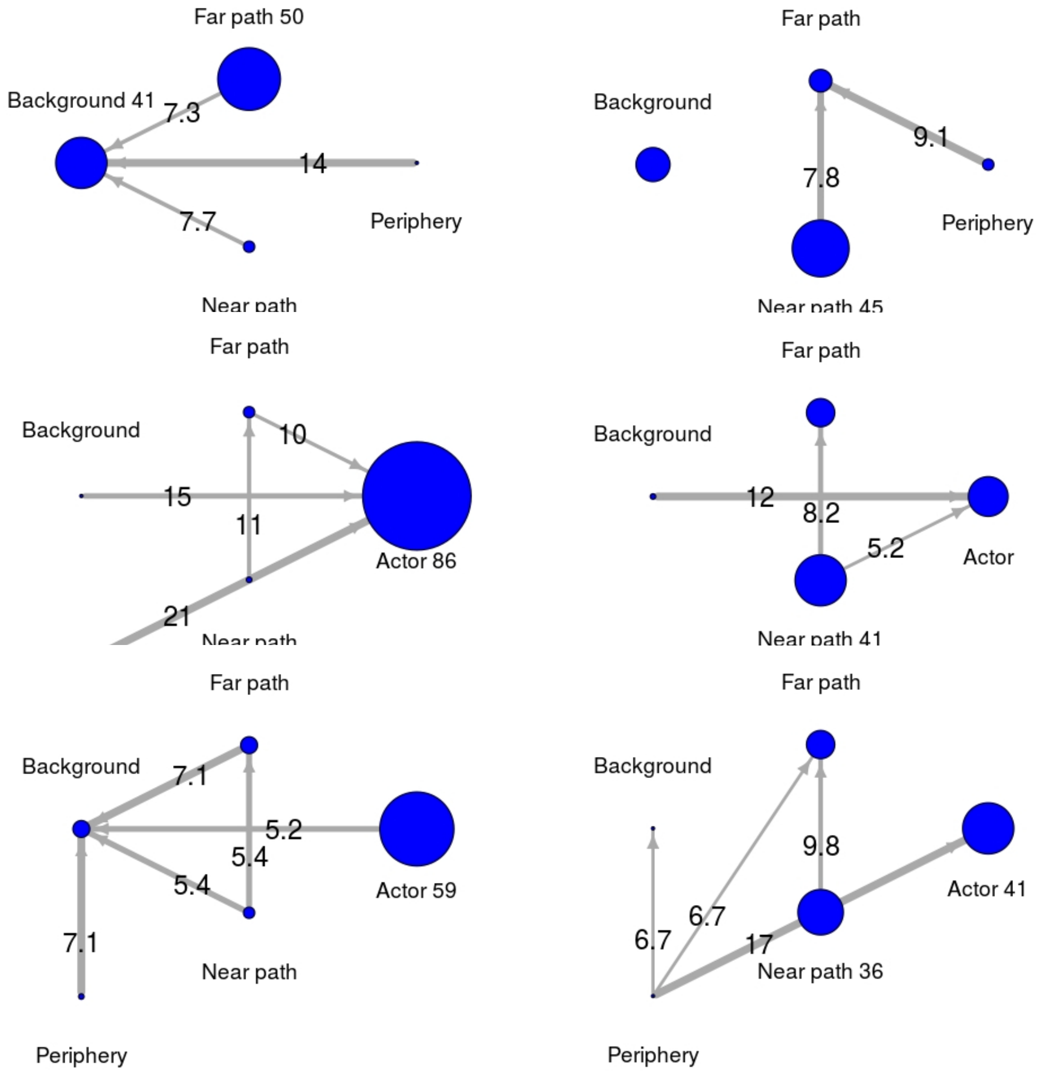


FIGURE 6.6: Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs (presented as percentages) during ABSENT: top, STAT: middle, and WALK: bottom, in young: left (n=11) and older: right (n=11) females. The blue circles denote initial fixations with the corresponding probability displayed underneath. The grey arrows denote transfers between ROIs with the corresponding probability superimposed. The size of the circles and arrows are relative to the magnitude of the probabilities. Note the bigger circles on the actor in the young participants, and the bigger circles on the near path in the older participants. Only probabilities significantly different from a Gaussian distribution and >5% are displayed.

6.4 Discussion

The present investigation assessed young and older adults' gaze behaviour when walking in a real-world waiting room. The young and older adults fixated the actor for a significant period, which has been shown to be negative for balance control (Chapter 5). The elders also initially looking down at the floor and for longer, before looking up to their direction heading.

During STAT, the elders fixated the actor for over 70% of fixation time. The results from Chapter 5 in this particular condition are, therefore, transferable to natural gaze patterns. During WALK, however, total fixation time was more evenly spread across the background and the far path. It is thus likely as the actor walked away from the centre of the actor area, the participants stopped fixated them and carried on looking ahead. This means the more detrimental gaze behaviour was not continued for as long during WALK.

There was also a general trend for both the young and older adults to fixate regions in the direction heading for the most time. These correspond to the background, the far path and even the actor when the actor was in the centre of the actor area. These results fall in line with previous laboratory-based studies, which show a bias of visual attention towards a direction heading (Higuchi, 2013), which is typically associated with the optic flow component of locomotor steering (Warren et al., 2001). This explains why the participants ignored the actor once the actor had left the centre of the actor area (which corresponded to the participants' direction heading). In addition to the heading direction, both the young and older participants fixated the near path. This finding is also similar to laboratory-based studies, where it was suggested that near path fixation was likely used to acquire information about the walkway, e.g. potential trip hazards or slippy surfaces (Uiga et al., 2015), making this the most likely explanation for the present findings.

Of particular interest from the present findings are the interaction effects, which begin to show differences in young and older adults' visual behaviour. For example, the young adults tended to look more at direction heading features (e.g. the background and actor) than the older adults, whilst the elders tended to look more at the ground (near path and far path) than the younger adults. These findings reflect typical behaviour in laboratory-based studies, where elders look lower in the visual field, possibly with greater head flexion (Maslivec et al., 2017), and has previously been related to things like reductions in visuospatial memory (Uiga et al., 2015). In effect, the present elders may have needed to fixate the floor for longer or more frequently to gather and retain sufficient information. Another factor might be that the elders were less able to process peripheral visual information about the floor. Previous studies, for example, have shown older adults to rely more on foveal vision than covert attention (Itoh and Fukuda, 2002). Therefore, the present elders might have fixated the walkway for longer to ensure it was safe, rather than relying on peripheral detection of hazards. It may also be that the older adults were less confident about the floor being clear of obstacles, and they ultimately checked it more often regardless of actual threat perception. Previous studies have linked anxiety to altered gaze behaviour (Young and Williams, 2015), for example, which certainly lends credence to that notion. These results suggest that, at least in the present cohort of participants, gaze behaviour found in the laboratory during locomotion with actual body movements are reflected in the real-world.

Surprisingly, there was no effect of pre-planning on gaze behaviour. It may be that the cognitive visuospatial mapping demands were relatively low considering the flat and relatively easy to navigate ground in the waiting room. This was likely not challenging enough to warrant altered visual behaviour. It would be interesting to examine the role of visual pre-planning over more challenging terrain. Notwithstanding this, both the young and older adults took longer to set off when given the opportunity to plan as opposed to being instructed to enter the room as soon as the sliding doors had opened. This probably simply reflects the more natural behaviour when not 'rushed' to set-off walking.

The present investigation probed visual behaviour during locomotion in a unique way by considering the visual scan paths as Markov sequences. The findings add a new perspective to the duration of fixation data. That is, the young adults were more likely to initially fixate direction heading regions first (such as the actor and the background), whilst the older adults were more likely to fixate the path first, and particularly the near path. This trend was the same across all conditions with the exception of WALK, where there is a probability for the elders to look at the actor first as well. Subsequently, there are interesting transfers of gaze from these initial fixation locations. Overall, the older adults were typically more likely to look from the path to their direction heading, whilst younger adults from regions in their direction heading to others in their direction heading. In short, the older adults were more likely to adopt a cautious gaze strategy by checking the floor first before looking ahead. This may be due to some of the factors mentioned above, such as increased anxiety about the ground being clear, or more reliance on foveal vision. It is probably not due to reduced visuospatial memory, since the initial fixation, being the first, cannot be associated with memory in that context.

There are some limitations with the Markov sequence methods adopted in the present investigation, in that due to the combination of only modelling 2 fixation scan paths, some information is inevitably lost. For example, during WALK, the young adults must have transferred their gaze to the far path since there is a transfer from this location, although there is no direct transfer from the actor (the initial fixation location in most participants) to the far path. In these circumstances, some inferences can be made. For example, some participants may have initially fixated the near path, and some the actor. Then those two groups fixated the far path together, and continued to transfer from the far path to the background. This, however, becomes a rather drawn out process, and is mostly speculative.

When putting the present findings in the context of fall risk, the first thing to consider is whether or not there was risky or maladaptive gaze behaviour. In both STAT and WALK, the older adults fixated the actor for around 70% and 20% of total fixation time, respectively. Since fixating a standing and walking actor was shown to be detrimental to balance (Chapter 5), this fixation behaviour can be considered undesirable, especially when the moving object is of no consequence to the navigation route. For the initial and longer floor fixations exhibited by the older adults, it is difficult to say whether this is negative. It may actually be beneficial for them to check the floor first for hazards, particularly if they are less able to correct a trip or a fall. In the context of planning, it may be suggested to be beneficial to visually 'absorb' the specifics of an environment. Even though gaze behaviour was the same across planning conditions in the present investigation, the environment was relatively easy to navigate. More challenging surfaces may require more planning time, and so it is likely more optimal not to rush into any environment. This is supported by the fact both young and older adults took longer to enter the room when given the option to plan, which reflects more natural behaviour. One useful component of the present results is that the participants ignored the actor after they had left the heading direction line of sight. This means the detrimental gaze behaviour was not continued. Aside from thinking about training older adults to fixate other stationary locations in a direction heading, as opposed to other people, a very simple solution would be to consider where to stand when greeting older adults in a waiting room. Put simply, distracting an elder so they look up to greet you would, a) reduce the likelihood they will initially floor fixate to check for slip/trip hazards, b) reduce the efficacy of visual balance control, and both of these would lead to increased fall risk.

6.5 Conclusion

The present experiment showed that young and older adults adopted negative gaze behaviour by fixating the actor. The older adults were also more likely to look down prior to setting off walking. To mitigate the negative gaze behaviour, it may be beneficial to think about not distracting older adults when greeting them in similar environments.

Chapter 7

General discussion

The present thesis examined the effects of eye movements on balance control in young and older adults during standing and walking in different environments. The rationale was derived from previous work in young adults, which showed smooth pursuits decrease stability during standing (Laurens et al., 2010, Glasauer et al., 2005). In contrast, saccades had been shown to maintain or improve stability during standing (Stoffregen et al., 2006, Rodrigues et al., 2013). Yet, despite their potential link to balance control (the negative effects of smooth pursuits and the positive effects of saccades), and the high incidence of falls in older populations, the effects of different eye movements on balance control had not been assessed in older populations.

The first experimental chapter laid the foundations by exploring eye movements and balance control during standing in young and older adults (Chapter 3). Using those results, the research was expanded to during locomotion – first in the laboratory (Chapter 4) and then in a real-world environment (Chapter 5). Finally, the results of those experiments were put into context by recording natural gaze behaviour, to determine if and how the previous results were transferable to natural gaze patterns (Chapter 6).

7.1 Smooth pursuits decrease stability

The research showed a clear link between smooth pursuit eye movements and decreases to balance control during standing and locomotion. This was the first time this had been uncovered in older adults, in the laboratory or the real-world.

In Chapter 3, various background visual conditions were presented to standing participants, e.g. static and oscillating large-field gratings, whilst they were visually fixating a static target. This showed how retinal flow could affect stability depending on the conditions, i.e how easy or difficult it is to interpret for balance control. Because background retinal flow during smooth pursuits can be subject to motion and blur, it can be considered as more difficult to interpret for balance control. Thus, the decrease in stability during smooth pursuits was likely caused, in part, by more complex retinal flow patterns. Indeed, this has previously been suggested in other experiments (Glasauer et al., 2005, Laurens et al., 2010). It was also thus likely that the decreased stability caused by smooth pursuits during locomotion in the subsequent Chapters (4 and 5) was also a result of more difficult retinal flow integration.

The work presented in Chapter 3 also showed how a small oscillating lit target in an otherwise dark room increased postural sway (in the absence of retinal flow), which highlights extraretinal balance control. Thus, more complex extraretinal signals likely contributed to the decreased stability caused by smooth pursuits, and this probably also occurred in the presence of retinal flow.

Surprisingly, the older adults were not more susceptible to the effects of smooth pursuits on balance during standing or walking. Yet, it was expected there would be a more profound change due to typical age-related declines in the ability to interpret retinal flow. Therefore, the older adults seemed to be able to process visual flow or down-weight the use of unreliable visual information during the eye movements as effectively as the younger adults. During the walking trials in Chapters 4 and 5, this must have occurred in the first 5 s after stimulus movement onset because of the short nature of the walks. This does fit in with some standing literature, where older adults adapted to an initial sudden change in visual conditions within the first 5 s similarly to younger adults (Jeka et al., 2010). Therefore, it is likely that the smooth pursuits in the present thesis did not challenge the healthy ageing CNS substantially to bring about a bigger reduction in stability. Another explanation is that the elders were working harder to maintain their balance outcomes through different muscle activation patterns as suggested in Chapter 3, but as EMG was not used, this went undetected.

Regardless of the specific mechanisms of why there was not a more profound change in the older adults, in Chapter 4, the older participants were already at a postural disadvantage, with lower baseline stability. Although this was not detected in Chapter 5, likely due to the limitations of inertial measurement units, this is typical in older adults. Therefore, the negative change to balance during smooth pursuits, although not more profound, is certainly undesirable in older populations.

7.2 Saccades maintain stability

In Chapters 3 and 4, saccades consistently maintained balance compared to fixating a static target. It was suggested that because the saccades were maintaining longer periods of fixation between the rapid eye movements, they were essentially providing similar retinal and extraretinal signals for balance control to that when fixating the static target. I.e. they preserved a useful visual reference frame for balance control. This was likely also the case in Chapter 5, where the most optimal condition for balance control was an empty room – as the participants walked through the room, they would have initiated saccades to various regions of the environment, which was later confirmed to be the case in Chapter 6.

7.3 Increased convergence decreases stability during locomotion

One limitation of the first 2 experimental chapters was that the visual stimuli were presented in two dimensions absent of depth cues. Therefore, effects of increasing convergence to focus on objects more in the foreground were not considered. To address this, eye movements in a real-world environment were assessed using an actor as the visual stimulus (Chapter 5). Visually tracking the walking actor decreased stability, which was expected. However, there was an interesting finding when the actor was stationary. The increased convergence required to fixate the actor as opposed to the background wall seemed to cause a similar amount of instability as when the actor was walking. This was the first time such an effect had been shown, and was attributed to dynamic retinal background blur induced by oscillatory movements of the head during the gait cycle.

7.4 Natural eye movements in the real world

Because the participants were instructed where to look in Chapters 3, 4 and 5 (with the exception of the free gaze condition in Chapter 5), which was necessary to isolate the effects of the eye movements on balance control, it was unknown whether the young or older adults would adopt a similar gaze pattern when given the option to look where they wanted. To address this, natural gaze patterns were measured in a similar real-world environment (Chapter 6). The results showed that the young and older participants fixated the actor for around 70% of total fixation time when they were stood in the participants' direction heading, and around 20% of total fixation time when the actor walked horizontally across their field of vision. Thus, the negative gaze behaviour was exhibited in natural conditions.

The findings from Chapter 6 also demonstrated previous laboratory-based results in the real-world for the first time. For example, the older adult typically spent more time looking at the ground than the young adults, whilst the young adults spent more time looking at their direction heading than the older adults. The novel application of the Markov sequence analysis also showed unique differences in young and older adults gaze behaviour. That is, as well as looking more at the ground, we now know that older adults are more likely to look at the ground first before looking ahead. It thus seems they are being more cautious.

7.5 Practical implications for practitioners and researchers working with older adults

The fact that smooth pursuits and increasing convergence (e.g. when fixating other people) can decrease balance control raises some concerns given that older adults are typically already at a postural disadvantage. That is, if they are more likely to trip or slip due to lower baseline stability or a reduced ability to correct a postural disturbance, any negative change to balance is undesirable. Further, since the present thesis has shown that older adults typically do fixate other people when walking in a waiting room environment, the small decrease in stability shown in Chapter 5 may be common in everyday life of elders using similar rooms.

One useful piece of real-world advice stemming from this is that it would likely be beneficial not to distract older adults when they are walking. For example, doing so could make them look at you, and this would not be optimal for visual balance control. Moreover, when considering that the older adults tended to look at the ground before looking ahead (Chapter 6), distracting them would also increase the chances of them not detecting any trip or slip hazards on the ground. This could lead to an increased fall risk.

Another solution to mitigate the negative gaze behaviour in more cluttered and busy environments could be to implement gaze training interventions. For example, Schulmann et al. (1987) proposed that posturally unstable patients should be trained to adopt fixations of static regions of the environment (either through prolonged fixation on one region, or with re-fixating saccades to scan the environment), thus ignoring moving objects and the use of smooth tracking eye movements. In Chapter 5, the condition in which older adults looked where they wanted (when the room was empty) fostered the most stable postural response. In this condition, visual information would have been acquired predominantly through fixations on static regions of the room. If older adults could be trained in the way described by Schulmann et al. (1987), it might elicit a similar favourable outcome to Chapter 5 even in busy environments, and this might have a place in clinical populations or those with previous experience of falls. However, there may be unintended consequences associated with making elders think about where they should look. It could increase anxiety, which has been linked to changes in postural control (Young and Williams, 2015), and older adults may even collide with other people if they are deliberately trying to ignore them when navigating the environment. Therefore, the efficacy of this type of intervention would need to be evaluated before putting it into practice.

The option of training elders to ignore other people and moving objects would also be teaching them to foster dependency on visual fixations. This has previously been suggested not to be optimal in patients undergoing vestibular rehabilitation (Han et al., 2011). Instead, Han et al. (2011) suggest it may be more optimal to train patients by watching conflicting moving visual stimuli during movements of the head. In General introduction section 1.4.4, it was suggested that if smooth pursuits caused a more profound change to postural control in older adults, a similar intervention could be an option. However, because smooth pursuits elicited the same postural response in the young and older adults, it is unlikely any further improvement would be gained by this type of training (at least in healthy older adults). Further research is needed to confirm this for those at higher risk of falls, or those with known vestibulo-ocular (VOR) and visual processing deficits. If improvements can be made in such populations, it could lay theoretical evidence for real-world training interventions. For example, during 'Gold Zumba', older adults dance whilst watching a moving instructor at the front of the class. This could potentially have a similar training effect, and also in combination with strength and mobility training. On the other hand, if higher risk older adults are shown to be at 'too much' risk during smooth tracking eye movements (which are used to watch the instructor), Zumba would not be ideal since it may put them at an increased risk of falling. This is just one idea, but the results could potentially be applied in a range of interventions.

Another option could be to consider the design/control of waiting room environments. Because the empty room fostered the most stable response in the present thesis (Chapter 5), a quiet and uncluttered waiting room would likely be optimal for reducing fall risk. For smaller environments which can be controlled, it may be useful to have a quiet sit down strategy. For example, if occupants of a waiting room are walking around unnecessarily, it may attract older adults gaze in a negative way. Enforcing such a policy would come with its own societal and cultural challenges, of course. In more busy environments, however, it would likely become difficult or impossible to achieve a similar outcome, and in which case, some sort of gaze training intervention targeted at the individual may be preferable.

The notion that tracking moving objects decreases stability has some implications when identifying those at higher risk of falls. For example, a typical measurement of visual balance is the Romberg Ratio, which is a simple measure of the difference between postural control with the eyes open and the eyes closed. If higher risk older adults become more unstable during smooth pursuits, it would theoretically be very easy to expand on the Romberg Ratio and test for this – by instructing a patient to watch an oscillating target (this could be a pendulum), and then measuring the difference in balance when looking at a space fixed target. The findings could be used to identify those at risk of falls, and refer them to a visual balance training intervention. It would be beneficial to collect data about normative values, so that a smooth pursuit to balance ratio can be determined and used accurately to classify visual balance deficits.

7.6 Limitations and Directions for future research

The present thesis has shown that fixating and tracking another person can reduce balance control in healthy young and older adults. This is the first time this has been shown. Consequently, the results raise a number of questions, and addressing these could generate further impact in the fall-risk literature. One example is if and how the reductions to balance shown in the present thesis link to actual fall-risk in everyday life.

Fall-risk is a multifaceted phenomenon with many contributing factors. These can be extrinsic, e.g. slippy and uneven surfaces in the environment, and intrinsic and related directly to the individual, e.g. dizziness, muscle weakness or behaviour (Ambrose et al., 2013). Indeed, the list is substantial. Determining the relative contribution of eye movements to actual fall risk is thus inherently difficult. For example, in the outside world, eye movements to track moving objects and other people typically occur regularly, and invariably with different magnitudes and speeds of rotation. These would also occur in tandem with other risk factors, e.g. when crossing a road, or traversing a curbed feature. One might envisage a reduction to balance control during a smooth pursuit to be exacerbated during a navigation goal associated with more difficulty. Thus, a logical first step for future research could be to incorporate a hazard avoidance task, or a dual task (e.g. reading from a moving display) in combination with a smooth pursuit eye movement. Probing the effects of eye movements on balance control in these conditions may shed light on reductions to balance control in more complex situations typically found in the outside world, and this could link the eye movements to actual fall risk. Future studies may also seek to address this in a range of fall risk groups, and with different levels of anxiety and fear of falling, since these have previously been shown to be determinants of gaze behaviour and postural control in older adults (Young and Hollands, 2010, Young and Williams, 2015, Ambrose et al., 2013).

Moreover, the present thesis proposed a number of potential options for mitigating the reductions to balance control during smooth pursuits. For example, to train older adults to modify their gaze behaviour by relying on fixations and saccades, or to become more adept at processing visual information during smooth pursuit eye movements, and indeed for indentifying those at risk of lower balance control. Exploring how eye movements link to fall-risk would also be important to guide further research in these areas.

The present thesis did not explicitly test whether the extraretinal component of balance persisted during walking. Thus, it can only suggested that more complex extraretinal signals were a contributing factor to the decreased balance control during locomotion. Possible techniques to address this include walking in complete darkness whilst focusing on a small LED, or perhaps immobilising the neck using a neck brace. Such an experiment would build a fuller picture of the physiological effects of smooth pursuits on the balance control system. The equipment used in the present thesis was unable to monitor very fine grained eye movements, such as onset latency and catch-up saccades. If there are deficits in the accuracy of the smooth pursuit/saccadic control systems in older adults in the real-world, these may link in some way to altered balance control. Combining highly accurate eye tracking equipment during measures of whole body movements during balancing tasks in a real-world environment may shed light on this.

With regard to explaining some of the results, it was difficult to say whether the older adults were working harder to maintain the balance response by using different muscle activation patterns. It can be suggested to use EMG to address this. However, EMG can be distracting for participants. Since it was intended to maximise natural gait patterns, particularly in the final experimental chapters, this option was not taken. Using EMG would, however, elucidate more to the underlying physiological control mechanisms. Future studies should consider using EMG if that is the main concern.

In previous experiments, AP optic flow perturbations led to changes in swing limb height. Because swing limb height was not measured in the present thesis, it is difficult to determine if any of the eye movements affected retinal flow enough to cause similar changes. This would be recommended in future studies.

7.7 Conclusion

The overarching message from the present thesis is that fixating other indoor pedestrians and/or moving objects can decrease stability during locomotion, and that young and older adults can exhibit this gaze behaviour naturally in real-world conditions. Older adults are also more likely to be more cautious and look to the ground prior to looking at their direction heading. When considering this, it is likely beneficial not to distract older adults when they are walking, since this may attract their gaze. This is not optimal for visual balance control, and increases the risk of them not checking the floor for hazards – both of these may lead to an increased risk of falls. Other strategies regarding gaze training interventions and techniques to identify those at risk of falls with modified visual balance tests during smooth pursuits require further research to determine their efficacy, and particularly in higher fall risk older adults. It is hoped the present findings can be used to guide such research.

Appendix A

Article 1

frontiers in Aging Neuroscience

ORIGINAL RESEARCH
published: 16 September 2016
doi: 10.3389/fnagi.2016.00216

Eye Movements Affect Postural Control in Young and Older Females

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Visual information is used for postural stabilization in humans. However, little is known about how eye movements prevalent in everyday life interact with the postural control system in older individuals. Therefore, the present study assessed the effects of stationary gaze fixations, smooth pursuits, and saccadic eye movements, with combinations of absent, fixed and oscillating large-field visual backgrounds to generate different forms of retinal flow, on postural control in healthy young and older females. Participants were presented with computer generated visual stimuli, whilst postural sway and gaze fixations were simultaneously assessed with a force platform and eye tracking equipment, respectively. The results showed that fixed backgrounds and stationary gaze fixations attenuated postural sway. In contrast, oscillating backgrounds and smooth pursuits increased postural sway. There were no differences regarding saccades. There were also no differences in postural sway or gaze errors between age groups in any visual condition. The stabilizing effect of the fixed visual stimuli show how retinal flow and extraocular factors guide postural adjustments. The destabilizing effect of oscillating visual backgrounds and smooth pursuits may be related to more challenging conditions for determining body shifts from retinal flow, and more complex extraocular signals, respectively. Because the older participants matched the young group's performance in all conditions, decreases of posture and gaze control during stance may not be a direct consequence of healthy aging. Further research examining extraocular and retinal mechanisms of balance control and the effects of eye movements, during locomotion, is needed to better inform fall prevention interventions.

Keywords: balance, elderly, eye tracking, gaze accuracy, saccadic, smooth pursuit, visual input

OPEN ACCESS

Edited by:
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Reviewed by:
Paul Gerson Unschuld, University of Zurich, Switzerland
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Received: *02 February 2016*
Accepted: *01 September 2016*
Published: *16 September 2016*

Citation:
Thomas NM, Bampouras TM, Donovan T and Dewhurst S (2016) Eye Movements Affect Postural Control in Young and Older Females. Front. Aging Neurosci. 8:216. doi: 10.3389/fnagi.2016.00216

1. INTRODUCTION

Vision is an important sensory cue to familiarize ourselves with the external environment, a prerequisite for which are voluntary or involuntary eye movements, necessary to process information such as recognition, localization and proprioception (Irwin, 1991; Lewis et al., 1994; Donaldson, 2000). Vision also facilitates stabilization of upright posture, by enabling detection of self-motion relative to structures in the visual field (Dichgans and Brandt, 1978). There is growing evidence to suggest eye movements interact with this process (Schulmann et al., 1987; Glasauer et al., 2005; Guerraz and Bronstein, 2008; Laurens et al., 2010; Rodrigues et al., 2015). However, this has received little attention in the gerontology literature, which is surprising given the prevalence of eye movements in everyday life (Kowler, 2011), their potential link with postural control, and the high incidence of falls and fall related injuries amongst the elderly (Sturnieks et al., 2008; Ambrose et al., 2013). Here our focus is on the effects of eye movements on postural control in young and older individuals.

Visual cues for postural stabilization have traditionally been associated with deformation of the retinal image. As a person shifts their position in space, changes in the pattern of light intensities about a central point of observation create an optic flow pattern, which is projected onto the retina. This projected image shifts/deforms creating retinal flow according to an individual's movements (Gibson, 1950), which the central nervous system (CNS) uses to estimate body position and initiate appropriate postural adjustments (Wapner and Witkin, 1950; Lestienne et al., 1977; Nashner and Berthoz, 1978). Optical changes at the retina can include uniform components (e.g., horizontal movement of the retinal image), parallax (generated by near and far structures in the visual environment), and expansion and contraction (indicative of anterior or posterior head motion; Gibson, 1950; Gibson et al., 1955). Evidence demonstrating how retinal flow guides postural adjustments can be taken from investigations involving moving visual surrounds, e.g., linearly oscillating walls, floors and tunnels, which have frequently shown a coupling of body sway with stimulus motion (Lee and Lishman, 1975; Stoffregen, 1985; Bronstein, 1986; Stoffregen, 1986; Flückiger and Baumberger, 1988; Dijkstra et al., 1994). This is believed to result from the CNS misinterpreting external-motion for self-motion and incorrectly adjusting body orientation (Guerraz and Bronstein, 2008).

There is a close relationship between the ways in which visual and vestibular information about head position are used for postural control (DeAngelis and Angelaki, 2012), and eye movements have been shown to affect posture during standing (Paulus et al., 1984). Fixating on a small lit target in an otherwise dark room improved stability compared to absolute dark (Paulus et al., 1984). In these conditions, visual and vestibular initiated compensatory eye movements in response to movements of the head keep gaze fixated on the target, implying diminished retinal flow. Therefore, eye movements relative to the target are used to infer body position in space (extraocular balance control; Guerraz and Bronstein, 2008). Visually tracking moving targets (smooth pursuits) caused increases of postural sway in young adults, in the presence of a static visual field and without (Glasauer et al., 2005; Laurens et al., 2010). This may be related to more challenging conditions for interpreting retinal flow for postural control (Schulmann et al., 1987), or, in part, more complex extraocular signals (Laurens et al., 2010). However, there are data which show an opposite effect, indicating posture can be modulated for more accurate gaze behavior (Rodrigues et al., 2015). This concurs with similar findings during rapid shifts of gaze from one target to another (saccades) in young (Stoffregen et al., 2006; Rougier and Garin, 2007; Stoffregen et al., 2007; Rodrigues et al., 2013, 2015) and older (Aguiar et al., 2015) adults, suggesting a functional integration of gaze and posture for both smooth pursuit and saccadic eye movements. These differences remain unexplained. Moreover, little is known about extraocular control of posture in elders, or how smooth pursuits effect balance in elders.

Older individuals have demonstrated declines in visual self-motion perception (Warren et al., 1989), and can become more unstable in the face of moving visual surrounds (Wade et al., 1995; Sundermier et al., 1996; Borger et al., 1998). This might reduce their ability to interpret retinal flow for postural control as effectively as younger adults during eye movements. Declines in vestibulo-ocular reflex (VOR) function with age (Peterka et al., 1990; Paige, 1991; Baloh et al., 2003) may additionally affect the extraocular component of postural control, since the VOR is one mechanism which serves to stabilize gaze, and eye movement signals appear to be used to infer body position. Further, an inaccurate smooth pursuit system in elders (Sharpe and Sylvester, 1978; Spooner et al., 1980; Moschner and Baloh, 1994; Ross et al., 1999; Knox et al., 2005) may potentially cause less efficient processing of more complex extraocular signals whilst visually tracking moving targets, exacerbating the increase in postural sway demonstrated by some young adults. Paquette and Fung (2011) indirectly assessed balance during smooth pursuits in older participants, but the authors focus was gaze accuracy, and they cannot clarify if declines in postural control were associated with the gaze outcomes.

Because loss of balance in the elderly can be costly and debilitating (Brunner et al., 2003), there is a pressing need to further understanding of the interplay between eye movements and postural control in this population. Therefore, our aim was to assess postural sway, increases of which can indicate increased risk of falls, during visual fixation of stationary targets, smooth pursuits and saccades, in young and older individuals. We also used combinations of absent, fixed, and horizontally oscillating visual backgrounds to generate different forms of retinal flow and to isolate the extraocular factors involved in visual control of balance. Finally, we assessed accuracy of gaze to determine if different backgrounds altered gaze behavior, and to examine differences in error rates between age groups. We hypothesized: (1) fixating a stable target to reduce body sway; (2) fixed backgrounds to have a stabilizing effect and oscillating backgrounds to have a destabilizing effect; (3) smooth pursuits to increase body sway; (4) saccades to decrease body sway; (5) elders to be more unstable throughout, with greater effects during smooth pursuits and oscillating backgrounds; (6) gaze accuracy to decline in the older group.

2. MATERIALS AND METHODS

2.1. Participants

Twelve young (mean ± SD: age: 26.1 ± 4.9 years, height: 1.68 ± 0.06 m, mass: 62.2 ± 13.7 kg) and 12 older (mean ± SD: age: 72.8 ± 6.9 years, height: 1.64 ± 0.05 m, mass: 63.6 ± 10.7 kg) females participated in the study. The older participants were interviewed by telephone to determine suitability. An initial cohort of 20 elders was reduced to 12 following screening by self-report for the following inclusion criteria: (1) No macular degeneration, glaucoma, cataracts or color blindness; (2) No muscle or bone conditions which could prevent standing for 30 min with breaks including (but not limited to) lower limb, hip or spine surgery within the previous year, present of recent injury or pain in any region which could arise from standing; (3) No psychological/neurological conditions which could prevent observation of a visual scene or standing for 30 min with breaks including (but not limited to) Parkinsons disease, vestibular impairment (dizziness/vertigo), numbness or loss of sensation in the lower limbs, or schizophrenia; (4) No severe motion sickness; (5) No medication which could depress the nervous system or effect balance (benzodiazepines, anti-depressants, anti-seizure, or anti-anxiety); (6) No multiple falls within the previous year; (7) No over-reliance on handrails when climbing the stairs; (8) No assistive walking devices (cane, crutches, or walking frame). Further, each older participant's mental state was examined with the mini mental status examination, and all achieved a score of ≥24, considered as a minimum acceptable threshold for involvement in the study. The investigation was carried out in accordance with the recommendations of the University of Cumbria's ethical principles and guidelines for research involving human subjects, and all procedures, information to the participants, and participant consent forms, were approved by the University of Cumbria Research Committee. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

2.2. Equipment

Visual scenes were rear projected (Sanyo PLC-XU74, Tokyo, Japan) onto a 3.2 × 2.4 m translucent screen. The lower border of the screen was placed at foot level. An AMTI AccuPower portable force platform (AMTI Force and Motion, Watertown, MA, USA) was positioned with its center 1 m adjacent to the middle of the screen. Participants wore eye tracking glasses (Tobii Glasses 2 Eye Tracker, Tobii Technology, Danderyd, Sweden) which have a one point calibration procedure, autoparallax compensation and slippage compensation allowing for persistent calibration throughout testing with no loss of data aside from blinking. The experiment was carried out in a light-controlled room.

2.3. Visual Scenes

Ten 45 s visual scenes were programmed with Psychopy open-source psychology software (Peirce, 2007). Visual stimuli included a red target (circle with its diameter equivalent to 3° of visual angle) and a large-field background (occupying the full width and height of the screen, made up of black and white vertical stripes each with a width equivalent to 3° of visual angle). Participants had an uncorrected visual acuity ≥20/100 measured on the day of testing. Discrimination of spatial patterns separated by a visual angle of 50/60th of 1° is possible even at lower visual acuities (Paquette and Fung, 2011). Therefore, stimuli utilized in the present investigation were visible at all times, always confirmed with the participant.

The target could be fixed (F), moving smoothly (P) or moving with saccadic motion (S). When fixed, the target would remain in the center of the screen at natural gaze height (see below). When moving smoothly, the target would displace from the center of the screen to 6° of visual angle on the vertical, horizontal or diagonal axis before returning to the center of the screen with a frequency of 0.33 Hz. For saccadic movement the same protocol was implemented, however, the target would disappear from the center of the screen and reappear at the 6° threshold, and vice versa. Target direction was programmed to be random on each oscillation. The large-field background could be absent (N), fixed (F) or oscillating horizontally (6° from the center position in each left and right direction) at 0.33 Hz (O). To simulate a condition of darkness (D) a black screen was projected absent of any stimuli. Letter codes used to identify visual conditions are presented in **Table 1**. Six degrees of visual angle was chosen to prevent head rotations which could affect measures of body sway, since gaze shifts of >15° are commonly are achieved without rotation of the head (Hallet, 1986), and this method has previously been effective in minimizing head movement (Glasauer et al., 2005; Stoffregen et al., 2006, 2007). We also initiated target movement randomly on the vertical, horizontal and diagonal planes to minimize any systematic bias on one particular axis.

TABLE 1 | Letter codes denoting combinations of large-field background and target state used to identify visual conditions.

	Target		
Large-field background	**Fixed**	**Smooth pursuit**	**Saccadic**
None	NF	NP	NS
Fixed	FF	FP	FS
Oscillating	OF	OP	OS
No large-field background or target: Dark (D)			

The first letters refer to the state of the background and second refer to the state of the visual target. Adapted from Laurens et al. (2010).

We used a novel approach regarding the height at which the visual targets were presented, as opposed to eye level. Elders have been shown to adopt forward trunk lean, which may be related to factors such as backward disequilibrium (Manckoundia et al., 2007) or poor balance and fear of falling (Sato and Maitland, 2008). Previous research has also shown focusing gaze at different heights affects measures of postural sway, e.g., 25° up or down from eye level decreased sway velocity and amplitude (Ustinova and Perkins, 2011). Consequently, if the targets were presented at eye level it may have forced the older participants to adopt an unnatural body lean and/or gaze height in order to maintain gaze on the target, which could have affected the results. Therefore, prior to testing, all participants were instructed to stand as still as possible with their feet together (no footwear) in the middle of the force platform (position marked with a cross for accurate relocation between trials) with their hands by their sides. They were then told to look ahead as comfortably as possible at a visual scene consisting of horizontal green lines (full horizontal width of the screen, each covering 2° of visual angle on the vertical plane, and each separated by 2°). After 30 s, gaze fixation settled at a specific line or in between lines. This was considered to be natural gaze height. The participants were subsequently instructed to adopt the same stance position throughout testing, which was reiterated before each trial.

2.4. Experimental Protocol

Two practice trials of 45 s duration separated by 10–20 s were granted following determination of natural gaze height to familiarize the participants with measurement of postural sway. Following a break of 2–5 min testing commenced. The participants, relocated on the cross and in the same stance as before, were instructed to fixate their gaze on the red target. If the target moved, they should follow it with their eyes only, making sure not to rotate or tilt their head. During the dark condition, they were told to keep looking ahead. The 10 visual scenes were displayed to each participant in a pre-determined random order, different for each participant. After the 3rd and 7th scene the participants were granted a 3–5 min break where they sat down. In between the remaining scenes there was a 10–20 s break where participants remained standing. A member of the research team was present behind each participant during testing in case of loss of balance. The eye tracking glasses were calibrated to each participant before determining natural gaze height, after the practice trials, and subsequently after each 3–5 min break. The calibration procedure adhered to the outlined standardized protocol.

2.5. Force Platform Data

Force platform data were sampled at 100 Hz for 45 s during each trial and analyzed offline (Scipy, Scientific Computing Tools for Python). Since the investigation was not concerned with how quickly the participants adapted to new stimuli, or end anticipation effects, the first and final 5 s were discarded, leaving 35 s of data for analysis (elders have been shown to have similar adaptation rates to young adults regarding sudden changes in visual stimulus motion during an initial 5 s period, Jeka et al., 2010). Medial/lateral (x) and anterior/posterior (y) center of pressure (COP) coordinate timeseries were then computed and passed through a 4th order zero-lag Butterworth filter with a cut-off frequency of 10 Hz. This choice of cut-off was determined with residual analysis of the raw data (Winter, 1995).

To characterize the size of the path traveled by the COP over the surface of support on both axis, we calculated the root mean square (RMS) of each de-trended timeseries, where N = number of data points and $n = 1, ..., N$:

$$RMS_{x,y} = [1/N \sum x, y[n]^2]^{1/2} \quad (1)$$

Rocchi et al. (2004) recommended RMS to characterize COP coordinate timeseries following principle component analysis. Further, repeated RMS measures of postural sway have been shown to be reliable in young and older populations (Lin et al., 2008).

2.6. Gaze Fixations

Gaze data (sampled at 50 Hz) was filtered with the Tobii I-VT fixation filter to yield gaze fixations (window length 20 ms, threshold 30°/s). 2D video sequences consisting of the participants point of view of each visual scene superimposed with their gaze fixations was exported. Position of the target and the position of each gaze fixation as x and y coordinates on the 2D video frame (**Figure 1**) was determined using motion tracking software (Open Vision Control). Each video sequence was optically filtered by adapting hue, saturation, brightness and contrast, and luma space level settings in order to improve the accuracy of the tracking algorithm. The resultant coordinate timeseries for each was then calculated where N = number of data points and $n = 1, ..., N$:

$$RC[n] = [x[n]^2 + y[n]^2]^{1/2} \quad (2)$$

The first and final 5 s of each timeseries were removed in concordance with the force platform data. Where no gaze data were sampled due to blinking, the target coordinate at the corresponding time point was converted to zero. Errors of gaze relative to the target was then assessed by computing the RMS of gaze subtracted from the target position throughout each video sequence (RMS-gaze error). Reliability of the tracking procedure was assessed by re-tracking the target and fixation position during scene OP from the young participants and computing the coefficient of variation (CV) between the gaze error outcome measures from each track. Scene OP was chosen as it presented with the most challenging optical conditions for motion tracking. The CV between tests (0.47%) indicated excellent reliability. No gaze data were collected for the dark (D) condition.

2.7. Statistical analysis

Age (young and older) and condition (10 × visual scenes) were considered as two independent factors. The effects of these two factors on the postural sway outcome variables RMS-x and RMS-y were examined with a two-way (age × condition) mixed analysis of variance (ANOVA). The effects of the same independent factors minus the dark condition on the gaze error outcome measure RMS-gaze error was also examined with a two-way mixed ANOVA. Where our data departed from normality, main effects were cross checked with a robust mixed ANOVA based on modified M-estimators and bootstrapping (Field et al., 2012). *Post-hoc* analyses (t-tests or Wilcoxon signed-rank tests) with Benjamini-Hochberg corrections were used where applicable. Where significant differences were found between conditions ($p < 0.05$), Hedges's g_{av} effect sizes were calculated as given by Lakens (2013). Common indicative effect thresholds for which include small (0.2), medium (0.5), and large (0.8), respectively.

3. RESULTS

3.1. Postural Sway

RMS of the COP coordinate timeseries on the medial/lateral (x) and anterior/posterior (y) axis for young and older participants are presented in **Tables 2**, **3** and **Figure 2**.

3.1.1. Medial/Lateral (x) Movement

There was no main effect of age on RMS-x. There was a significant main effect of condition on RMS-x [$F_{(1, 198)} = 17.769, p < 0.001$]. This was confirmed with a robust mixed ANOVA ($p < 0.001$). *Post-hoc* comparisons revealed: (1) A reduction of postural sway with a fixed target in dark (NF) compared to dark alone (D; $p = 0.032$, 12.75%, $g_{av} = 0.40$); (2) A reduction of postural sway with a fixed background and a fixed target (FF) compared to dark alone (D; $p < 0.001$, 27.18%, $g_{av} = 0.96$), compared to a fixed target in dark (NF; $p = 0.005$, 16.54%, $g_{av} = 0.63$), and a reduction of postural sway with a fixed background and saccades (FS) compared to saccades in dark (NS; $p = 0.001$, 17.68%, $g_{av} = 0.66$); (3) An increase in postural sway with an oscillating background and a fixed target (OF) compared to a fixed background and a fixed target (FF; $p < 0.001$, 48.20%, $g_{av} = 1.16$), an oscillating background and smooth pursuits (OP)

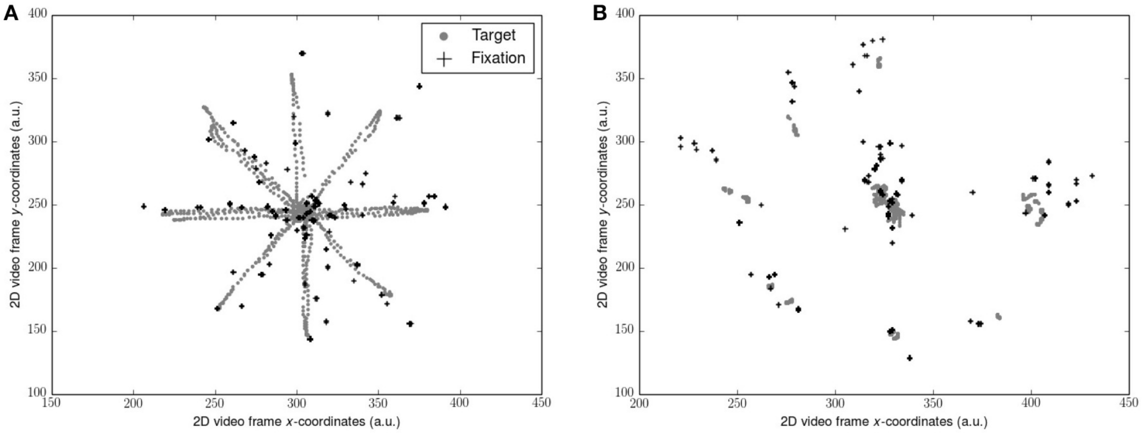

FIGURE 1 | Representation of target trajectory and gaze fixations from 1 participant: (A) during smooth pursuits; (B) during saccades. Coordinates along each axis were taken from the 2D video scene relative to the observer and represent arbitrary units (a.u.). Note that the target position is not stable due to the body sway of the observer. Also note the errors of the fixations compared to the target locations.

TABLE 2 | RMS of COP coordinate timeseries on the medial/lateral (*x*) axis in young (*n* = 12) and older (*n* = 12) participants during different visual scene conditions.

	RMS-*x* (mm)	
Condition	**Young**	**Older**
D	4.95 ± 1.68	4.70 ± 1.73
NF	4.43 ± 1.39	3.99 ± 1.11
FF	3.44 ± 1.08	3.58 ± 0.55
OF	5.69 ± 1.89	4.72 ± 1.64
NP	5.06 ± 1.21	4.85 ± 1.43
FP	4.82 ± 1.56	4.33 ± 0.92
OP	5.81 ± 1.96	5.36 ± 1.76
NS	4.59 ± 1.62	4.01 ± 0.85
FS	3.63 ± 0.79	3.46 ± 1.03
OS	6.32 ± 2.31	5.09 ± 2.28

D, dark; N, none; F, fixed; O, oscillating; P, pursuit; S, saccadic.

TABLE 3 | RMS of COP coordinate timeseries on the anterior/posterior (*y*) axis in young (*n* = 12) and older (*n* = 12) participants during different visual scene conditions.

	RMS-*y* (mm)	
Condition	**Young**	**Older**
D	5.66 ± 1.78	5.22 ± 1.75
NF	4.79 ± 1.70	4.67 ± 1.27
FF	5.18 ± 2.39	4.78 ± 1.30
OF	4.99 ± 1.52	4.68 ± 0.95
NP	5.89 ± 2.15	5.14 ± 2.00
FP	4.78 ± 1.23	4.94 ± 0.89
OP	5.66 ± 1.84	5.44 ± 1.42
NS	4.80 ± 1.29	4.41 ± 0.73
FS	3.97 ± 1.11	4.26 ± 1.12
OS	4.89 ± 0.94	5.13 ± 1.30

D, dark; N, none; F, fixed; O, oscillating; P, pursuit; S, saccadic.

compared to a fixed background and smooth pursuits (FP; $p = 0.001$, 22.03%, $g_{av} = 0.62$), and an oscillating background and saccades (OS) compared to a fixed background and saccades (FS; $p < 0.001$, 60.91%, $g_{av} = 1.18$); (4) An increase in postural sway with smooth pursuits in dark (NP) compared to a fixed target in dark (NF; $p = 0.038$, 17.85%, $g_{av} = 0.57$), and smooth pursuits with a fixed background (FP) compared to a fixed target with a fixed background (FF; $p < 0.001$, 30.36%, $g_{av} = 0.95$); (5) Saccades did not significantly alter sway compared to a fixed target in any condition; There was no interaction effect between age and condition on RMS-*x*.

3.1.2. Anterior/Posterior (*y*) Movement

There was no main effect of age on RMS-*y*. There was a significant effect of condition on RMS-*y* [$F_{(1, 198)} = 4.372$, $p = 0.020$]. This was confirmed with a robust mixed ANOVA ($p < 0.001$). *Post-hoc* comparisons revealed: (1) No change in postural sway with a fixed target; (2) No change in postural sway with fixed backgrounds; (3) An increase in postural sway with an oscillating background and saccades (OS) compared to a fixed background and saccades (FS; $p = 0.008$, 21.77%, $g_{av} = 0.78$), but no other changes in postural sway with oscillating backgrounds; (4) No change in postural sway with smooth pursuits; (5) No change in postural sway with saccades. There was no interaction effect between age and condition on RMS-*y*.

3.2. Gaze error

RMS of gaze subtracted from target position for young and old participants is presented in **Table 4** and **Figure 3**. There was no significant effect of age on RMS-gaze error. There was a significant effect of condition on RMS-gaze error [$F_{(1, 186)} = 17.629$, $p < 0.001$]. This was confirmed with a robust mixed ANOVA ($p < 0.001$). *Post-hoc* comparisons revealed: (1) No change in gaze error with fixed or oscillating backgrounds; (2)

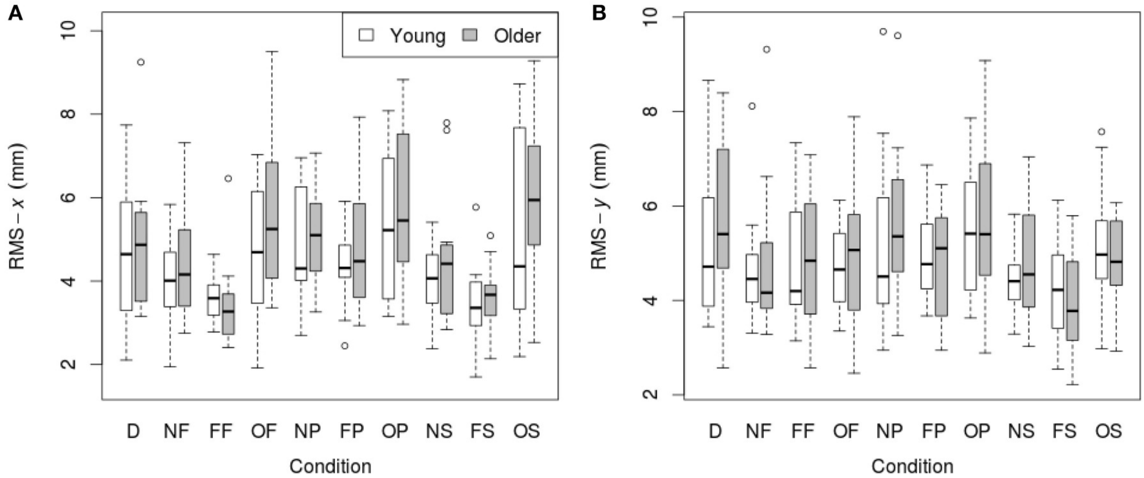

FIGURE 2 | RMS of COP coordinate timeseries: (A) on the medial/lateral (*x*) axis; (B) on the anterior/posterior (*y*) axis in young (*n* = 12) and older (*n* = 12) participants during different visual scene conditions. D, dark; N, none; F, fixed; O, oscillating; P, pursuit; S, saccadic. Data are displayed as medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately).

An increase in gaze error with smooth pursuits in dark (NP) compared to a fixed target in dark (NF; $p < 0.001$, 74.37% $g_{av} = 1.13$), smooth pursuits with a fixed background (FP) compared to a fixed target with a fixed background (FF; $p = 0.007$, 57.4% $g_{av} = 0.67$), and smooth pursuits with an oscillating background (OP) compared to a fixed target with an oscillating background (OF; $p = 0.001$, 38.61%, $g_{av} = 0.64$); (3) An increase in gaze error with saccades in dark (NS) compared to smooth pursuits in dark (NP; $p = 0.001$, 34.22%, $g_{av} = 0.98$), saccades with a fixed background (FS) compared to smooth pursuits with a fixed background (FP; $p = 0.016$, 23.22%, $g_{av} = 0.55$), and saccades with an oscillating background (OS) compared to smooth pursuits with an oscillating background (OP; $p = 0.001$, 38.63%, $g_{av} = 0.87$); There was no interaction effect between age and condition on RMS-gaze error.

4. DISCUSSION

The present work aimed to assess the effects of eye movements on balance in young and older individuals. We took a novel approach by assessing postural sway during three primary occulomotor behaviors with different forms of retinal flow, whilst simultaneously assessing gaze accuracy. Alterations of posture with different visual conditions were found predominantly on the medial/lateral (x) axis, with fixed stimuli having a stabilizing effect, and oscillating backgrounds and smooth pursuits having a destabilizing effect. There were no differences between age groups for any of the posture and gaze measures. The underpinning mechanisms and potential causes are discussed.

4.1. Visual Fixation of a Stationary Target

In support of extraocular postural control, or the ability of the CNS to interpret eye movement signals to gain positional information (Guerraz and Bronstein, 2008), we found a decrease of body sway when visually fixating a stationary target in dark. Two lines of reasoning have been discussed to explain this phenomenon; the inflow and outflow hypotheses. The former suggests that proprioceptors located in the extraocular muscles provide information about the magnitude of eye movements, which can be interpreted for estimates of body shifts during postural sway. This can only occur after eye movements have been initiated. The latter suggests such information can be gained from a copy of the motor command used to signal eye movements, or neural outflow used by the CNS to maintain visual consistency, and thus the magnitude of the eye movements may be anticipated in a feed forward manner.

Since there were no changes in postural sway with age in this condition, it seems likely the older participants were able to perceive head motion relative to the target as effectively as the young group. There were also no changes in gaze errors with age, which indicates a similar reduction of retinal flow for both young and older. Therefore, the extraocular factors involved in the control of posture might have been preserved. Because maintaining gaze on a fixed target requires compensatory eye movements, initiated in part by the VOR, the present findings also suggest that the elders had no substantial VOR deficits, which lends support to a recent study indicating such declines are limited to individuals aged 80 years and over (Li et al., 2015). To this point, our suggestion that age-related declines in VOR may affect extraocular balance control seems not to have occurred in our participants. Future research should seek to examine extraocular postural control mechanisms in populations with known VOR deficits.

4.2. Fixed and Oscillating Backgrounds

The addition of fixed backgrounds attenuated postural sway during all eye movements apart from smooth pursuits (discussed below). This reflects integration of the static visual field, and thus retinal flow, into the postural control system, allowing for more accurate visual estimates of body position (Glasauer et al., 2005; Laurens et al., 2010). The magnitude of gaze errors did not change, suggesting the participants were not distracted from the visual target.

Oscillating backgrounds generating horizontally translational retinal flow absent of parallax cues had a destabilizing effect during all eye movements. Previous work examined coupling of postural sway to stimulus motion with frequency response ratios (Logan et al., 2010). Strong coupling typically occurs at frequencies below 0.2 Hz, which is believed to be a result of the CNS misinterpreting external-motion for self-motion and initiating incorrect postural responses. At higher frequencies (>0.3 Hz), coupling is largely diminished (Guerraz and Bronstein, 2008). This is logical, considering if coupling were to remain, loss of balance might ensue. Since oscillation of the background in the present study was 0.33 Hz, and the participants did not lose their balance, it is likely there was a weak or no coupling of body sway with the background, probably through distinguishing between retinal flow caused by self-motion, and retinal flow caused by external-motion (DeAngelis and Angelaki, 2012). Vestibular and proprioceptive signals may be of particular importance in such a process, since they provide independent sources of information about head and body position in space (DeAngelis and Angelaki, 2012). Notwithstanding this, there were still increases in postural sway. This may be attributed to more challenging integration of the non-static retinal flow. In effect, it was likely harder to make visual estimates of body position against the dynamic background visual field. Interestingly, this occurred even with the stationary fixed target in the center of the field of vision, which supports the theory that the central area of the retina at which the fixed target would have been located is associated more with object recognition (Guerraz and Bronstein, 2008), and the peripheral visual field in which the oscillating background would be located is more dominant in control of posture in moving visual fields (Piponnier et al., 2009). In this respect, it seems the effect of the retinal flow was stronger than potential extraocular factors which might have been at play. There were no differences in gaze errors when oscillating backgrounds were added, suggesting again that the participants were not distracted from the target.

We found no differences between age groups for static or oscillating backgrounds. This was surprising as older individuals typically demonstrate greater body sway when standing in both stable visual information rich environments, such as a lit room, (Prieto et al., 1996) and in oscillating visual fields (Wade et al., 1995; Sundermier et al., 1996; Borger et al., 1998). We normalized the data to body height and body mass which have been shown to be determinants of postural sway in females during feet together stance (Kim et al., 2010) but were still unable to find any changes. This suggests that the older participants integrated all of the visual information for postural control as effectively as the young group, including determining body shifts from static and dynamic visual fields, and solving the external-motion from self-motion separation issue. We also found no differences in gaze errors between age groups with the addition of fixed or oscillating background information. Previous findings have suggested that elders may be more distracted by background motion, possibly related to a reduction in GABA-mediated inhibition, and this may have consequences for discriminating motion of moving objects from their backgrounds (Tadin and Blake, 2005). The present results do not support this idea.

TABLE 4 | RMS of gaze subtracted from target position (in arbitrary units) for young (n = 12) and older (n = 12) participants during different visual scene conditions.

	RMS-gaze error (a.u.)	
Condition	**Young**	**Older**
NF	10.33 ± 9.35	13.06 ± 6.32
FF	10.63 ± 8.97	16.98 ± 14.23
OF	12.90 ± 7.76	14.91 ± 8.77
NP	20.85 ± 5.82	19.94 ± 8.13
FP	21.73 ± 9.38	21.74 ± 12.34
OP	18.11 ± 6.61	20.44 ± 9.44
NS	25.96 ± 6.69	28.78 ± 7.09
FS	25.16 ± 5.40	28.39 ± 7.50
OS	22.87 ± 5.29	30.58 ± 9.55

D, dark; N, none; F, fixed; O, oscillating, P, pursuit; S, saccadic.

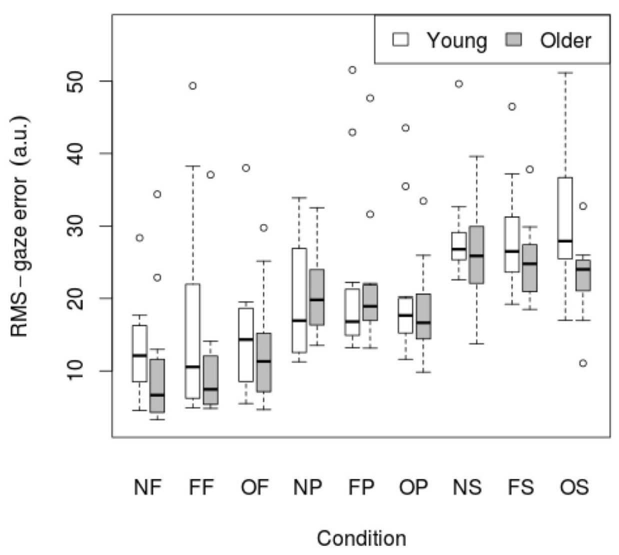

FIGURE 3 | RMS of gaze subtracted from target position for young (n = 12) and older (n = 12) participants during different visual scene conditions. D, dark; N, none; F, fixed; O, oscillating; P, pursuit; S, saccadic. Data are displayed as medians and lower and upper quartiles with Tukey style whiskers (outliers plotted seperately).

4.3. Smooth Pursuits

Smooth pursuits increased postural sway in the absence of retinal flow. We suggested above that eye movement signals were used to infer body position during fixation of a stable target with no background information (extraocular balance control). An increase in task complexity during smooth pursuits may complicate such extraocular signals, which in turn may have caused the increase in postural sway. The neural basis of these findings goes beyond the scope of this investigation, but might be related to the factors previously outlined.

Tracking a moving target over a fixed background also increased postural sway, yet we predicted the static visual field would have a stabilizing effect. One can argue that preserving stability of a given visual field on the retina is important for accurate measurement of postural shifts (Schulmann et al., 1987). During smooth pursuits, however, the image of the visual target may appear stable on the fovea (Thier and Ilg, 2005), but the background visual field shifts on the retina in the opposite direction to the target movement (Schulmann et al., 1987). This would generate similar retinal flow patterns to an oscillating background visual field, which may in turn lead to more challenging conditions for estimation of body position. Such results also support the notion that whilst smooth pursuits are good at maintaining the image of an object on the fovea, subserving a central analytical function, they are not efficient regarding spatial orientation, due to apparent motion of the background in the peripheral visual field (Schulmann et al., 1987).

In the previous experiments, the addition of a fixed background reduced the effect of the moving target on postural sway (Glasauer et al., 2005; Laurens et al., 2010). The differences between these and the present findings could be related to the nature of the stimulus movement. In the previous investigations, stimulus trajectory consisted of either horizontal, or vertical oscillations, which may have been easy to predict. In the present experiment, target movement was random on the vertical, horizontal and diagonal axis during each condition reflecting more unpredictability, more complex movement of the background visual information, and more complex extraocular signals. Thus, integration of retinal flow into the postural control system might have been more challenging, and this reduced the effect of an otherwise stabilizing visual anchor.

Our findings contrast with Rodrigues et al. (2015) who found a reduction of body sway during smooth pursuits. A potential cause lies with more challenging foot placement strategies used in the present investigation (and in Laurens et al., 2010 and Glasauer et al., 2005). Rodrigues et al. (2015) suggested postural sway was attenuated to gain more accurate gaze control during normal stance. When standing with feet together, or on foam/semi tandem stance in the previous experiments, such attenuation did not occur. It seems likely, therefore, that stance position dictates the outcome of postural response during smooth pursuits in the presence of stable visual background information. As Rodrigues et al. (2015) did not assess smooth pursuit movements independent of background visual information, it cannot be inferred whether stance would have any impact in such conditions.

Surprisingly, there were no differences between age groups for balance during smooth pursuits in any condition. It is thus possible that the older participants processed the potentially more complex extraocular signals, and dynamic retinal flow for postural control as efficiently as the young group. We also found no differences between age groups for gaze errors. This contradicts previous results showing age-related declines in smooth pursuit accuracy (Sharpe and Sylvester, 1978; Spooner et al., 1980; Moschner and Baloh, 1994; Ross et al., 1999; Knox et al., 2005). It may be the Tobii I-VT fixation filter we used to process the raw gaze data being a velocity-threshold identifier was not sufficiently accurate to discern small changes between the age groups which would require finer grained gaze data analysis such as that previously used Paquette and Fung (2011). With that said, a recent study found no difference between smooth pursuit parameters of young and older adults tracking targets in an ecologically valid environment (Dowiasch et al., 2015). We cannot ultimately say for sure which previous results would appropriately describe our participants. However, our previous suggestion that a decline in the accuracy of the smooth pursuit system with age may affect extraocular control of balance is incorrect, at least in our participants.

4.4. Saccades

We found no changes in postural sway during saccades compared to fixating a stable target in the absence of a visual background. Since in both conditions, the target was the predominant source of visual information, one must assume a similarity in the way it was used for postural control. This may be explained by the frequency of the target movement (0.33 Hz). Each saccadic shift of the target was completed at the projector refresh rate, in the order of sub 20 ms. Consequently, the target remained at the center position, or at 6° of visual angle at any given trajectory, for close to 1.5 s on each half oscillation. Since a saccadic shift of the human eye also with a displacement of 6° can be completed in around 40.6 ms (Abrams et al., 1989), gaze would have been fixated on a static target for relatively long periods during the saccadic trials aside from corrective saccades due to gaze errors. This suggests that similar to fixating a static target in dark, extraocular factors were involved in balance control. Future investigations should examine such extraocular contributions, during saccades with a range of movement frequencies.

The addition of a fixed background did attenuate postural sway further. As saccades aim to depict the visual environment as stable, e.g., to connect pre- and post-saccadic views, and gaze would have been fixated in the same position for relatively long periods, as above, the CNS might gain better estimates of head position from the background visual field in this condition (Schulmann et al., 1987), which seems to have occurred in our experiment regardless of changes in eye orientation.

The present findings do not align with previous data showing improvements in upright stability during saccades (Rodrigues et al., 2013, 2015; Aguiar et al., 2015). Stance position was the same as in Aguiar et al. (2015) and Rodrigues et al. (2013) and thus can be excluded as a causal factor. In these previous investigations, the authors suggested that postural sway was modulated to afford more accurate gaze shifts, since they found more sway attenuation at higher frequency saccades (1.1 Hz compared to 0.5 Hz). The frequency of saccades in the present investigation was lower at 0.33 Hz, and may not have required the same magnitude of postural sway attenuation.

We additionally found no differences in postural sway or gaze error between age groups during saccades. Therefore, the older participants may have been visually fixated on the target for similar time scales as the young group, suggesting a similar amount of positional information was interpreted, either extraocular or from retinal flow. Although it is possible that we failed to detect small effects of age on saccadic accuracy, such as longer onset latencies, or more saccades to reach the target (Paquette and Fung, 2011), this certainly had no effect on the postural outcomes.

Another possible explanation as to why we found no differences for postural sway with age during saccades and smooth pursuits relates to rigidity. Melzer et al. (2001) showed that when performing a dual task whilst stood with their feet together, elders reduced their body sway by increasing muscle activity in the tibialis anterior and soleus muscles. This coactivation about the ankle was thought to be a consequence of a threat to postural stability. Other findings from older individuals also point toward increases in muscle coactivation during standing, which may be a mechanism to compensate for natural age-related declines in the postural control system (Nagai et al., 2011). Such a mechanism has indeed been suggested to occur during saccadic eye movements (Aguiar et al., 2015). In the present study, the older participants may have been more challenged in terms of central integration of visual cues for postural control, and subsequently adopted a more rigid postural response through muscle coactivation, but this was not detected through measures of postural sway alone. Simultaneous assessment of muscle activity would be needed to confirm or reject this idea.

The present findings demonstrate the effects of eye movements on postural control in young and older females. In younger males and females, similar effects have previously been demonstrated (Glasauer et al., 2005; Laurens et al., 2010). In older males, we hypothesize that our findings would be replicated, since a previous study which manipulated visual parameters, in elders, was unable to detect significant gender differences in postural sway during quiet stance (Wolfson et al., 1994).

4.5. Axis Effects

The only change in posture on the anterior/posterior (y) axis was found with the addition of an oscillating background, whilst all other changes were found on the medial/lateral (x) axis. This indicates more stability on the anterior/posterior (y) axis compared to the medial/lateral (x) axis overall, which likely results from a reduced base of support on the medial/lateral (x) axis during feet together stance compared to normal stance. With that said, we did not utilize anterior/posterior (y) translations of the visual background during the eye movements to generate expansion and contraction retinal deformation patterns. Such conditions may have caused greater instability on this particular axis during eye movements, similar to changes in postural sway previously shown by Jeka et al. (2008). This is a recommendation for future experiments.

4.6. Method Consideration

With regard to previous studies investigating postural sway during eye movements, the participants were instructed to focus on the visual stimuli, but not directly examined as to whether they did so. The present results suggest that such instruction is appropriate and participants are able to remain fixated on the target, aside from natural gaze errors. Therefore, we suggest this set-up should continue being used for assessment of postural sway and eye movements during quiet stance.

4.7. Conclusion

The present investigation supports growing evidence that eye movements interact with the postural control system in humans, which could have important implications for practitioners and researchers working with a variety of populations. Extraocular components have been shown to contribute to postural control in a number of laboratory conditions. Thus, if extraocular balance control is impeded in individuals with substantial declines in VOR and/or visual proprioceptive function, discerning the relative contribution of extraocular and retinal mechanisms to balance control in an ecologically valid environment and during different eye movements would be an important step in developing a targeted training intervention. Moreover, since we and other studies found increases of postural sway during smooth pursuits in more challenging stance positions, stability whilst tracking moving targets may also be affected during locomotion or perturbed stance. This could place populations less able to correct postural disturbances, including elders, at a greater risk of falls. Should such individuals be instructed to refrain from observing moving objects, thus suppressing visual tracking, and only utilize static fixations and saccades which maintain or improve stability to scan their environment? Or perhaps training programs should focus on improving postural control during smooth pursuit eye movements in a variety of conditions. Some of these points were first raised by Schulmann et al. (1987). Here, we suggest further research is still needed, and should also take account of extraocular factors. With that said, in the present context, our older participants were able to match the younger group's postural and visual performances. This may be said on the cognitive level (sensory integration of visual cues to the postural control system), and on the physical functioning level (musculoskeletal responses to maintain upright stabilty). How this translates to more dynamic situations such as locomotion, and with different populations, now remain the topics of interest.

AUTHOR CONTRIBUTIONS

NT conceived the investigation, led the data collection and analysis and interpretation of the results, and drafted the first manuscript. TB, TD, and SD contributed to all aspects of the investigation, including methodological design, data collection, and analysis, interpretation of the results, and revision of the manuscript for important intellectual content. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

ACKNOWLEDGMENTS

This research was funded by the Dowager Countess Eleanor Peel Trust.

REFERENCES

Abrams, R. A., Meyer, D. E., and Kornblum, S. (1989). Speed and accuracy of saccadic eye movements: characteristics of impulse variability in the oculomotor system. *J. Exp. Psychol. Hum. Percept. Perform.* 15:529.

Aguiar, S. A., Polastri, P. F., Godoi, D., Moraes, R., Barela, J. A., and Rodrigues, S. T. (2015). Effects of saccadic eye movements on postural control in older adults. *Psychology. Neurosci.* 8:19. doi: 10.1037/h0100352

Ambrose, A. F., Paul, G., and Hausdorff, J. M. (2013). Risk factors for falls among older adults: a review of the literature. *Maturitas* 75, 51–61. doi: 10.1016/j.maturitas.2013.02.009

Baloh, R. W., Ying, S. H., and Jacobson, K. M. (2003). A longitudinal study of gait and balance dysfunction in normal older people. *Arch. Neurol.* 60, 835–839. doi: 10.1001/archneur.60.6.835

Borger, L., Whitney, S., Redfern, M., and Furman, J. (1998). The influence of dynamic visual environments on postural sway in the elderly. *J. Vestib. Res.* 9, 197–205.

Bronstein, A. (1986). Suppression of visually evoked postural responses. *Exp. Brain Res.* 63, 655–658.

Brunner, L. C., Eshilian-Oates, L., and Kuo, T. Y. (2003). Hip fractures in adults. *Am. Fam. Physician* 67, 537–542.

DeAngelis, G. C., and Angelaki, D. E. (2012). "Visual-vestibular integration for self-motion perception," in *The Neural Bases of Multisensory Processes*, Chapter 31, eds M. M. Murray and M. T. Wallace (Boca Raton, FL: CRC Press/Taylor & Francis). Available online at: http://www.ncbi.nlm.nih.gov/books/NBK92839/

Dichgans, J., and Brandt, T. (1978). "Visual-vestibular interaction: effects on self-motion perception and postural control," in *Perception*, eds R. Held, H. W. Leibowitz, and H.-L. Teuber (Berlin; Heidelberg: Springer), 755–804.

Dijkstra, T., Schöner, G., and Gielen, C. (1994). Temporal stability of the action-perception cycle for postural control in a moving visual environment. *Exp. Brain Res.* 97, 477–486.

Donaldson, I. (2000). The functions of the proprioceptors of the eye muscles. *Philos. Trans. R. Soc. B Biol. Sci.* 355, 1685–1754. doi: 10.1098/rstb.2000.0732

Dowiasch, S., Marx, S., Einhäuser, W., and Bremmer, F. (2015). Effects of aging on eye movements in the real world. *Front. Hum. Neurosci.* 9:46. doi: 10.3389/fnhum.2015.00046

Field, A., Miles, J., and Field, Z. (2012). *Discovering Statistics Using R*. London: SAGE Publications.

Flückiger, M., and Baumberger, B. (1988). The perception of an optical flow projected on the ground surface. *Perception* 17, 633–645.

Gibson, J. J. (1950). *The Perception of the Visual World*. Boston, MA: Houghton Mifflin.

Gibson, J. J., Olum, P., and Rosenblatt, F. (1955). Parallax and perspective during aircraft landings. *Am. J. Psychol.* 68, 372–385.

Glasauer, S., Schneider, E., Jahn, K., Strupp, M., and Brandt, T. (2005). How the eyes move the body. *Neurology* 65, 1291–1293. doi: 10.1212/01.wnl.0000175132.01370.fc

Guerraz, M., and Bronstein, A. (2008). Ocular versus extraocular control of posture and equilibrium. *Neurophysiol. Clin.* 38, 391–398. doi: 10.1016/j.neucli.2008.09.007

Hallet, P. E. (1986). "Eye movements," in *Handbook of Human Perception and Performance*, Vol. 1, eds K. R. Boff, L. Kaufman, and J. P. Thomas (New York, NY: Wiley) 10.1–10.112.

Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cogn. Psychol.* 23, 420–456.

Jeka, J. J., Allison, L. K., and Kiemel, T. (2010). The dynamics of visual reweighting in healthy and fall-prone older adults. *J. Mot. Behav.* 42, 197–208. doi: 10.1080/00222895.2010.481693

Jeka, J. J., Oie, K. S., and Kiemel, T. (2008). Asymmetric adaptation with functional advantage in human sensorimotor control. *Exp. Brain Res.* 191, 453–463. doi: 10.1007/s00221-008-1539-x

Kim, J.-W., Eom, G.-M., Kim, C.-S., Kim, D.-H., Lee, J.-H., Park, B. K., et al. (2010). Sex differences in the postural sway characteristics of young and elderly subjects during quiet natural standing. *Geriatr. Gerontol. Int.* 10, 191–198. doi: 10.1111/j.1447-0594.2009.00582.x

Knox, P. C., Davidson, J. H., and Anderson, D. (2005). Age-related changes in smooth pursuit initiation. *Exp. Brain Res.* 165, 1–7. doi: 10.1007/s00221-005-2265-2

Kowler, E. (2011). Eye movements: the past 25years. *Vis. Res.* 51, 1457–1483. doi: 10.1016/j.visres.2010.12.014

Lakens, D. (2013). Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and anovas. *Front. Psychol.* 4:863. doi: 10.3389/fpsyg.2013.00863

Laurens, J., Awai, L., Bockisch, C., Hegemann, S., van Hedel, H., Dietz, V., et al. (2010). Visual contribution to postural stability: interaction between target fixation or tracking and static or dynamic large-field stimulus. *Gait Posture* 31, 37–41. doi: 10.1016/j.gaitpost.2009.08.241

Lee, D., and Lishman, J. (1975). Visual proprioceptive control of stance. *J. Hum. Mov. Stud.* 1, 87–95.

Lestienne, F., Soechting, J., and Berthoz, A. (1977). Postural readjustments induced by linear motion of visual scenes. *Exp. Brain Res.* 28, 363–384.

Lewis, R. F., Zee, D. S., Gaymard, B. M., and Guthrie, B. L. (1994). Extraocular muscle proprioception functions in the control of ocular alignment and eye movement conjugacy. *J. Neurophysiol.* 72, 1028–1031.

Li, C., Layman, A. J., Geary, R., Anson, E., Carey, J. P., Ferrucci, L., et al. (2015). Epidemiology of vestibulo-ocular reflex function: data from the baltimore longitudinal study of aging. *Otol. Neurotol.* 36:267. doi: 10.1097/MAO.0000000000000610

Lin, D., Seol, H., Nussbaum, M. A., and Madigan, M. L. (2008). Reliability of cop-based postural sway measures and age-related differences. *Gait Posture* 28, 337–342. doi: 10.1016/j.gaitpost.2008.01.005

Logan, D., Kiemel, T., Dominici, N., Cappellini, G., Ivanenko, Y., Lacquaniti, F., et al. (2010). The many roles of vision during walking. *Exp. Brain Res.* 206, 337–350. doi: 10.1007/s00221-010-2414-0

Manckoundia, P., Mourey, F., Pfitzenmeyer, P., Van Hoecke, J., and Pérennou, D. (2007). Is backward disequilibrium in the elderly caused by an abnormal perception of verticality? A pilot study. *Clin. Neurophysiol.* 118, 786–793. doi: 10.1016/j.clinph.2006.11.274

Melzer, I., Benjuya, N., and Kaplanski, J. (2001). Age-related changes of postural control: effect of cognitive tasks. *Gerontology* 47, 189–194. doi: 10.1159/000052797

Moschner, C., and Baloh, R. W. (1994). Age-related changes in visual tracking. *J. Gerontol.* 49, M235–M238. doi: 10.1093/geronj/49.5.m235

Nagai, K., Yamada, M., Uemura, K., Yamada, Y., Ichihashi, N., and Tsuboyama, T. (2011). Differences in muscle coactivation during postural control between healthy older and young adults. *Arch. Gerontol. Geriatr.* 53, 338–343. doi: 10.1016/j.archger.2011.01.003

Nashner, L., and Berthoz, A. (1978). Visual contribution to rapid motor responses during postural control. *Brain Res.* 150, 403–407.

Paige, G. (1991). Senescence of human visual-vestibular interactions. 1. vestibulo-ocular reflex and adaptive plasticity with aging. *J. vestib. Res.* 2, 133–151.

Paquette, C., and Fung, J. (2011). Old age affects gaze and postural coordination. *Gait Posture* 33, 227–232. doi: 10.1016/j.gaitpost.2010.11.010

Paulus, W., Straube, A., and Brandt, T. (1984). Visual stabilization of posture. *Brain* 107, 1143–1163.

Peirce, J. W. (2007). Psychopy—psychophysics software in python. *J. Neurosci. Methods* 162, 8–13. doi: 10.1016/j.jneumeth.2006.11.017

Peterka, R., Black, F., and Schoenhoff, M. (1990). Age-related changes in human vestibulo-ocular reflexes: sinusoidal rotation and caloric tests. *J. Vestib. Res.* 1, 49–59.

Piponnier, J.-C., Hanssens, J.-M., and Faubert, J. (2009). Effect of visual field locus and oscillation frequencies on posture control in an ecological environment. *J. Vis.* 9:13. doi: 10.1167/9.1.13

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., and Myklebust, B. M. (1996). Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans. Biomed. Eng.* 43, 956–966. doi: 10.1109/10.532130

Rocchi, L., Chiari, L., and Cappello, A. (2004). Feature selection of stabilometric parameters based on principal component analysis. *Med. Biol. Eng. Comput.* 42, 71–79. doi: 10.1007/BF02351013

Rodrigues, S. T., Aguiar, S. A., Polastri, P. F., Godoi, D., Moraes, R., and Barela, J. A. (2013). Effects of saccadic eye movements on postural control stabilization. *Motriz Rev. Educ. Fis.* 19, 614–619. doi: 10.1590/S1980-65742013000300012

Rodrigues, S. T., Polastri, P. F., Carvalho, J. C., Barela, J. A., Moraes, R., and Barbieri, F. A. (2015). Saccadic and smooth pursuit eye movements attenuate postural sway similarly. *Neurosci. Lett.* 584, 292–295. doi: 10.1016/j.neulet.2014.10.045

Ross, R. G., Olincy, A., Harris, J. G., Radant, A., Adler, L. E., Compagnon, N., et al. (1999). The effects of age on a smooth pursuit tracking task in adults with schizophrenia and normal subjects. *Biol. Psychiatry* 46, 383–391.

Rougier, P., and Garin, M. (2007). Performing saccadic eye movements or blinking improves postural control. *Motor Control* 11:213. doi: 10.1123/mcj.11.3.213

Sato, H., and Maitland, M. E. (2008). Relationship between forward trunk lean during walking and musculoskeletal functions for females. *J. Mech. Med. Biol.* 8, 459–471. doi: 10.1142/S0219519408002796

Schulmann, D. L., Godfrey, B., and Fisher, A. G. (1987). Effect of eye movements on dynamic equilibrium. *Phys. Ther.* 67, 1054–1057.

Sharpe, J., and Sylvester, T. (1978). Effect of aging on horizontal smooth pursuit. *Invest. Ophthalmol. Vis. Sci.* 17, 465–468.

Spooner, J. W., Sakala, S. M., and Baloh, R. W. (1980). Effect of aging on eye tracking. *Arch. Neurol.* 37, 575–576.

Stoffregen, T. A. (1985). Flow structure versus retinal location in the optical control of stance. *J. Exp. Psychol. Hum. Percept. Perform.* 11:554.

Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Percept. Psychophys.* 39, 355–360.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., Hove, P., and Oullier, O. (2007). Postural sway and the frequency of horizontal eye movements. *Mot. Control* 11:86.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., and Pagulayan, R. J. (2006). Postural stabilization of visually guided eye movements. *Ecol. Psychol.* 18, 191–222. doi: 10.1207/s15326969eco1803_3

Sturnieks, D., St George, R., and Lord, S. (2008). Balance disorders in the elderly. *Neurophysiol. Clin.* 38, 467–478. doi: 10.1016/j.neucli.2008.09.001

Sundermier, L., Woollacott, M. H., Jensen, J. L., and Moore, S. (1996). Postural sensitivity to visual flow in aging adults with and without balance problems. *J. Gerontol. Ser. A Biol. Sci. Med. Sci.* 51, M45–M52.

Tadin, D., and Blake, R. (2005). Motion perception getting better with age? *Neuron* 45, 325–327. doi: 10.1016/j.neuron.2005.01.017

Thier, P., and Ilg, U. J. (2005). The neural basis of smooth-pursuit eye movements. *Curr. Opin. Neurobiol.* 15, 645–652. doi: 10.1016/j.conb.2005.10.013

Ustinova, K., and Perkins, J. (2011). Gaze and viewing angle influence visual stabilization of upright posture. *Brain Behav.* 1, 19–25. doi: 10.1002/brb3.10

Wade, M. G., Lindquist, R., Taylor, J. R., and Treat-Jacobson, D. (1995). Optical flow, spatial orientation, and the control of posture in the elderly. *J. Geront. Ser. B Psychol. Sci. Soc. Sci.* 50, P51–P54.

Wapner, S., and Witkin, H. A. (1950). The role of visual factors in the maintenance of body-balance. *Am. J. Psychol.* 63, 385–408.

Warren, W. H., Blackwell, A. W., and Morris, M. W. (1989). Age differences in perceiving the direction of self-motion from optical flow. *J. Gerontol.* 44, P147–P153.

Winter, D. A. (1995). Human balance and posture control during standing and walking. *Gait Posture* 3, 193–214.

Wolfson, L., Whipple, R., Derby, C. A., Amerman, P., and Nashner, L. (1994). Gender differences in the balance of healthy elderly as demonstrated by dynamic posturography. *J. Gerontol.* 49, M160–M167.

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix B

Article 2

Exp Brain Res (2017) 235:2661–2668
DOI 10.1007/s00221-017-4996-2

RESEARCH ARTICLE

Smooth pursuits decrease balance control during locomotion in young and older healthy females

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Received: 25 October 2016 / Accepted: 23 May 2017 / Published online: 3 June 2017

Abstract Dynamic balance control—characterised as movement of the trunk and lower limbs—was assessed during fixation of a fixed target, smooth pursuits and saccadic eye movements in ten young (22.9 ± 1.5 years) and ten older (72.1 ± 8.2 years) healthy females walking overground. Participants were presented with visual stimuli to initiate eye movements, and posture and gaze were assessed with motion analysis and eye tracking equipment. The results showed an increase in medial/lateral (ML) trunk movement (C7: $p = 0.012$; sacrum: $p = 0.009$) and step-width variability ($p = 0.052$) during smooth pursuits compared to a fixed target, with no changes for saccades compared to a fixed target. The elders demonstrated greater ML trunk movement (sacrum: $p = 0.037$) and step-width variability ($p = 0.037$) than the younger adults throughout, although this did not interact with the eye movements. The findings showed that smooth pursuits decreased balance control in young and older adults similarly, which was likely a consequence of more complicated retinal flow. Since healthy elders are typically already at a postural disadvantage, further decreases in balance caused by smooth pursuits are undesirable.

Keywords Elderly gait · Eye movements · Postural control · Saccades · Step-variability · Walking posture

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Introduction

Vision is important for balance control during locomotion.[1] Experiments manipulating the visual field of young adult treadmill walkers, for example, have resulted in forward and backward trunk lean (Logan et al. 2010) and increased medial/lateral (ML) trunk movement and step-width variability (Warren et al. 1996; McAndrew et al. 2010). Step-width variability is of particular interest as it is linked to control of the bodies centre of mass (COM) on a step-to-step basis and is important for maintaining balance (Bauby and Kuo 2000). These findings were thought to result from the central nervous system (CNS) detecting changes to the visual field and adjusting posture (albeit in error) accordingly.

Visual sensing of the external environment and self-motion within it occurs at the retina. In a 3D world, patterns of light reflected off structures reaching the retina create an optic array. If the observer moves, it changes the structure of the array about a point of central observation (Gibson 1950). Such changes in patterns of light which flow across the retina are thought to be interpreted to estimate body position (Warren et al. 1996; Logan et al. 2014). However, eye movements can change the structure of the array, and flow patterns on the retina can be a combination of those caused by self-motion in addition to those caused by eye movements (Lappe and Hoffmann 2000). The CNS must, therefore, solve a source separation issue between the two when judging self-motion (DeAngelis and Angelaki 2012).

1 In the present manuscript, the term 'balance control' defines maintenance of an upright posture during locomotion.

Despite investigations about how humans control their direction heading during eye movements (Royden et al. 1994), studies manipulating visual flow and assessing balance during walking have not considered eye movements. If changes to flow caused by eye movements affect how humans interpret the optic array, it may in turn affect balance control.

The nature of changes to balance control would likely depend on the type of eye movement. For instance, visually fixating a stationary object straight ahead would cause radial flow from forward progression, and this would emanate from the central point of observation (Lappe and Hoffman 2000). Such flow may be considered useful for balance control since it provides a stable reference frame (assuming healthy vestibulo-ocular and vestibulo-colic reflexes) from which self-motion with respect to the vertical can be determined. Conversely, tracking an object in horizontal motion would cause horizontal flow from eye rotation in addition to radial flow from forward progression. The resulting pattern would resemble a curved movement with a shifting focus of expansion (Lappe and Hoffmann 2000). Moreover, although the object of fixation would appear stabilised on the fovea, the background information would become blurred (Kowler 2011). This added complexity may cause difficulty when estimating self-motion, thus decreasing balance control. Saccades are another kind of eye movement used during walking. These are rapid shifts of gaze from one region to another (Kowler 2011). However, because saccades are a series of fixations separated by rapid intervals, unless the saccades were to an extreme displacement and/or with unnaturally high frequency, the stable reference frame provided by fixation should be preserved.

Of interest when considering the above are older individuals. Elders can be more sensitive to ML perturbations of the visual field during walking resulting in greater reduction of trunk stabilisation and increased step-width variability when compared to younger adults (Franz et al. 2015). Further, it is thought the ageing CNS relies on vision more for balance control because of vestibular and musculoskeletal sensory declines (Yeh et al. 2014). Therefore, because elders cannot decompose retinal flow as effectively as young adults, and can be more reliant on visual information, any decrease in balance control caused by smooth pursuits may be more profound in this age group. One study found a comparable increase in postural sway during smooth pursuits between young and older adults during standing (Thomas et al. 2016). However, because the biomechanical constraints and nature of visual flow during walking are so different to standing, further investigation is warranted.

Therefore, the present study assessed balance control during fixation of a fixed target, smooth pursuits and saccades in healthy young and older females walking overground. It was hypothesised that: (1) smooth pursuits would increase medial/lateral (ML) trunk movement and step-width variability compared to a fixed target; (2) saccades would maintain balance compared to a fixed target; (3) the reduced balance during smooth pursuits would be more profound in the older adults.

Materials and methods

Participants

Ten young (mean ± SD: 22.9 ± 1.5 years; 1.7 ± 0.06 m; 59.5 ± 7.2 kg) and ten older (mean ± SD: 72.1 ± 8.2 years; 1.6 ± SD 0.03 m; 57.3 ± 5.6 kg) healthy females participated in the study. The elders were interviewed initially to determine suitability for the study. All participants adhered to inclusion criteria previously outlined (Thomas et al. 2016). In short, they had no known musculoskeletal or neurophysiological conditions which could affect normal balance during standing and walking. All participants had an uncorrected visual acuity (without glasses or contact lenses) ≥20/100 and were able to ambulate in the community without visual correction. The investigation was carried out in accordance with the recommendations of the University of Cumbria ethical principles and guidelines for research involving human subjects, and all procedures, information to the participants and participant consent forms were approved by the University of Cumbria Research Committee. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Equipment

Visual scenes were projected (Sanyo PLC-XU74, Tokyo, Japan) onto a 3.2 × 2.4 m screen on the wall of the laboratory. Participants wore eye tracking glasses (Tobii Glasses 2 Eye Tracker, Tobii Technology, Danderyd, Sweden) which have a one-point calibration procedure, autoparallax compensation and slippage compensation allowing for persistent calibration throughout testing with no loss of data aside from blinking. A 7 camera Vicon system (MX3, Oxford, UK; sampling frequency 100 Hz) recorded three-dimensional positions of eight passive reflective markers located at the left and right front and back head, C7, sacrum, and left and right heel anatomical landmarks of each participant. A custom-made contact mat was used to initiate visual stimulus movement (see “Experimental protocol”).

Visual stimuli

Visual stimuli were programmed with Psychopy stimuli presentation software (Peirce 2007). The visual target presented was a light blue circle displayed over a black background. Each participant could see the target at all times during testing. Three experimental conditions were implemented: fixed target (FIX), smooth pursuit (PUR) and saccade (SAC). For FIX, the target remained in the centre of the screen at eye level. During PUR, the target displaced from the centre of the screen in the horizontal direction to a defined threshold of visual angle (described below) before returning to the centre of the screen with a frequency of 0.33 Hz (Laurens et al. 2010). The target moved randomly left or right on each oscillation, which had no bearing or relation to the participants side dominance. This choice reflects spontaneous tracking movements occurring in everyday activities (Kowler 2011). For SAC, the same protocol was implemented. However, the target disappeared from the centre of the screen and reappeared at the defined threshold stimulating a saccadic eye movement, and then disappeared and reappeared back at the centre.

The stimuli were programmed in degrees of visual angle enabling standardisation between laboratories/experiments. It was considered to update the size and displacement of the visual target relative to each participant as they progressed along the walkway. This would have maintained a constant degree of visual angle for the size of the target, and visual angle change for the displacement of the target. However, this would have made the target appear to move away from the observer as they progressed forward. In everyday life, objects do not typically reduce in size as an observer approaches. Likewise, objects moving across the field of vision such as a passing pedestrian often maintain a linear heading. The magnitude of the tracking movement is such a case is thus always dependent on how far the observer is from a given visual target. It was decided, therefore, not provide real-time adjustments. As such, the size of the visual target relative to each participant corresponded to 1° at the start of the data capture area, and 2° at the end. The displacement of the target (left or right) in the horizontal direction corresponded to 6° at the start of the data capture area and 12° at the end.

Experimental protocol

Five trials for each condition (FIX, PUR and SAC) were completed. The conditions were sorted randomly and segregated into 3 blocks of 5 trials. Each block was separated by 2 min of rest. The participants walked overground on a flat level walkway in the laboratory for 7.5 m. The walkway consisted of a 2.5 m entry area to achieve a steady-state velocity, which has previously been recommended for older individuals (Lindemann et al. 2008), a 4 m data capture area where balance control was assessed, and a 1 m exit area (Fig. 1). At least 2.5 strides of data were collected from each participant during each trail which totalled at least 12.5 strides for each participant in each condition. FIX was presented at the beginning of the entry area before the participants

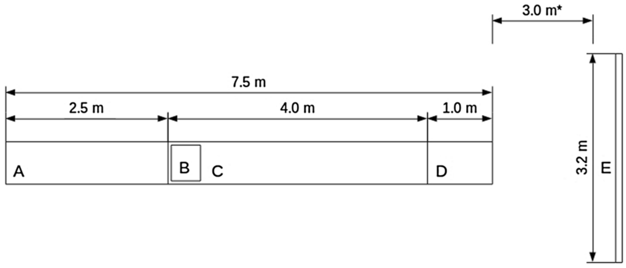

Fig. 1 Walkway consisting of entry area (**a**); contact mat (**b**); data collection area (**c**); exit area (**d**); and projection screen (**e**). *Asterisk* distance between walkway and projection screen not to scale

set off during all trials. On the first heel strike on entering the data capture area, which was arranged to be in the first 30 cm, visual target movement or no movement depending on the condition was initiated by the custom-made contact mat.

Participants were instructed to fixate their gaze on the visual target at all times. If it moved, they should follow it with their eyes only making sure not to rotate or tilt their head. Gaze shifts less than 15° are commonly achieved without rotation of the head (Hallet 1986), and eye movements up to 35° have been performed whilst minimising head movements (Paquette and Fung 2011). This accommodates the maximum target displacement of 12° in the present investigation. Head rotations during testing were assessed to ensure any changes in the outcome measures were not a result of head movements corresponding to the direction of the visual target movement.

Method considerations

The visual stimuli and experimental set-up aimed to replicate as closely as possible eye movements used in everyday life and their changes to flow whilst standardising eye movement velocity and displacement. Using a virtual reality environment with 3D cues, which would generate similar retinal flow patterns as to walking through a room, was considered. However, this would require treadmill walking which for reasons discussed below was not appropriate. Instead, the 2D visual target was projected at the wall of the laboratory, and as such there would have been visual flow generated from the rest of the room as the participants walked forward, e.g. from the walls running adjacent to the walkway. With regard to the target, this just provided a visual fixation point—during a smooth pursuit it is the background visual information (the rest of the room in the present experiment) that becomes more difficult to interpret, and this is what has previously been suggested to affect standing postural control (Laurens et al. 2010; Thomas et al. 2016). The object of fixation is, therefore, not of particular concern.

With regard to locating the target at eye level and in the centre of the visual field, although humans have been shown to fixate on points at which they will step around a second or so before stepping on them (Patla and Vickers 2003), walking humans also locate their gaze centrally along the horizontal and vertical relative to the direction heading. In other words, toward a heading point (Foulsham et al. 2011). Moreover, they often fixate on fixed and moving objects including near and far standing and moving humans (Foulsham et al. 2011) and things located in the field of vision such as posters affixed to walls (Dowiasch et al. 2015). One study found that of 133 pedestrians, a walker fixated 83% of them at least once whilst navigating a university campus (Foulsham et al. 2011). This coupled with a previously documented visual attentional bias towards people's faces and eyes (Birmingham et al. 2008) suggests that gaze is often allocated at eye level in front of the observer, and sometimes on moving targets.

Finally, the number of recommended strides for assessing gait variability has ranged between 5 and 8 to the order of hundreds whilst dual tasking in older individuals (Owings and Grabiner 2004; Hollman et al. 2010). Additionally, separating data collection into a series of stop-start walks as in the present experiment can increase lower-limb variability when compared to one continuous walk (Paterson et al. 2009). However, measuring gait for long duration walking would typically require a treadmill which has been shown to significantly alter gait (Dingwell et al. 2001). Further, replicating normal retinal flow patterns on a treadmill would require virtual reality. In addition to the limited availability of such a set up, virtual reality has also been shown to alter gait compared to normal conditions, and may even cause instability in healthy subjects (Hollman et al. 2007). The present investigation, therefore, placed emphasis on repeated short overground walks. First, this more closely replicates everyday walking (Orendurff et al. 2008) in a more familiar way for elders (Schellenbach et al. 2010). Second, it was important to assess immediate effects of visual stimulus onset. In everyday life, eye movements can be initiated spontaneously, and objects of interest may not be observed for many continuous strides. This was important considering the CNS can re-weight its use of vision over longer time frames (Allison et al. 2006) and short-term effects may have gone unnoticed during longer walks.

Data analysis

Raw marker data were extracted using the Biomechanical Toolkit Python bindings (Barre and Armand 2014) and analysed offline (Scipy, scientific computing tools for Python). Marker trajectories were low-pass filtered using a fourth order zero-phase Butterworth filter with a cutoff frequency of 10 Hz. Heel strike events were determined based on the position of the heel marker in relation to the Sacrum marker (Zeni et al. 2008). In short, the y coordinate of the Sacrum marker at each time frame was subtracted from the y coordinate of each heel marker at the corresponding time frame, and peaks in the resulting time series which represent heel strikes determined. This method has been shown to estimate overground heel strike events to within 0.0021 s of gold standard force platform measurements.

Trunk movement

Movement of the lower and upper trunk in the ML direction was quantified as the root mean square (RMS) of the ML component of the C7 and Sacrum markers, where N = number of data points and $n = 1, \ldots, N$:

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum n^2}.$$

Trunk lean was defined as the inclination angle of the trunk with respect to the vertical axis, which was calculated from the inverse tangent of the distance between the C7 and Sacrum markers in the ML axis divided by the same distance in the vertical axis. RMS of the resulting time series was then computed. The present experiment focused on the ML axis for trunk kinematics as this is sensitive to the visual component of balance control (Warren et al. 1996; McAndrew et al. 2010).

Lower limbs

Step-width was defined as the ML distance between heel markers at heel strike. Mean and coefficient of variation (CV) where SD = standard deviation:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{mean}} \times 100$$

was then calculated for step-width across successive steps (Brach et al. 2005; McAndrew et al. 2010; Franz et al. 2015).

Head rotations

The four head markers were used to construct a head segment. Then, rotation matrices were calculated between consecutive frames and converted to Euler angles expressed in degrees of yaw rotation about the vertical. This corresponds to the direction of the visual target movement. RMS of the head rotation time series was then computed.

Gaze fixations

Where participants were looking in relation to the target was assessed to ensure the protocol was completed accurately. Gaze data (sampled at 50 Hz) was filtered with a Tobii I-VT fixation filter to yield gaze fixations (window length 20 ms; threshold 30°/s^{-1}). 2D video sequences consisting of the participant's point of view of each visual scene superimposed with their gaze fixations was exported. Position of the target and the position of each gaze fixation as *x* and *y* coordinates on the 2D video frame was then determined using a motion tracking algorithm (OpenCV Python libraries). The resultant coordinate time series for each was then calculated. Data before stimulus onset and at the end of the data collection area was removed in accordance with the motion capture data. Where no gaze data were sampled to due blinking, the target coordinate at the corresponding time frame was removed (Thomas et al. 2016). Pearson correlation coefficients were then calculated between the coordinate time series of the target and that of the gaze fixations, and finally RMS of gaze subtracted from the target position (RMS gaze error) throughout each video sequence.

Reliability of the tracking procedure used to determine the coordinates of the target and the gaze fixations was assessed by re-tracking all of the video sequences and computing the CV between gaze error RMS results. A CV of 0% indicated perfect reliability throughout.

Statistical analysis

The mean or median of the 5 trials for each participant in each condition was used for statistical analysis of the relevant outcome measures depending on a normal or nonnormal distribution of the raw data. Condition (3 × visual scenes) and age (young and older) were considered as two independent factors. The effect of these two factors on C7 and sacrum RMS; trunk lean RMS; step-width mean and CV; head rotation RMS; correlation coefficients between the target coordinates and gaze fixation coordinates; and gaze error RMS were examined with a two way (condition × age) mixed analysis of variance (ANOVA). Where the averages/medians of the trials for each outcome measure departed from normality, effects were re-examined using robust mixed ANOVAs based on trimmed means (Field et al. 2012). Post hoc analyses included *t* tests or Wilcoxon signed-rank tests with Bonferroni corrections. Finally, where significant differences were found ($p \leq 0.05$), Hedges' g_{av} effect sizes were calculated (Lakens 2013). Common indicative

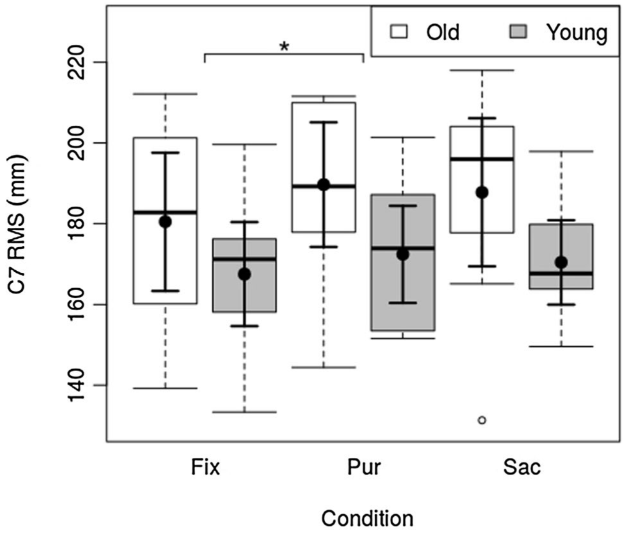

Fig. 2 C7 RMS in the ML direction in young ($n = 10$) and older ($n = 10$) participants during different eye movements. *Fix* fixed target, *Pur* smooth pursuit, *Sac* Saccade. Data are displayed as means and 95% confidence intervals in *bold*, and medians and lower and upper quartiles with *Tukey style whiskers* (outliers plotted separately). *Asterisk* significant difference between conditions

thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8). Statistical results were interpreted in the context of strength of evidence against the null hypotheses, which was determined by the magnitude of the *p* values (smaller values indicate stronger evidence), magnitude of effect sizes, and 95% confidence intervals. Statistical analyses were performed with the R software package.

Results

Trunk movement

C7 and Sacrum RMS along the ML direction are shown in Fig. 2 and Fig. 3. C7 RMS showed a main effect of condition ($F_{2,36} = 4.71$, $p = 0.015$). Post hoc comparisons revealed larger C7 RMS during PUR compared to FIX ($p = 0.012$, $g_{av} = 0.32$), but no change for SAC compared to FIX. C7 RMS showed no main effect of age or interaction effect between condition and age.

Sacrum RMS showed a main effect of condition ($F_{2,36} = 5.06$, $p = 0.011$). Post hoc comparisons revealed larger Sacrum RMS during PUR compared to FIX ($p = 0.009$, $g_{av} = 0.27$), but no change for SAC compared to FIX. Sacrum RMS showed a main effect of age ($F_{1,18} = 5.05$, $p = 0.037$), with larger Sacrum RMS in the older group. Sacrum RMS showed no interaction effect between condition and age.

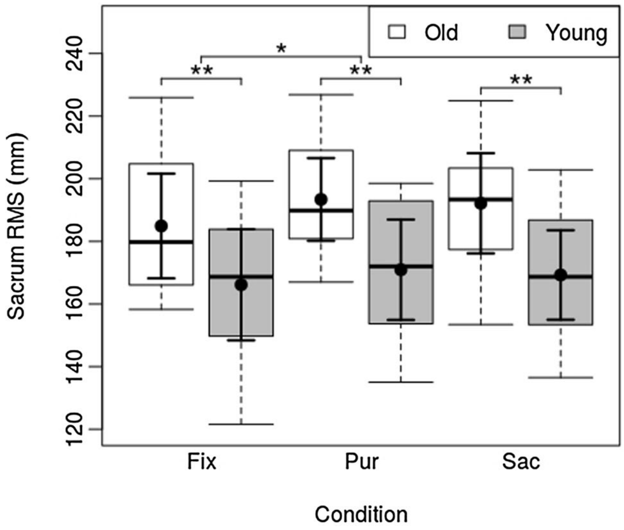

Fig. 3 Sacrum RMS in the ML direction in young ($n = 10$) and older ($n = 10$) participants during different eye movements. *Fix* fixed target, *Pur* smooth pursuit, *Sac* Saccade. Data are displayed as means and 95% confidence intervals in *bold*, and medians and lower and upper quartiles with *Tukey style whiskers* (outliers plotted separately). *Asterisk* significant difference between conditions. *Double asterisk* significant difference between age groups

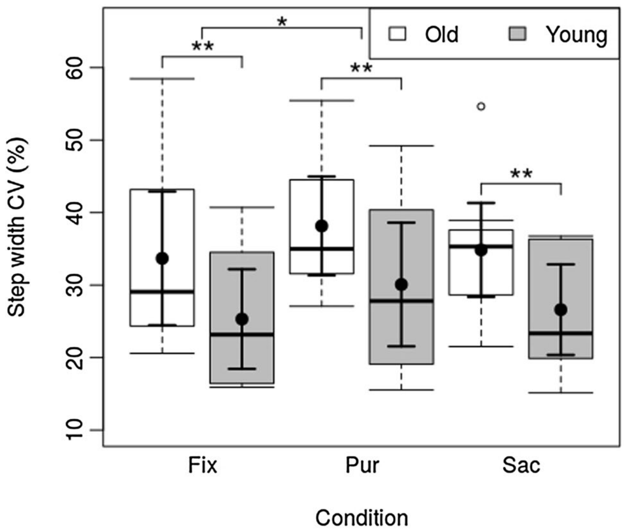

Fig. 4 Step-width variability in young ($n = 10$) and older ($n = 10$) participants during different eye movement conditions. *Fix* fixed target, *Pur* smooth pursuit, *Sac* saccade. Data are displayed as means and 95% confidence intervals in bold, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Asterisk* significant difference between conditions. *Double asterisk* significant difference between age groups

Trunk lean RMS showed no main effect of condition or age, or any interaction effect between condition and age.

Lower limbs

Mean step-width showed no main effect of condition or age, or any interaction effect between condition and age. Step-width CV (Fig. 4.) showed a main effect of condition ($F_{2,36} = 4.75$, $p = 0.049$). Post hoc comparisons revealed larger step-width CV during PUR compared to FIX ($p = 0.052$, $g_{av} = 0.39$), but no change for SAC compared to FIX. Step-width CV showed a main effect of age ($F_{1,18} = 5.08$, $p = 0.037$), with larger step-width CV in the older group. Step-width CV showed no interaction effect between condition and age.

Head rotation

Head rotation showed no main effect of condition or age, or any interaction effect between condition and age. This suggests that all participants refrained from using head rotation in the direction of target movement.

Gaze variables

The correlation coefficients between the coordinate time series of the target and the gaze fixations, and gaze error RMS showed no main effect of condition or age, or any interaction effect between condition and age. The correlation analysis showed strong correlations ($r > 0.8$) in all conditions for all participants. These results indicate all of the participants followed instructions and completed the visual tasks aside from natural gaze errors.

Discussion

The present investigation assessed dynamic balance control during fixation of a fixed target, and smooth pursuit and saccadic eye movements in young and older healthy females steady state walking. Smooth pursuits increased ML trunk movement and step-width variability compared to the fixed target similarly in both age groups, whilst there were no changes for saccades compared to the fixed target. The elders demonstrated less baseline stability in all conditions.

The present results support the first hypothesis that visually tracking a moving target with smooth pursuits decreases balance control during walking. This was likely related to changes in retinal flow caused by the eye movements. Processing of optic flow for self-motion during eye movements is thought to occur in the medial superior temporal (MST) (Duffy and Wurtz 1991) and ventral intraparietal (VIP) areas of the visual cortex (Schaafsma and Duysens 1996). These regions have been linked to judging direction heading from optic flow (Zhang et al. 2004), and compensation for changes in the focus of expansion during smooth pursuits (Page and Duffy 1999). In the present experiment, the added complexity to optic flow caused by smooth pursuits would likely lead to increased processing demands within the MST and VIP areas, and this may have reduced visual sensitivity to self-motion.

Another factor which may have contributed to decreased balance during smooth pursuits is more complex extraocular signals. Extra-ocular signals have been shown to improve balance in standing humans, where small eye movements used to maintain gaze fixations during postural sway (initiated by the vestibulo-ocular reflex) provide information about body position relative to the fixation point (Guerraz and Bronstein 2008). During locomotion, fixation of a fixed target would produce similar signals. For example, researchers found a minimum threshold of 0.3 degrees of eye movement for 1 cm of translational head movement was useful during standing (Guerraz and Bronstein 2008). During locomotion, the gait cycle would induce translation head movements meeting this threshold (Borg et al. 2015). It is thus likely that the extraocular component of balance control persists during walking, and if so, it is also likely that during a smooth pursuit, the eye rotation required to keep gaze fixated on the moving target would surpass any extraocular signals useful for balance control. This was also thought to occur during standing in previous experiments (Laurens et al. 2010; Thomas et al. 2016).

Supporting the second hypothesis, there were no changes to balance during saccades compared to the fixed target. Because saccades are a series of fixations separated by rapid eye movements, and the target movement during the saccades was completed in sub 20 ms and each saccade in 40–50 ms (Abrams et al. 1989), gaze was fixated on a stationary target for the majority of the saccadic eye movement trials. Such conditions likely preserved the stable reference frame similar to the fixed target. It is also probable, therefore, that any element of extraocular postural stabilisation was also preserved. Even though the final displacement of the eye rotation during saccades was the same as during smooth pursuit, the nature of eye rotation and neural control to reach that displacement are different (Kowler 2011). In effect, the continuing rotation during smooth pursuits complicates extraocular signals, whilst the short rapid shifts of saccades preserve longer periods (pre and post-saccade) of fixation and thus useful extraocular signals.

Contrary to the third hypothesis, the negative change to balance during smooth pursuits was not more profound in the older adults. This is interesting since elders have previously been shown to have difficulties in interpreting optic flow for self-motion (Berard et al. 2009). However, comparing the present results with others is difficult since there have been no studies considering eye movements and balance in walking elders. One explanation is there was only a small effect (trunk: $g_{av} = 0.32$; lower limbs: $g_{av} = 0.39$) of smooth pursuits on balance in both age groups. The changes to retinal flow, therefore, may not have been profound enough to 'challenge' the ageing CNS enough to bring about a greater change. This would indicate that healthy elders are able to process visual flow for balance purposes during smooth pursuits as effectively as younger adults. However, the older adults demonstrated reduced balance throughout testing, with greater Sacrum displacement and step-width variability in all conditions. Thus, the elders were already at a disadvantage, which was probably due to a combination of musculoskeletal and sensory deficits which are considered normal in healthy ageing (Ambrose et al. 2013). Any further decrease to balance such as that shown in the present experiment is, therefore, certainly undesirable, particularly considering that greater baseline instability indicates a higher risk of falls (Ambrose et al. 2013). Further research is needed to assess whether smooth pursuits affect balance control in pathological ageing. For example, in patients with vestibular dysfunction and/or eye conditions such as peripheral vision loss—peripheral vision is more dominant in balance control (Guerraz and Bronstein 2008), and the loss of which may, therefore, exacerbate negative changes to balance during smooth pursuits. Such research may be important for identifying those at increased risk of falls.

Acknowledgements This research was funded by the Dowager Countess Eleanor Peel Trust. The authors would like to thank Aurora Leo and Michela Colli for their help during testing. All testing took place at the University of Rome Foro Italico.

References

Abrams RA, Meyer DE, Kornblum S (1989) Speed and accuracy of saccadic eye movements: characteristics of impulse variability in the oculomotor system. J Exp Psychol Hum Percept Perform 15:529. doi:10.1037/0096-1523.15.3.529

Allison LK, Kiemel T, Jeka JJ (2006) Multisensory reweighting of vision and touch is intact in healthy and fall-prone older adults. Exp Brain Res 175:342–352. doi:10.1007/s00221-006-0559-7

Ambrose AF, Paul G, Hausdorff JM (2013) Risk factors for falls among older adults: a review of the literature. Maturitas 75:51–61. doi:10.1016/j.maturitas.2013.02.009

Barre A, Armand S (2014) Biomechanical ToolKit: open-source framework to visualize and process biomechanical data. Comput Methods Programs Biomed 114:80–87. doi:10.1016/j.cmpb.2014.01.012

Bauby CE, Kuo AD (2000) Active control of lateral balance in human walking. J Biomech 33:1433–1440. doi:10.1016/S0021-9290(00)00101-9

Berard JR, Fung J, McFadyen BJ, Lamontagne A (2009) Aging affects the ability to use optic flow in the control of heading during locomotion. Exp Brain Res 194:183–190. doi:10.1007/s00221-008-1685-1

Birmingham E, Bischof WF, Kingstone A (2008) Gaze selection in complex social scenes. Vis Cogn 16:341–355. doi:10.1080/13506280701434532

Borg O, Casanova R, Bootsma RJ (2015) Reading from a head-fixed display during walking: adverse effects of gaze stabilization mechanisms. PLoS One 10:e0129902. doi:10.1371/journal.pone.0129902

Brach JS, Berlin JE, VanSwearingen JM et al (2005) Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed. J Neuroeng Rehabil 2:1. doi:10.1186/1743-0003-2-21

DeAngelis GC, Angelaki DE (2012) Visual-vestibular integration for self-motion perception. In: Murray MM, Wallace MT (eds) The Nueral Basis of Multisensory Processes. CRC Press, Boca Raton, FL

Dingwell J, Cusumano J, Cavanagh P, Sternad D (2001) Local dynamic stability versus kinematic variability of continuous overground and treadmill walking. J Biomech Eng 123:27–32. doi:10.1115/1.1336798

Dowiasch S, Marx S, Einhäuser W, Bremmer F (2015) Effects of aging on eye movements in the real world. Front Hum Neurosci 9:46. doi:10.3389/fnhum.2015.00046

Duffy CJ, Wurtz RH (1991) Sensitivity of MST neurons to optic flow stimuli. II. Mechanisms of response selectivity revealed by small-field stimuli. J Neurophysiol 65:1346–1359

Field A, Miles J, Field Z (2012) Discovering Statistics Using R. SAGE Publications, London

Foulsham T, Walker E, Kingstone A (2011) The where, what and when of gaze allocation in the lab and the natural environment. Vision Res 51:1920–1931. doi:10.1016/j.visres.2011.07.002

Franz JR, Francis CA, Allen MS et al (2015) Advanced age brings a greater reliance on visual feedback to maintain balance during walking. Hum Mov Sci 40:381–392. doi:10.1016/j.humov.2015.01.012

Gibson JJ (1950) The perception of the visual world. Houghton Mifflin, Boston

Guerraz M, Bronstein A (2008) Ocular versus extraocular control of posture and equilibrium. Neurophysiol Clin Neurophysiol 38:391–398. doi:10.1016/j.neucli.2008.09.007

Hallet PE (1986) Eye movements. In: Boff KR, Kaufman L, Thomas JP (eds) Handbook of human perception and performance. Wiley, New York, pp 10.1–10.112

Hollman JH, Brey RH, Bang TJ, Kaufman KR (2007) Does walking in a virtual environment induce unstable gait? An examination of vertical ground reaction forces. Gait Posture 26:289–294. doi:10.1016/j.gaitpost.2006.09.075

Hollman JH, Childs KB, McNeil ML et al (2010) Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals. Gait Posture 32:23–28. doi:10.1016/j.gaitpost.2010.02.017

Kowler E (2011) Eye movements: the past 25years. Vision Res 51:1457–1483. doi:10.1016/j.visres.2010.12.014

Lakens D (2013) Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. Front Psychol 4:863. doi:10.3389/fpsyg.2013.00863

Lappe M, Hoffmann K (2000) Optic flow and Eye Movements. Int Rev Neurobiol 44:29–47

Laurens J, Awai L, Bockisch C et al (2010) Visual contribution to postural stability: interaction between target fixation or tracking and static or dynamic large-field stimulus. Gait Posture 31:37–41. doi:10.1016/j.gaitpost.2009.08.241

Lindemann U, Najafi B, Zijlstra W et al (2008) Distance to achieve steady state walking speed in frail elderly persons. Gait Posture 27:91–96. doi:10.1016/j.gaitpost.2007.02.005

Logan D, Kiemel T, Dominici N et al (2010) The many roles of vision during walking. Exp Brain Res 206:337–350. doi:10.1007/s00221-010-2414-0

Logan D, Ivanenko YP, Kiemel T et al (2014) Function dictates the phase dependence of vision during human locomotion. J Neurophysiol 112:165–180. doi:10.1152/jn.01062.2012

McAndrew PM, Dingwell JB, Wilken JM (2010) Walking variability during continuous pseudo-random oscillations of the support surface and visual field. J Biomech 43:1470–1475. doi:10.1016/j.jbiomech.2010.02.003

Orendurff MS, Schoen JA, Bernatz GC, Segal AD (2008) How humans walk: bout duration, steps per bout, and rest duration. J Rehabil Res Dev 45:1077–1090. doi:10.1682/JRRD.2007.11.0197

Owings TM, Grabiner MD (2004) Variability of step kinematics in young and older adults. Gait Posture 20:26–29. doi:10.1016/S0966-6362(03)00088-2

Page WK, Duffy CJ (1999) MST neuronal responses to heading direction during pursuit eye movements. J Neurophysiol 81:596–610

Paquette C, Fung J (2011) Old age affects gaze and postural coordination. Gait Posture 33:227–232. doi:10.1016/j.gaitpost.2010.11.010

Paterson KL, Lythgo ND, Hill KD (2009) Gait variability in younger and older adult women is altered by overground walking protocol. Age Ageing 38:745–748. doi:10.1093/ageing/afp159

Patla AE, Vickers JN (2003) How far ahead do we look when required to step on specific locations in the travel path during locomotion? Exp Brain Res 148:133–138. doi:10.1007/s00221-002-1246-y

Peirce JW (2007) PsychoPy—psychophysics software in Python. J Neurosci Methods 162:8–13. doi:10.1016/j.jneumeth.2006.11.017

Royden CS, Crowell JA, Banks MS (1994) Estimating heading during eye movements. Vision Res 34:3197–3214. doi:10.1016/0042-6989(94)90084-1

Schaafsma S, Duysens J (1996) Neurons in the ventral intraparietal area of awake macaque monkey closely resemble neurons in the dorsal part of the medial superior temporal area in their responses to optic flow patterns. J Neurophysiol 76:4056–4068

Schellenbach M, Lövdén M, Verrel J et al (2010) Adult age differences in familiarization to treadmill walking within virtual environments. Gait Posture 31:295–299. doi:10.1016/j.gaitpost.2009.11.008

Thomas NM, Bampouras TM, Donovan T, Dewhurst S (2016) Eye movements affect postural control in young and older females. Front Aging Neurosci 8:216. doi:10.3389/fnagi.2016.00216

Warren WH, Kay BA, Yilmaz EH (1996) Visual control of posture during walking: functional specificity. J Exp Psychol Hum Percept Perform 22:818–838. doi:10.1037/0096-1523.22.4.818

Yeh TT, Cluff T, Balasubramaniam R (2014) Visual reliance for balance control in older adults persists when visual information is disrupted by artificial feedback delays. PLoS One 9:1–9. doi:10.1371/journal.pone.0091554

Zeni J, Richards J, Higginson J (2008) Two simple methods for determining gait events during treadmill and overground walking using kinematic data. Gait Posture 27:710–714. doi:10.1016/j.gaitpost.2007.07.007

Zhang T, Heuer HW, Britten KH (2004) Parietal area VIP neuronal responses to heading stimuli are encoded in head-centered coordinates. Neuron 42:993–1001. doi:10.1016/j.neuron.2004.06.008

Appendix C

Article 3

Visually fixating an indoor pedestrian decreases balance control in young and older healthy females walking in a real-world environment

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Abstract

Abstract: Dynamic balance control during overground walking was assessed in 10 young (23.6 ± 3.4) and 10 older (71.0 ± 5.5 years) healthy females during free gaze, and when fixating a standing or walking indoor pedestrian in an everyday use waiting room. Balance was characterised by medial/lateral sacrum acceleration dispersion, and gaze fixations were simultaneously assessed with eye tracking equipment. The results showed increased sacrum dispersion during fixation of both the stationary (p=0.006, g_{av}=0.21) and walking (p=0.001, g_{av}=0.23) pedestrian compared to free gaze. There were, however, no differences between age groups for sacrum dispersion, or between conditions or ages for gaze fixations. The findings were likely a result of blurred background information during the fixation tasks, which facilitated less reliable estimates of self-motion through vision. Such a decrease in balance control, the first to be shown in a real-world scenario, may warrant further investigation in those at high risk of falls.

Keywords: Elderly gait; Eye movements; Postural control; Smooth pursuits; Trunk accelerations; Walking balance

1. Introduction

Vision helps maintain an upright posture during locomotion [1, 2]. This is facilitated by changes in patterns of light intensities caused by relative motion between an observer and their environment, which are sensed at the retina [3]. Lateral trunk lean, for example, would generate a translational flow on the retina in the opposite direction [4]. The central nervous system uses this to estimate shifts in body position and initiate postural adjustments.

Eye movements can affect how retinal information is used for balance control. Visually tracking a moving target with smooth pursuits increased mediolateral (ML) trunk movement

Preprint submitted to Neuroscience Letters *November 4, 2017*

and step-width variability during walking in young and older females similarly – factors which reflect decreased stability [5]. During such eye movements, although the target of fixation is stabilised on the fovea, the background information can be prone to blurring [6]. This, in turn, may make it more difficult to estimate self-motion through visual means.

Previous investigation about eye movements and balance employed targets projected in 2D [7, 8]. This mimics viewing of a background scene, where focusing on the target requires similar convergence to other locations surrounding the target [9]. Humans often, however, fixate stationary and moving objects located more in the foreground, such as stationary and walking pedestrians [10]. This requires more convergence to bring focus to the object, which in turn causes background blurring [11]. If the blur makes it more difficult to determine self-motion with visual information, it may result in decreased balance control even when the object is stationary. Presumably, such an effect will be more profound when the object is moving due to more dynamic blurring. However, whilst a recent study assessed standing balance during fixation of near and far light targets [12], the authors did not consider fixation of the background alone. Further, walking balance whilst tracking fixed or moving objects more in the foreground has not previously been examined.

These considerations may have important implications in older adults. Elders typically demonstrate less 'baseline' stability and a reduced ability to correct loss of balance during walking [13], and this may place them at an even greater risk of falls during such visual fixation tasks. Assessing elders walking balance whilst fixating static and moving objects more in the foreground may, therefore, further understanding of risk factors of falls in elders. Moreover, conducting the experiment in a realistic setting will offer a more direct application of the results.

The present investigation, therefore, assessed dynamic balance in young and older adults during free gaze, and when visually tracking a standing or walking indoor pedestrian in a real-world environment. It was hypothesised: 1) visually fixating the standing and walking pedestrian would decrease balance control compared to free gaze in young and older participants similarly, 2) there would be a more profound effect whilst tracking the walking pedestrian, 3) the elders would exhibit less baseline stability throughout.

1.1. Participants

Ten young (mean $\pm$ SD: age: 23.6 $\pm$ 3.4 years, height: 1.68 $\pm$ 0.06 m, mass: 69.0 $\pm$ 9.9 kg) and 10 older (mean $\pm$ SD: age: 71.0 $\pm$ 5.5 years, height: 1.61 $\pm$ 0.06 m, mass: 63.9 $\pm$ 10.3 kg) healthy females participated in the investigation. The elders were interviewed by telephone to determine eligibility and adhered to inclusion criteria previously outlined [14]. In brief, they had no known musculoskeletal or neurophysiological conditions which could negatively affect balance control during walking. The participants had an uncorrected visual acuity of $\geq$20/100 and were able to ambulate in the community without visual correction. The investigation was carried out in accordance with the University of Cumbria recommendations and guidelines for research involving human subjects, and all procedures, information to the participants, and participant consent forms, were approved by the University of Cumbria Research Committee. All participants gave written informed consent in accordance with the Declaration of Helsinki.

1.2. Equipment

Testing was carried out on a flat walkway into a waiting room (Fig. 1). The walkway consisted of a 2.5 m entry area to achieve a steady-state velocity, which has previously been recommended for older individuals [15], a 4 m data capture area where dynamic balance characteristics were assessed, and a 1 m exit area. Sliding doors concealed the waiting room from the participants when they were at the start of the walkway. A member of the research team (pedestrian) would be absent from or standing or walking within a standardised pedestrian area at the far end of the waiting room (Fig. 2, see Experimental protocol section 1.3). A custom-made contact mat was used to send a signal to a laptop informing the pedestrian when to begin walking and in which direction (also see Experimental protocol section 1.3). Four inertial measurement units (IMUs: Opal, APDM, Portland, Oregon) measured accelerations of the centre front head, sacrum, and left and right ankle anatomical land marks of each participant. Participants wore eye tracking glasses (Tobii Glasses 2 Eye Tracker, Tobii Technology, Danderyd, Sweden) which have a one-point calibration procedure, autoparallax compensation and slippage compensation allowing for persistent calibration throughout testing with no loss of data aside from blinking.

1.3. Experimental protocol

The sliding doors were shut before each trial and then opened signalling the trial to commence. The participants then walked straight into the room at a self-selected pace along the length of the walkway towards the exit area. Three conditions were implemented: free gaze (FREE), stationary pedestrian (STAT) and walking pedestrian (WALK). For FREE, the waiting room was void of the pedestrian. For STAT, the pedestrian stood stationary in the centre of the pedestrian area. For WALK, on the first heel strike on entering the data capture area, the contact mat (beginning at the start of the data capture area and ending 30 cm along the walkway) sent a signal to a laptop out of view of the participant which informed the pedestrian to walk 1.5 m across the pedestrian area, before standing still. The direction was random on each trial. During FREE, the participants were given no instructions where to look. During STAT and WALK, they were informed to look at the pedestrian at all times, and if the pedestrian moved, to track them with their eyes only making sure not to rotate or tilt their heads. The 1.5 m threshold corresponded to 12 of visual angle relative to the participants while they were at the start of the data capture area, and 26 at the end. During STAT and WALK, the pedestrian was present on door opening and was thus visible to the

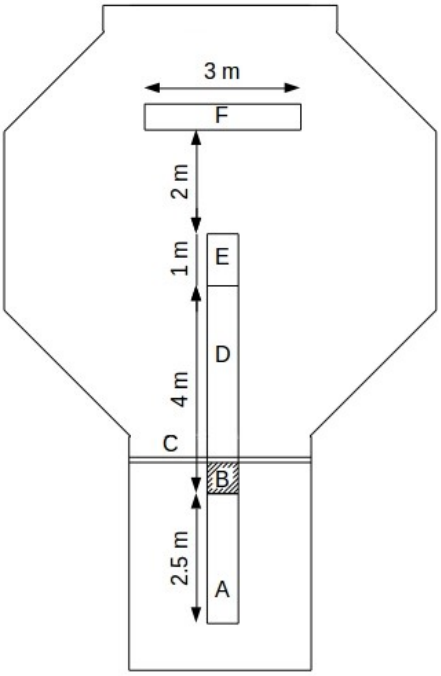

Figure 1: A schematic diagram of the experimental environment. The walkway into the waiting room consists of A: entry area, B: contact mat, C: sliding doors, D: data collection area, E: exit area, F: pedestrian area. All distances are to scale.

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

participants at the start of the walkway. However, prior to door opening, the participants were blinded to the conditions in the room.

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

1.4. Data analysis

Raw data from the IMU devices were exported and analysed offline (Scipy, Scientific Computing Tools for Python). Raw data were filtered with a phase-corrected low-pass Butterworth filter (20Hz cuttoff). Heel strikes and mid-stance phases were determined using validated methods previously described in detail [16, 17]. All data were truncated to the first right heel strike upon entering the data capture area, and the third left stride midstance period. Standard deviation (SD) of Sacrum acceleration in the global ML direction then defined sacrum acceleration dispersion [18], which characterised balance control.

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

1.5. Statistical analysis

The mean/median of the 5 trials for each participant in each condition was used for statistical analysis of the relevant outcome measure depending on normal or non-normal distribution of the raw data. Condition (3 $\times$ visual scenes) and age (young and older) were considered as 2 independent factors. The effects of these factors on Head rotation and Sacrum SD were examined with a 2 way (condition $\times$ age) mixed analysis of variance (ANOVA). The same model was applied to the correlation coefficients between pedestrian and gaze fixation coordinates and RMS gaze error, but with only STAT and WALK considered. Post-hoc analyses were t-tests with Bonferroni corrections. Finally, where significant differences were found ($p<0.05$), Hedges' g_{av} effect sizes were calculated [19]. Common indicative thresholds for effect sizes are small (0.2), medium (0.5) and large (0.8). Statistical analyses were performed with the R software package.

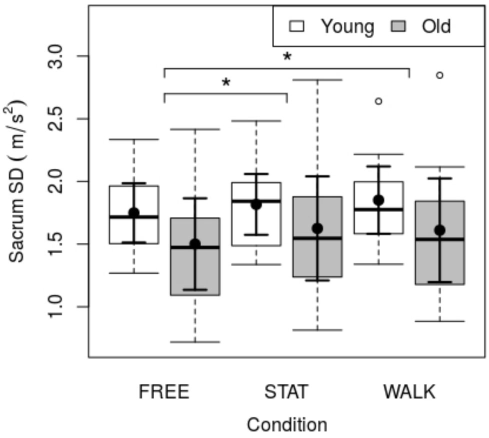

Figure 3: Sacrum RMS in the ML direction in young (n = 10) and older (n = 10) females during different eye movement conditions. FREE: free gaze, STAT: stationary pedestrian, WALK: walking pedestrian. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower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

2. Results

Sacrum SD in the ML direction is shown in Fig. 3. Sacrum SD showed a main effect of condition ($F_{2,36}$=11.81, p<0.001). Post-hoc comparisons revealed larger Sacrum SD during STAT (p=0.006, g_{av}=0.21) and WALK (p=0.001, g_{av}=0.23) compared to FREE. Sacrum SD showed no main effect of age or interaction effect between condition and age.

Head rotation SD showed no main effect of condition or age, or any interaction effect between condition and age. The correlation coefficients (all above 0.7) between the pedestrian and gaze fixation coordinates and RMS gaze error showed no main effects of condition or age, or any interaction effects between condition and age. This suggests the participants followed instructions and tracked the pedestrian with their eyes whilst refraining from using head rotations.

3. Discussion

The present investigation assessed balance control during walking in young and older adults visually fixating an indoor pedestrian. Increases in Sacrum acceleration dispersion were found on the ML axis when the pedestrian was standing still and walking. There were, however, no differences between age groups.

In support of the first hypothesis, there was an increase in sacrum acceleration dispersion whilst visually fixating the stationary and walking pedestrian as opposed to free gaze in both young and older participants. This is the first experiment to show such an effect, and in a real-world environment. The result is likely a consequence of more complicated or blurred background retinal information generated by fixation of the pedestrian, which made it more difficult to determine translational trunk movements through visual information alone. In contrast to the second hypothesis, there was a similar increase in sacrum acceleration dispersion during fixation of the stationary pedestrian compared to the walking pedestrian. Since there were no differences in gaze errors between conditions or ages, and the correlations coefficients between the pedestrian and the fixation coordinates were all strong, it can be assumed that the participants fixated the pedestrian satisfactorily in each condition. Thus, it seems that the amount of blur induced by fixation of the stationary pedestrian was sufficient to decrease balance control to the same level as when the pedestrian was walking, even with the dynamic blurring which would have occurred when tracking the walking pedestrian. This may be a consequence of the gait cycle inducing various oscillatory components of retinal flow from the background information which would be blurred due to fixation of the nearer object, even when the object was stationary. In effect, background blur would have been dynamic when fixating both the stationary and the walking pedestrian.

The fact there were no differences between fixation of the stationary and the walking pedestrian raises a question as to why there was a decrease in balance control during smooth pursuit compared to fixation in previous work [5]. This may be attributed to the location of the target with respect to the background. For example, during the free gaze condition in the present experiment, there were no objects located in the foreground to observe, and thus, visual fixation of any point in the room required similar convergence to locations immediately surrounding that point. This actually reflects both the fixation and saccadic conditions in the previous experiment, where the target was projected onto a flat screen. Fixating the pedestrian in the present experiment better reflected the smooth pursuit condition of the previous experiment, since that was the only condition which would have caused blurring. This is why there was a similar increase with smooth pursuits compared to stationary fixation in the previous experiment (g_{av}=0.27), and with fixation of the stationary pedestrian compared to free gaze in the present experiment (g_{av}=0.21).

In contrast to the third hypothesis, there was no difference in baseline sacrum acceleration dispersion in the elders compared to the younger adults. Therefore, it appears they were able to match the younger participant's performance throughout – processing the visual information and completing the eye movement tasks. The elderly participants were healthy and could all ambulate within the community without visual correction, and other older populations have been shown to exhibit resistance to visual motion perception ageing effects due to compensatory mechanisms [20]. Therefore, detrimental performance of visual tasks similar to those in the present experiment may not be a necessary consequence of ageing. With that said, the small increase in sacrum acceleration dispersion during both fixations tasks may warrant further investigation in those at greater risk of falling – particularly in those with vestibular/ocular dysfunction.

4. Conclusion

The present experiment showed that visually fixating another pedestrian can decrease balance control in young and older adults during locomotion. The findings may be useful to those working with elders. It may not be unusual, for example, for older adults to walk into waiting room environments and fixate on other people. Since this can negatively affect balance control, a quiet room void of people would be more optimal for reducing fall-risk in those who are less stable. Professionals may consider this for interventions as well as designing and maintaining areas high fall-risk older adults are likely to use. Future research should seek to examine if older adults adopt similar gaze fixation behaviour (i.e. fixating other people) during free viewing in a similar real-world environment, which would help put the present results into context.

References

[1] W. H. Warren, B. A. Kay, E. H. Yilmaz, Visual control of posture during walking: functional specificity., Journal of Experimental Psychology: Human Perception and Performance 22 (4) (1996) 818–838. doi:10.1037/0096-1523.22.4.818.

[2] D. Logan, T. Kiemel, N. Dominici, G. Cappellini, Y. Ivanenko, F. Lacquaniti, J. J. Jeka, The many roles of vision during walking, Experimental brain research 206 (3) (2010) 337–350. doi:10.1007/s00221-010-2414-0.

[3] J. J. Gibson, The perception of the visual world., Houghton Mifflin, Boston, 1950.

[4] M. Guerraz, A. Bronstein, Ocular versus extraocular control of posture and equilibrium, Neurophysiologie Clinique/Clinical Neurophysiology 38 (6) (2008) 391–398. doi:10.1016/j.neucli.2008.09.007.

[5] N. M. Thomas, S. Dewhurst, T. M. Bampouras, T. Donovan, A. Macaluso, G. Vannozzi, Smooth pursuits decrease balance control during locomotion in young and older healthy females, Experimental Brain Research (2017) 1–8doi:10.1007/s00221-017-4996-2.

[6] D. L. Schulmann, B. Godfrey, A. G. Fisher, Effect of eye movements on dynamic equilibrium, Physical therapy 67 (7) (1987) 1054–1057.

[7] J. Laurens, L. Awai, C. Bockisch, S. Hegemann, H. van Hedel, V. Dietz, D. Straumann, Visual contribution to postural stability: interaction between target fixation or tracking and static or dynamic large-field stimulus, Gait & posture 31 (1) (2010) 37–41. doi:10.1016/j.gaitpost.2009.08.241.

[8] S. Glasauer, E. Schneider, K. Jahn, M. Strupp, T. Brandt, How the eyes move the body, Neurology 65 (8) (2005) 1291–1293. doi:10.1212/01.wnl.0000175132.01370.fc.

[9] L. E. Mays, Neural control of vergence eye movements: convergence and divergence neurons in midbrain, Journal of Neurophysiology 51 (5) (1984) 1091–1108.

[10] T. Foulsham, E. Walker, A. Kingstone, The where, what and when of gaze allocation in the lab and the natural environment, Vision Research 51 (17) (2011) 1920 – 1931. doi:10.1016/j.visres.2011.07.002.

[11] W. W. Sprague, E. A. Cooper, S. Reissier, B. Yellapragada, M. S. Banks, The natural statistics of blur, Journal of Vision 16 (10). doi:10.1167/16.10.23.

[12] E. Matheron, Q. Yang, V. Delpit-Baraut, O. Dailly, Z. Kapoula, Active ocular vergence improves postural control in elderly as close viewing distance with or without a single cognitive task, Neuroscience Letters 610 (2016) 24 – 29. doi:https://doi.org/10.1016/j.neulet.2015.10.065.

[13] A. F. Ambrose, G. Paul, J. M. Hausdorff, Risk factors for falls among older adults: a review of the literature, Maturitas 75 (1) (2013) 51–61. doi:10.1016/j.maturitas.2013.02.009.

[14] N. M. Thomas, T. M. Bampouras, T. Donovan, S. Dewhurst, Eye Movements Affect Postural Control in Young and Older Females, Frontiers in Aging Neuroscience 8 (2016) 216. doi:10.3389/fnagi.2016.00216.

[15] U. Lindemann, B. Najafi, W. Zijlstra, K. Hauer, R. Muche, C. Becker, K. Aminian, Distance to achieve steady state walking speed in frail elderly persons, Gait & posture 27 (1) (2008) 91–96. doi:10.1016/j.gaitpost.2007.02.005.

[16] J. R. Rebula, L. V. Ojeda, P. G. Adamczyk, A. D. Kuo, Measurement of foot placement and its variability with inertial sensors, Gait & Posture 38 (4) (2013) 974 – 980. doi:https://doi.org/10.1016/j.gaitpost.2013.05.012.

[17] K. Btzel, F. M. Marti, M. . C. Rodrguez, A. Plate, A. O. Vicente, Gait recording with inertial sensors How to determine initial and terminal contact, Journal of Biomechanics 49 (3) (2016) 332 – 337. doi:https://doi.org/10.1016/j.jbiomech.2015.12.035.

[18] J. M. Huisinga, M. Mancini, R. J. St. George, F. B. Horak, Accelerometry Reveals Differences in Gait Variability Between Patients with Multiple Sclerosis and Healthy Controls, Annals of Biomedical Engineering 41 (8) (2013) 1670–1679. doi:10.1007/s10439-012-0697-y.

[19] D. Lakens, Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs, Frontiers in psychology 4 (2013) 863. doi:10.3389/fpsyg.2013.00863.

[20] J. Billino, F. Bremmer, K. R. Gegenfurtner, Differential aging of motion processing mechanisms: Evidence against general perceptual decline, Vision Research 48 (10) (2008) 1254 – 1261. doi:https://doi.org/10.1016/j.visres.2008.02.014.

Appendix D

Article 4

Visual sampling during locomotion in a real-world environment: effects of ageing and pre-planning, and considerations for reducing fall risk

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ABSTRACT

A variety of age-related changes to gaze behaviour have previously been shown in laboratory-based paradigms. However, they have been little explored in real-world environments, which would be an important step to consider them in the context of fall-risk reduction. The present investigation thus recorded 11 young (mean±SD: 23.4±3.2 years) and 11 older (70.9±5.2 years) healthy females' eye movements whilst walking into waiting room. The participants were able to visually pre-plan or not before entering the room, and 3 conditions were implemented inside the room, including another standing person (known as actor), a walking actor, or a room absent of the actor. Outcome variables included duration of fixation on regions of interest, set-off times, and Markov sequence probabilities. Both the young and older adults typically fixated the actor when they were present, which has previously been shown to be detrimental to postural control. The older adults also adopted a more cautious approach by fixating regions on the ground initially, and for longer, before looking to their direction heading. Although the young and older adults took longer to set-off walking when given the option to plan, this was not reflected in altered gaze behaviour. These findings reflect typical laboratory results, which have been associated with factors such as reduced visuospatial memory, slowed visual processing times, and fear and anxiety about falling. Future studies should seek to examine older adults' natural gaze behaviour during locomotion over more complex real-world terrain.

Keywords: Elderly, Eye tracking, Older adults, Saccadic, Smooth pursuit, Visual input, Walking balance

1 INTRODUCTION

Vision plays several important roles for successful locomotion. It enables pre-planning for upcoming movements, such as a route to an intended destination (Patla, 1997), or a foot-placement location (Patla and Vickers, 2003). It facilitates online postural adaptations, for example, modifying swing limb trajectory to accommodate for changing terrain (Hollands et al., 1995), and it provides a useful means to estimate self-motion, which is important for control of balance (Logan et al., 2010) and direction heading (Warren et al., 2001).

Visual sensing of the world and self-motion within it occurs at the retina, where patterns of light reflected off structures in the environment are detected (Kowler, 2011). The centre of the retina – the 'fovea' – is the region with the highest visual acuity, and during locomotion, this is typically directed 'overtly' to various regions of the environment to extract information relevant to task demands. These can include predictive footfall locations around one or two steps ahead (Paquette and Vallis, 2010), potential hazards and obstacles (Chapman and Hollands, 2006), and often toward a direction heading (Higuchi, 2013). In addition, attention can be directed 'covertly' to features in the periphery of vision, such as trip hazards, without the need for reorientations of gaze (Marigold and Patla, 2008). Visual self-motion detection is facilitated, in part, by 'retinal flow'. This refers to a change in patterns of light intensities at the retina caused by relative motion between an observer and their environment, about a point of central observation. Forward motion, for example, would generate an expanding flow emanating from the centre of vision (Gibson, 1950). The central nervous system (CNS) can use this to estimate shifts in body position and initiate postural adjustments (Guerraz and Bronstein, 2008).

We recently demonstrated a unique interplay between the region/object of foveal fixation and visually derived estimates of self-motion. When young and older participants visually tracked an oscillating computer generated target (Thomas et al., 2017), and a standing or walking actor in a real-world environment (in review), they exhibited increased medial/lateral trunk movement and step-width variability – factors which reflect decreased stability. We suggested the visual tasks generated more retinal blur surrounding the foveal region. This would have been caused by the smooth pursuit eye movement to track the moving target and the walking actor, which would also complicate retinal flow due to the rotational eye movement, or by greater convergence to focus on the stationary actor when compared to the background. This likely made it more difficult to determine translational trunk movements with vision, thus reducing the accuracy of visual postural corrections. The findings had important implications for elders' postural control in that any negative change to balance is undesirable in older populations (Ambrose et al., 2013).

In these studies, the participants were instructed where to look, which was necessary to isolate the effects of the visual tasks. What is not known is whether young or older adults would adopt similar detrimental gaze behaviour during free viewing. Further investigation of natural gaze behaviour in a similar real-world environment, will elucidate to whether the decreased balance is transferable to natural gaze patterns. Another reason to assess older adults natural gaze behaviour in such a context is that there are actually very limited data obtained from walking elders in real-world environments. Previous laboratory-based investigations have revealed older adults to look lower in the visual field, and to rely on foveal vision more to acquire relevant information (Itoh and Fukuda, 2002). This has been linked to reduced visuospatial memory, slowed visual information processing, and fear and anxiety about falling (Uiga et al., 2015; Young et al., 2012). It is not known, however, if these results are reflected in real-world conditions, since gaze behaviour has been shown to differ between the laboratory and the real world (Dowiasch et al., 2015; Foulsham et al., 2011; Zeuwts et al., 2016). Further investigations are important to bridge the gap between the lab and the real world.

Another factor which has been relatively little explored in the real world is the role of visual pre-planning. If participants are allowed to pre-scan the environment prior to gait initiation, it would presumably allow more time to understand visuospatial relationships. Therefore, gaze behaviour might differ to that when instructed to walk straight away with no prior view. This may also be more profound in older adults, since elders typically have slowed visual information processing times (Uiga et al., 2015). However, it is currently not known if given the opportunity, elders take longer to pre-scan the environment or change their gaze behaviour as opposed to being instructed to walk straight away. Laboratory-based studies which have explored gaze behaviour in elders during locomotion, for example, have instructed the participants to look straight ahead until they set off walking, after which they are free to look where they want (Richard P. Di Fabio, 2001), or have had their view of the walkway obstructed completely prior to trial commencement (Zietz and Hollands, 2009). In the present experiment, it would be beneficial to implement pre-planning and no planning conditions. This will not only address concerns of internal and external validity (i.e. constraining participants to either condition may affect their natural gaze behaviour, or at the very least only tell half of the story), but will further understanding of the role of visual pre-planning on gaze characteristics.

Finally, investigations of gaze during locomotion typically utilise metrics such as frequency and duration of fixations at specific regions of interest (ROI) (Foulsham et al., 2011). Although this can provide useful information about where participants were looking and for how long, it cannot objectively describe the sequence of events, particular with multiple participants. A possible approach to address this, which is used in other areas of vision research including facial recognition (Boccignone, 2015) and driving (Underwood et al., 2005), is Markov sequence analysis. This considers each visual scan path (i.e. sequence of fixations at each ROI) as a deliberate sequential process which unfolds over time, and can provide an objective overview of how likely the participants were to fixate a certain ROI first, and how likely they were to transfer their gaze between ROIs (Boccignone, 2015). Another advantage of this method is that multiple scan paths can be modelled together, which is useful when comparing data from two groups, e.g. young and older adults (Coutrot et al., 2017). Such an approach, although not previously implemented during locomotion, will provide a richer understanding of natural gaze behaviour.

To these ends, the present study assessed gaze behaviour during free-viewing in young and older adults walking into a real-world waiting room environment with the option to plan before entry, or walking straight in. Replicating the conditions of our previous study inside the waiting room (in review), the participants were presented with another standing or walking actor, or a room absent of the actor. The aims were to: 1) determine if young and older adults fixate the actor, which can equate to an increased fall risk; 2) examine age-related changes to visual behaviour observed in previous laboratory contexts in the real world; 3) uncover potential differences in strategies when given the option to pre-plan a route into the room; 4) probe visual behaviour in a novel way by implementing Markov sequence analysis.

2 MATERIAL & METHODS

2.1 Participants

Eleven young (mean±SD: age: 23.4±3.2 years, height: 1.71±0.07 m, mass: 70.8±10.3 kg) and 11 older (mean±SD: age: 70.9±5.2 years, height: 1.62±0.05 m, mass: 63.7±9.8 kg) healthy females participated in the investigation. The elders were interviewed initially by telephone to determine eligibility and had no known musculoskeletal or neurophysiological conditions which could negatively affect normal locomotion or gaze strategies specific to that age category. All participants had an uncorrected visual acuity (without glasses or contact lenses) ≥20/100 and were able to ambulate in the community without visual correction. This study was carried out in accordance with the recommendations of the University of Cumbria's ethical principles and guidelines for research involving human subjects with written informed consent from all participants. All participants gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the University of Cumbria's Research Committee.

2.2 Experimental environment

Testing was carried out on flat ground in a waiting room (Fig. 1). A custom-made contact mat was used to record set-off times of each participant (see Experimental protocol). The entrance to the waiting room was a well-lit hallway, which was separated from the room by opaque sliding doors. Similar to our previous study (in review), an actor was trained to follow standardised pseudo-random behaviour patterns inside the waiting room, e.g. standing still or walking a pre-defined trajectory (see Experimental protocol), reflecting what might occur in a typical waiting room, e.g. a doctor greeting a patient. Participants wore eye tracking glasses (Tobii Glasses 2 Eye Tracker, Tobii Technology, Danderyd, Sweden) which have a one point calibration procedure, autoparallax compensation and slippage compensation allowing for persistent calibration throughout testing.

2.3 Experimental protocol

The participants stood at a start position on the contact mat, which was located behind the sliding doors (Fig. 1). The sliding doors were shut before each trial so the participants could not see into the waiting room. The doors then opened signalling the trial to commence. Following this, the participants walked into the room at a self-selected pace until verbally informed to stop when they reached a 4 m threshold only known to the researcher. Two planning conditions were implemented: PLAN and No PLAN. For PLAN, the participants were instructed before the trial started to enter the room when they felt comfortable doing so after the doors had opened. For No PLAN, they were instructed before the trial started to enter the room as soon as the doors had opened. The time from the start of the door opening to first heel off (i.e. gait initiation) was recorded with the contact mat. Three conditions were implemented inside the waiting room: empty room (ABSENT), stationary actor (STAT) and walking actor (WALK). For ABSENT, the waiting room was absent of the actor. For STAT, the actor stood stationary in the centre of the participants' field of vision. For WALK, the actor walked horizontally across the room in the actor area for 1.5 m before standing still. The direction was random on each trial. The actor set off walking as soon as the doors had opened in all conditions.

One trial for each visual and planning condition was implemented, which totalled 6 trials per participant. The trials were performed randomly with around 30s of rest between them. No instructions or cues as to where to look were given to the participants.

2.4 Data analysis

Gaze data sampled at 50 Hz were filtered with the Tobii I-VT fixation filter to yield gaze fixations (window length 20 ms; threshold 30°/s). 2D video sequences consisting of the participants' point of view during walking in each trial superimposed with their gaze fixations were exported and analysed offline in custom-made software (Video Feature Logger; github.com/N-M-T/FLo). Five ROIs within the room typically fixated by the participants were identified by watching several videos from the young and older participants. These included the background wall closely surrounding the actor, the actor, the near and far path (near was defined as <4 m) and regions in the surrounding visual area, such as the ceiling, chairs, and walls running adjacent to the room. The duration spent fixating each ROI was then expressed as a percentage of total fixation time.

2.5 Statistical analysis

To examine the effects of ageing on fixation behaviour, a 2-way robust mixed analysis of variance (ANOVA) was implemented, with age (Young$\times$Older) and ROI ($\times$5) considered as between and within factors, respectively. The same model was applied to examine the effects of planning on fixation behaviour, and again to assess the effects of planning on set-off times, with planning (PLAN$\times$NO PLAN) considered as a within factor. Post-hoc analyses were Wilcoxon signed-rank tests with Bonferroni corrections. Separate analyses were conducted for each room condition (ABSENT, STAT and WALK) with only 4 ROIs considered in ABSENT due to no actor being present. All statistical analysis were performed in the R software package.

2.6 Markov sequence modelling

When considering visual scanpaths as Markov processes, fixation locations must be defined as a 'states' in some context (Boccignone, 2015). Previous studies have taken a data-driven approach to learning states using methods such as the Variational Bayesian Framework for Gaussian mixture models (Coutrot et al., 2017). This can be beneficial for optimising the number of states where pre-defined regions of interest are unclear. E.g. examining faces. In the present study, individual differences in head movement and walking speed, and a lower resolution of the visual scene (participant walking through a room as opposed to a single close-up image of a face) negate the applicability of such methods. Instead, each ROI identified from the video sequences was defined as a state, which provides a reasonable compromise between a priori definitions, e.g. dividing a face into equal portions, and objective learning.

Probability distributions over the initial ROI fixations (reflecting where the participants looked first) and probabilities of transfers between ROIs (reflecting a saccade) were calculated from the young and older adults scan paths using the seqHMM package in R. This resulted in one transfer probability matrix and one set of initial probabilities for each age group (young and old). Then, all of the observed probabilities (initial fixation and transfer probabilities) were compared to a Gaussian distribution with a binomial test (Underwood et al., 2005). The Gaussian distribution would indicate a random probability of initial fixation or shifting gaze to any ROI to be 20% during STAT and WALK (as there are five ROIs in this condition) and 25% during ABSENT (as there are four ROIs in this condition). Anything significantly different from this indicates a deliberate initial fixation or shift of gaze as opposed to a stratified random sampling process. Probabilities which were significant but very small $<5\%$ were not presented since they represent infrequent fixations (Underwood et al., 2005).

In order to assess differences between young and older adults, the probabilities from each group (young and older) in each condition (ABSENT, STAT and WALK) were compared with the methods of Kullback et al. (1962) using the markovchain package in R. This approach statistically verifies whether the two sequences belong to the same unknown discrete model. If they do not, they can be considered as describing significantly different processes.

3 RESULTS

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during STAT is presented in Fig. 2. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{4,80}$=94.45, p<0.001) and a significant interaction effect between age and ROI ($F_{4,80}$=2.84, p=0.045). Post-hoc analyses revealed more time spent looking at the actor than the background (p<0.001), far path (p<0.001), near path (p<0.001) and periphery (p<0.001). More time spent looking at the background than the periphery (p=0.033), more time spent looking at the far path than the periphery (p<0.001) and the near path than the periphery (p=0.008). Examination of the interaction plot showed the young adults tended to look more at the actor than the elders, whilst the elders tended to look more at the near path than the young adults.

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during WALK is presented in Fig. 3. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{4,80}$=16.63, p<0.001) and a significant interaction effect between age and ROI ($F_{4,80}$= 4.34, p=0.008). In contrast to STAT, gaze was more evenly distributed across the ROIs. Post-hoc analyses revealed more time spent looking at the actor than the periphery (p<0.001). More time spent looking at the background than the near path (p<0.001) and the periphery (p<0.001), and more time spent looking at the far path than the near path (p<0.001) and the periphery (p<0.001). Analysis of the interaction plot showed that the young adults tended to look more at the background than the elders, whilst the elders looked more at the far path than the young adults. The young adults also tended to look more at the actor than the elders, whilst the elders looked more at the near path than the young adults.

The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during ABSENT is presented in Fig. 4. There was no main effect of planning condition. There was, however, a significant main effect of ROI ($F_{3,60}$=29.96, p<0.001) and a significant interaction effect between age and ROI ($F_{3,60}$=7.14, p¡0.001). Post-hoc analyses revealed more time spent looking at the background than the near path (p<0.001) and the periphery (p<0.001), and more time spent looking at the far path than the near path (p<0.001) and the periphery (p<0.001). Examination of the interaction plot showed the young adults tended to look more at the background than the elders, whilst the elders tended to look more at the far path than the young adults.

Participant set-off times for PLAN and NO PLAN during STAT, WALK and ABSENT are presented in Fig. 5. There were significant effects of planning condition for STAT ($F_{1,20}$=15.69, p=0.003), WALK ($F_{1,20}$=8.42, p=0.019) and ABSENT ($F_{1,20}$=19.57, p=0.010), with longer set-off times during PLAN compared to NO PLAN. There were no main effects of age, or any interaction effects between planning condition and age for any of the three conditions.

Markov sequence analyses were directed at age groups as opposed to planning conditions since this is where the time-integrated analysis highlighted significant differences. Sequence analyses were calculated for some of the planning data, but as expected, the probabilities were relatively homogeneous across planning conditions. Most infrequent probabilities under the 5% threshold were also very low in all of the conditions, e.g. <0.1%.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during STAT are presented in Fig. 6. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the actor first. In contrast, the older adults were more likely to fixate the near path first. The young adults showed significant transfers from the far path, the background and the periphery to the actor, and from the near path to the far path. The older adults showed significant transfers from the near path and the background to the actor, and from the near path to the far path.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during WALK are presented in Fig. 7. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the actor first. In contrast, the older adults were more likely to fixate the near path or the actor first. The young adults showed significant transfers from the far path, the actor and the near path to the background, from the near path to the far path, and from the periphery to the background. The older adults showed significant transfers from the near path to the far path, and from the periphery to the background, the far path, and the actor.

Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs during ABSENT are presented in Fig. 8. The young and older adults' data were confirmed to describe significantly different processes (p<0.001). The young adults were more likely to fixate the far path and the background first. In contrast, the older adults were more likely to fixate the near path first. The young adults showed significant transfers from the far path, the near path and the periphery to the background. The older adults showed significant transfers from the near path and the periphery to the far path.

4 DISCUSSION

The first aim of the present study was to examine whether older adults adopted similar gaze behaviour to that in our previous investigation (in review) – that is, fixations of the actor. During STAT, the elders fixated the actor for over 70% of fixation time. The results from our previous study in this particular condition are, therefore, transferable to natural gaze patterns. During WALK, however, total fixation time is more evenly spread across the background and the far path. It is thus likely as the actor walked out of the centre of the participants' field of vision, the participants stopped fixated the actor and carried on looking ahead. This means the more detrimental gaze behaviour was not continued.

There was also a general trend for both the young and older adults to fixate regions in the direction heading for the most time. These correspond to the background, the far path and even the actor when the actor was in the centre of the participants' field of vision. These results fall in line with previous laboratory-based studies, which show a bias of visual attention towards a direction heading (Higuchi, 2013), which is typically associated with the optic flow component of locomotor steering (Warren et al., 2001). This explains why the participants ignored the actor once the actor had left the participants' direction heading (the centre of the actor area). In addition to the heading direction, both the young and older participants fixated the near path. This finding is also similar to laboratory-based studies, where it was suggested that near path fixation was likely used to acquire information about the walkway, e.g. potential trip hazards or slippy surfaces (Uiga et al., 2015), making this the most likely explanation for the present findings.

Of particular interest from the present findings are the interaction effects, which begin to show differences in young and older adults' visual behaviour. For example, the young adults tended to look more at direction heading features, e.g. background and actor than the older adults, whilst the elders tended to look more at the ground (near path and far path) than the younger adults. These findings reflect typical behaviour in laboratory-based studies, where elders look lower in the visual field, possibly with greater head flexion (Maslivec et al., 2017), and has previously been related to things like reductions in visuospatial memory (Uiga et al., 2015). In effect, the present elders may have needed to fixate the floor for longer or more frequently to gather and retain sufficient information. Another factor might be that elders were less able to process peripheral visual information about the floor. Previous studies, for example, have shown older adults to rely more on foveal vision than covert attention (Itoh and Fukuda, 2002). Therefore, the present elders might have fixated the walkway for longer to ensure it was safe, rather than relying on peripheral detection of hazards. It may also be that the older adults were less confident about the floor being clear of obstacles, and they ultimately checked it more often regardless of actual threat perception. Previous studies have linked anxiety to longer obstacle fixations, for example, which certainly lends credence to that notion (Young and Mark Williams, 2015). These results suggest that, at least in our cohort of participants, gaze behaviour found in the laboratory during locomotion with actual body movements are reflected in the real-world.

Surprisingly, there was no effect of pre-planning on gaze behaviour. It may be that the cognitive visuospatial mapping demands were relatively low considering the flat and relatively easy to navigate ground in the waiting room. This was likely not challenging enough to warrant altered visual behaviour. It would be interesting to examine the role of visual pre-planning over more challenging terrain. Notwithstanding this, both the young and older adults took longer to set off when given the opportunity to plan as opposed to being instructed to enter the room as soon as the sliding doors had opened. This probably simply reflects the more natural behaviour when not 'rushed' to set-off walking.

The present study probed visual behaviour during locomotion in a unique way by considering the visual scan paths as Markov sequences. The findings add a new perspective to the duration of fixation data. That is, the young adults were more likely to initially fixate direction heading regions first (such as the actor and the background), whilst the older adults were more likely to fixate the path first, and particularly the near path. This trend was the same across all conditions with the exception of WALK, where there is a probability for the elders to look at the actor first as well. Subsequently, there are interesting transfers of gaze from these initial fixation locations. Overall, the older adults were typically more likely to look from the path to their direction heading, whilst younger adults from regions in their direction heading to others in their direction heading. In short, the older adults were more likely to adopt a cautious gaze strategy by checking the floor first before looking ahead. This may be due to some of the factors mentioned above, such as increased anxiety about the ground being clear, or more reliance on foveal vision. It is probably not due to reduced visuospatial memory, since the initial fixation, being the first, cannot be associated with memory in that context.

There are some limitations with the Markov sequence methods adopted in the present investigation, in that due to the combination of only modelling 2 fixation scan paths, some information is inevitably lost. For example, during WALK, the young adults must have transferred their gaze to the far path since there is a transfer from this location, although there is no direct transfer from the actor (the initial fixation location in most participants) to the far path. In these circumstances, we can make some inferences. E.g. some participants may have initially fixated the near path, and some the actor. Then those two groups fixated the far path together, and continued to transfer from the far path to the background. This, however, becomes a rather drawn out process, and is mostly speculative.

When putting the present findings in the context of fall risk, the first thing to consider is whether or not there was risky or maladaptive gaze behaviour. In both STAT and WALK, the older adults fixated the actor for around 70% and 20% of total fixation time, respectively. Since fixating a standing and walking actor has recently been shown to be detrimental to balance (in review), this fixation behaviour can considered undesirable, especially when the moving object is of no consequence to the navigation route. For the initial and longer floor fixations exhibited by the older adults, it is difficult to say whether this is negative. It may actually be beneficial for them to check the floor first for hazards, particularly if they are less able to correct a trip or a fall. In the context of planning, we can only suggest it is beneficial to visually 'absorb' the specifics of an environment. Even though gaze behaviour was the same across planning conditions in the present investigation, the environment was relatively easy to navigate. More challenging surfaces may require more planning time, and so it is likely more optimal not to rush into any environment. This is supported by the fact both young and older adults took longer to enter the room when given the option to plan, which reflects more natural behaviour. One useful component of the present results is that the participants ignored the actor after they had left the heading direction line of sight. This means the detrimental gaze behaviour was not continued. Aside from thinking about training older adults to fixate other stationary locations in a direction heading, as opposed to other people, a very simple solution would be to consider where to stand when greeting older adults in a waiting room. Put simply, distracting an elder so they look up to greet you would, a) reduce the likelihood they will initially floor fixate to check for slip/trip hazards, b) reduce the efficacy of visual balance control, and both of these would lead to increased fall risk.

5 DISCLOSURE/CONFLICT-OF-INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 AUTHOR CONTRIBUTIONS

NT conceived the investigation, led the data collection and analysis and interpretation of the results, and drafted the first manuscript. TB, TD and SD contributed to all aspects of the investigation, including methodological design, data collection and analysis, interpretation of the results, and revision of the manuscript for important intellectual content. All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

7 ACKNOWLEDGEMENTS

This research was funded by the Dowager Countess Eleanor Peel Trust.

REFERENCES

Ambrose, A. F., Paul, G., and Hausdorff, J. M. (2013). Risk factors for falls among older adults: a review of the literature. *Maturitas* 75, 51–61. doi:10.1016/j.maturitas.2013.02.009

Boccignone, G. (2015). Advanced statistical methods for eye movement analysis and modeling: A gentle introduction. *arXiv preprint arXiv:1506.07194*

Chapman, G. and Hollands, M. (2006). Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion. *Gait & Posture* 24, 288–294. doi:10.1016/j.gaitpost.2005.10.002

Coutrot, A., Hsiao, J. H., and Chan, A. B. (2017). Scanpath modeling and classification with hidden Markov models. *Behavior Research Methods* doi:10.3758/s13428-017-0876-8

Dowiasch, S., Marx, S., Einhuser, W., and Bremmer, F. (2015). Effects of aging on eye movements in the real world. *Frontiers in Human Neuroscience* 9, 46. doi:10.3389/fnhum.2015.00046

Foulsham, T., Walker, E., and Kingstone, A. (2011). The where, what and when of gaze allocation in the lab and the natural environment. *Vision Research* 51, 1920 – 1931. doi:https://doi.org/10.1016/j.visres.2011.07.002

Gibson, J. J. (1950). *The perception of the visual world.* (Boston: Houghton Mifflin)

Guerraz, M. and Bronstein, A. (2008). Ocular versus extraocular control of posture and equilibrium. *Neurophysiologie Clinique/Clinical Neurophysiology* 38, 391–398. doi:10.1016/j.neucli.2008.09.007

Higuchi, T. (2013). Visuomotor Control of Human Adaptive Locomotion: Understanding the Anticipatory Nature. *Frontiers in Psychology* 4, 277. doi:10.3389/fpsyg.2013.00277

Hollands, M. A., Marple-Horvat, D. E., Henkes, S., and Rowan, A. K. (1995). Human eye movements during visually guided stepping. *Journal of Motor Behavior* 27, 155–163. doi:10.1080/00222895.1995.9941707

Itoh, N. and Fukuda, T. (2002). Comparative Study of Eye Movements in Extent of Central and Peripheral Vision and Use by Young and Elderly Walkers. *Perceptual and Motor Skills* 94, 1283–1291. doi:10.2466/pms.2002.94.3c.1283

Kowler, E. (2011). Eye movements: The past 25years. *Vision research* 51, 1457–1483. doi:10.1016/j.visres.2010.12.014

Kullback, S., Kupperman, M., and Ku, H. H. (1962). Tests for Contingency Tables and Marltov Chains. *Technometrics* 4, 573–608. doi:10.1080/00401706.1962.10490041

Logan, D., Kiemel, T., Dominici, N., Cappellini, G., Ivanenko, Y., Lacquaniti, F., et al. (2010). The many roles of vision during walking. *Experimental brain research* 206, 337–350. doi:10.1007/s00221-010-2414-0

Marigold, D. S. and Patla, A. E. (2008). Visual information from the lower visual field is important for walking across multi-surface terrain. *Experimental Brain Research* 188, 23–31. doi:10.1007/s00221-008-1335-7

Maslivec, A., Bampouras, T. M., and Dewhurst, S. (2017). Head flexion and different walking speeds do not affect gait stability in older females. *Human Movement Science* 55, 87–93. doi:10.1016/j.humov.2017.08.001

Paquette, M. R. and Vallis, L. A. (2010). Age-related kinematic changes in late visual-cueing during obstacle circumvention. *Experimental Brain Research* 203, 563–574. doi:10.1007/s00221-010-2263-x

Patla, A. E. (1997). Understanding the roles of vision in the control of human locomotion. *Gait & Posture* 5, 54–69. doi:10.1016/S0966-6362(96)01109-5

Patla, A. E. and Vickers, J. N. (2003). How far ahead do we look when required to step on specific locations in the travel path during locomotion? *Experimental brain research* 148, 133–138. doi:10.1007/s00221-002-1246-y

Richard P. Di Fabio, J. F. G. S. P., Alongkot Emasithi (2001). Suppression of the vertical vestibulo-ocular reflex in older persons at risk of falling. *Acta Oto-Laryngologica* 121, 707–714. doi:10.1080/00016480152583656

Thomas, N. M., Dewhurst, S., Bampouras, T. M., Donovan, T., Macaluso, A., and Vannozzi, G. (2017). Smooth pursuits decrease balance control during locomotion in young and older healthy females. *Experimental Brain Research* , 1–8doi:10.1007/s00221-017-4996-2

Uiga, L., Cheng, K. C., Wilson, M. R., Masters, R. S., and Capio, C. M. (2015). Acquiring visual information for locomotion by older adults: A systematic review. *Behavior, Energy Overload and Brain Health: From Science to Society* 20, 24–34. doi:10.1016/j.arr.2014.12.005

Underwood, G., Phelps, N., Wright, C., van Loon, E., and Galpin, A. (2005). Eye fixation scanpaths of younger and older drivers in a hazard perception task. *Ophthalmic & physiological optics : the journal of the British College of Ophthalmic Opticians (Optometrists)* 25, 346–356. doi:10.1111/j.1475-1313.2005.00290.x

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., and Sahuc, S. (2001). Optic flow is used to control human walking. *Nat Neurosci* 4, 213–216. doi:10.1038/84054

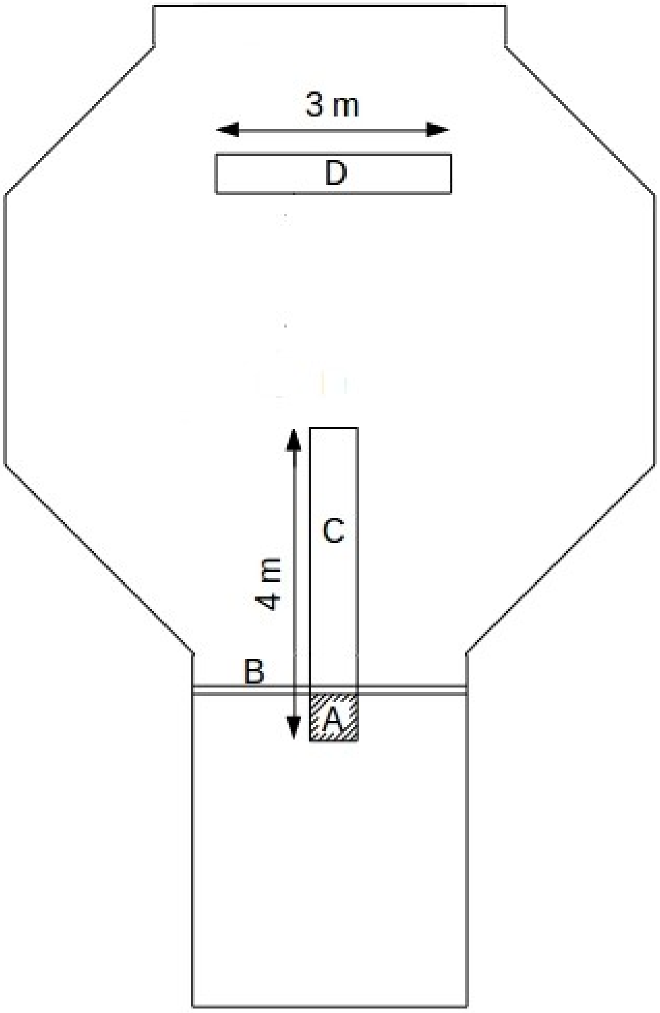


Figure 1: A schematic diagram of the experimental environment. A: participants' starting position; B: sliding doors; C: walkway; and D: actor area. All distances are to scale. Note that the walkway outlines were not visible to the participants, and only verbal cues were used to terminate the participants' gait.

Young, W. R. and Mark Williams, A. (2015). How fear of falling can increase fall-risk in older adults: Applying psychological theory to practical observations. *Gait & Posture* 41, 7–12. doi:10.1016/j.gaitpost.2014.09.006

Young, W. R., Wing, A. M., and Hollands, M. A. (2012). Influences of State Anxiety on Gaze Behavior and Stepping Accuracy in Older Adults During Adaptive Locomotion. *The Journals of Gerontology: Series B* 67B, 43–51. doi:10.1093/geronb/gbr074

Zeuwts, L., Vansteenkiste, P., Deconinck, F., van Maarseveen, M., Savelsbergh, G., Cardon, G., et al. (2016). Is gaze behaviour in a laboratory context similar to that in real-life? A study in bicyclists. *Transportation Research Part F: Traffic Psychology and Behaviour* 43, 131–140. doi:10.1016/j.trf.2016.10.010

Zietz, D. and Hollands, M. (2009). Gaze behavior of young and older adults during stair walking. *Journal of Motor Behavior* 41, 357–366. doi:10.3200/JMBR.41.4.357-366. PMID: 19508962

8 FIGURES

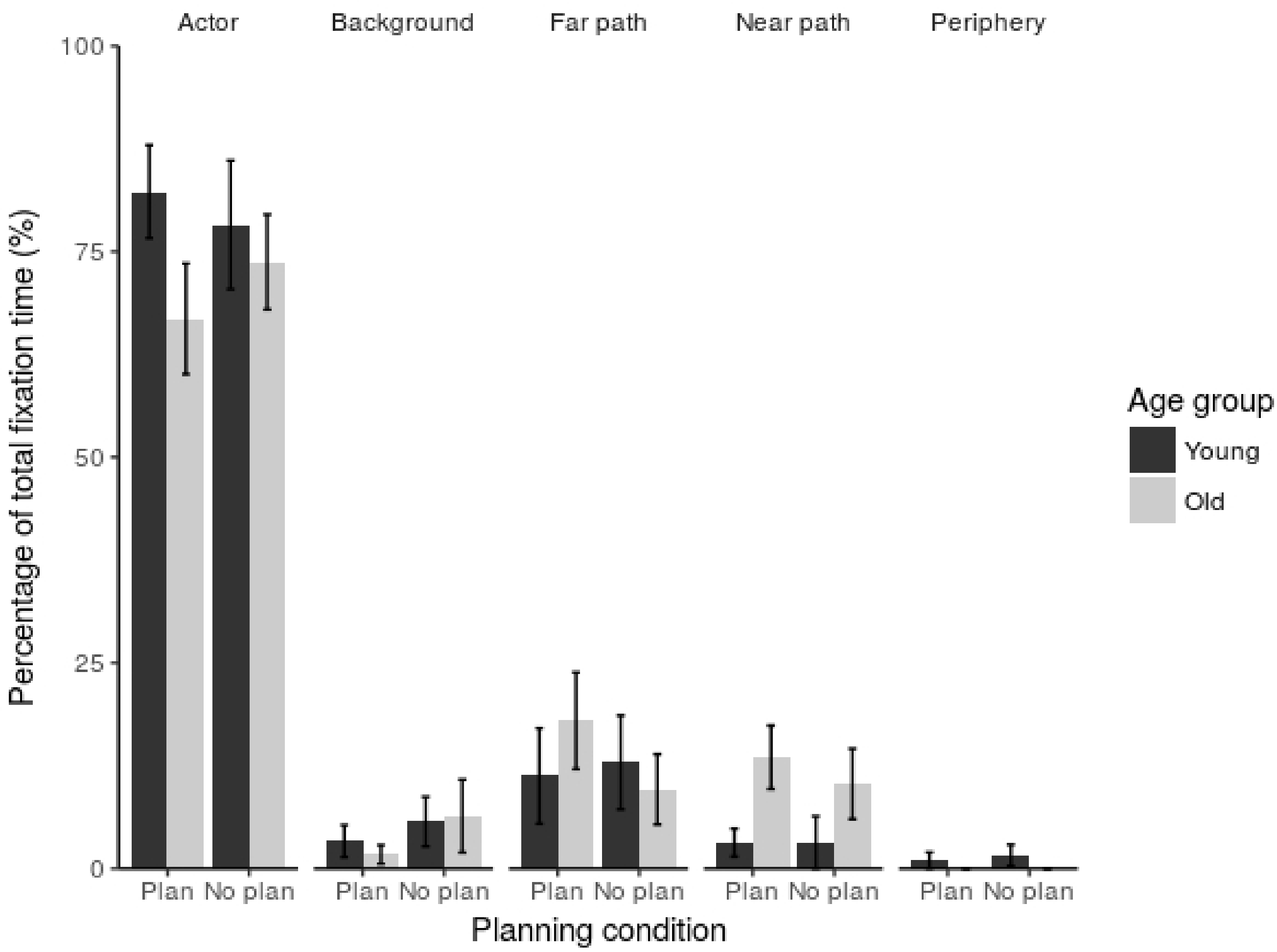


Figure 2: Duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during STAT(±SD) in young (n=11) and older (n=11) females. Significant differences are reported in the main text of the results section.

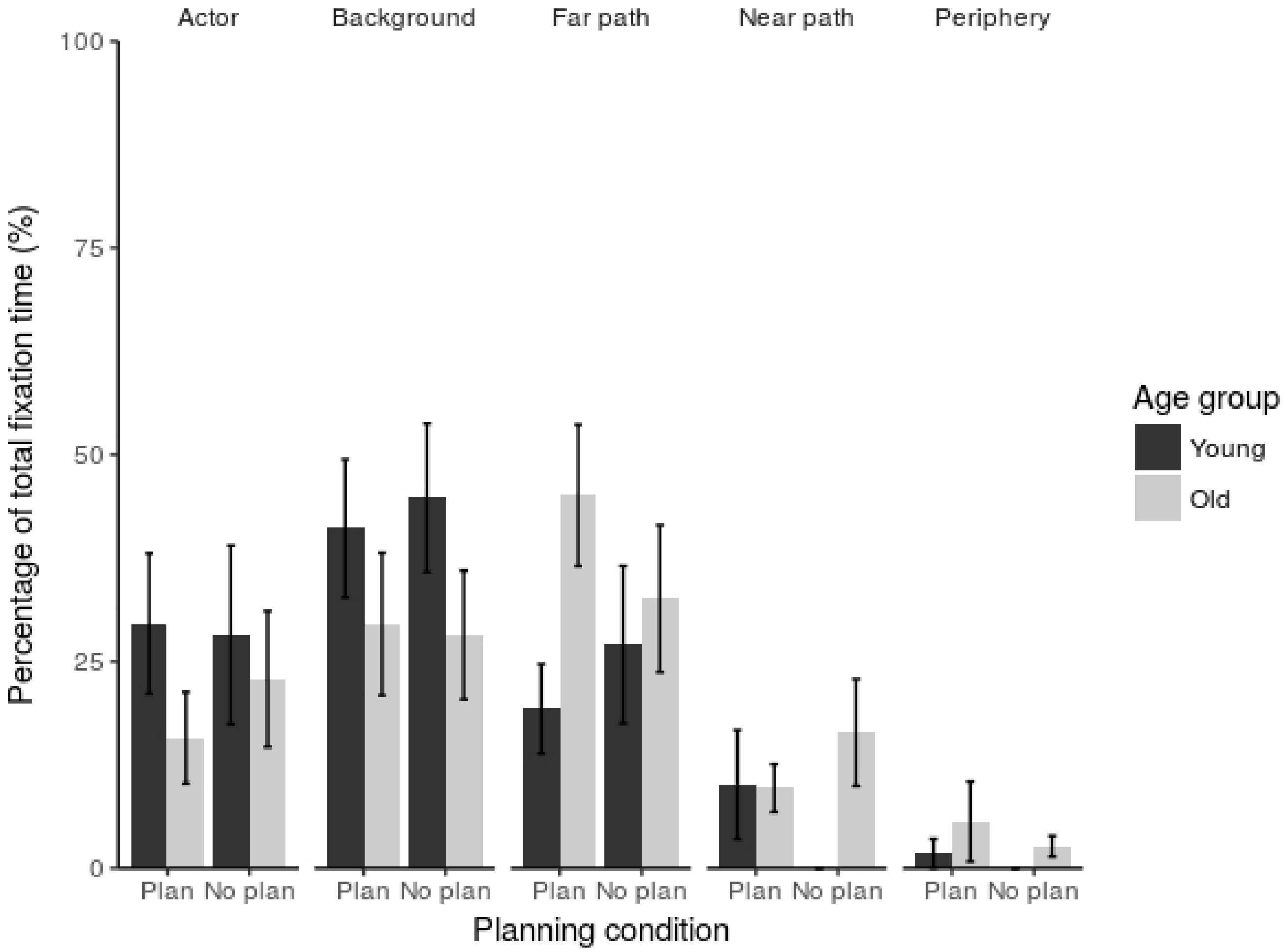


Figure 3: The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during WALK($\pm$SD) in young (n=11) and older (n=11) females. Significant differences are reported in the main text of the results section.

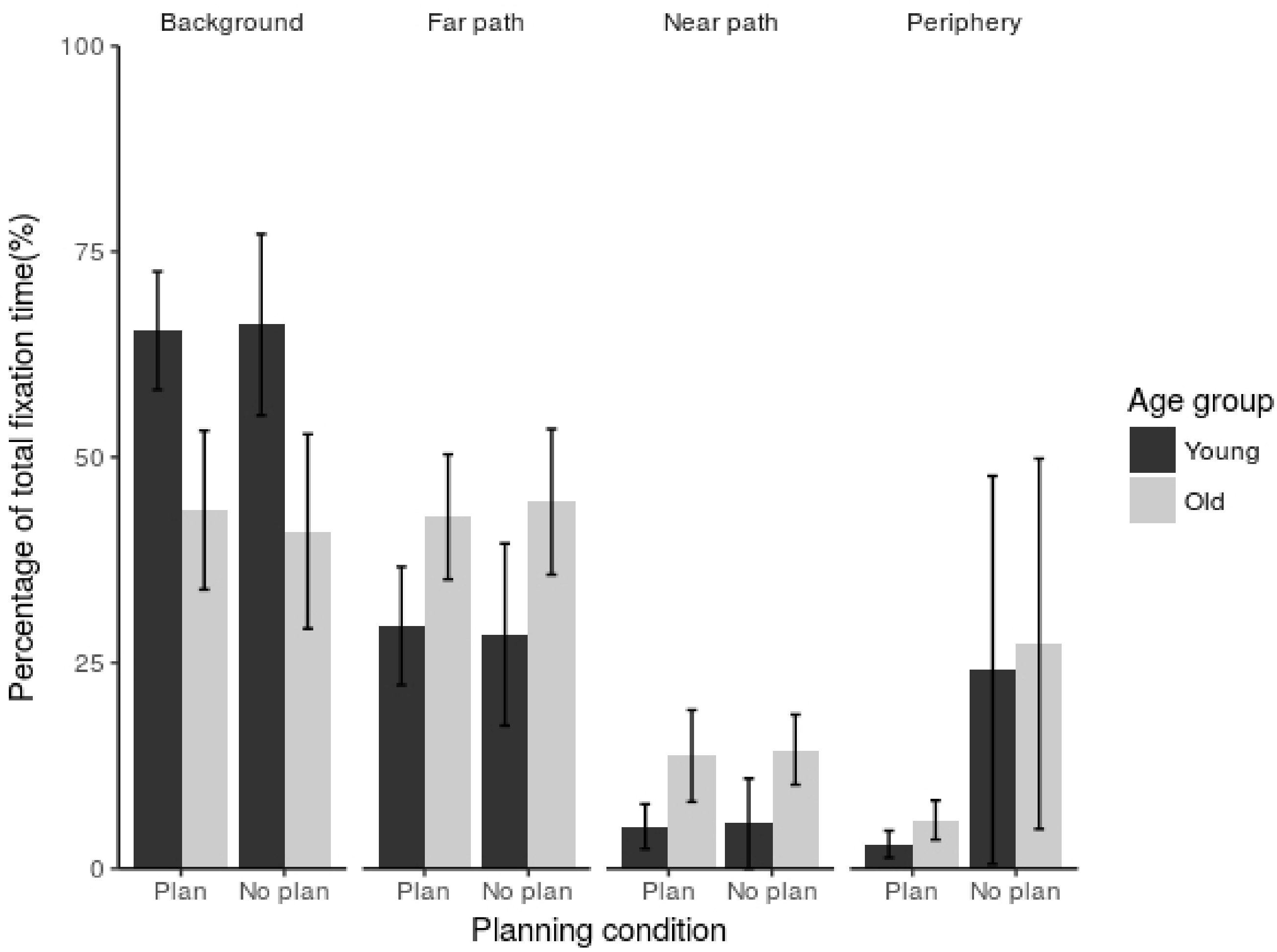


Figure 4: The duration of fixation on each ROI expressed as a percentage of total fixation time for PLAN and NO PLAN during ABSENT(±SD) in young (n=11) and older (n=11) females. Significant differences are reported in the main text of the results section.

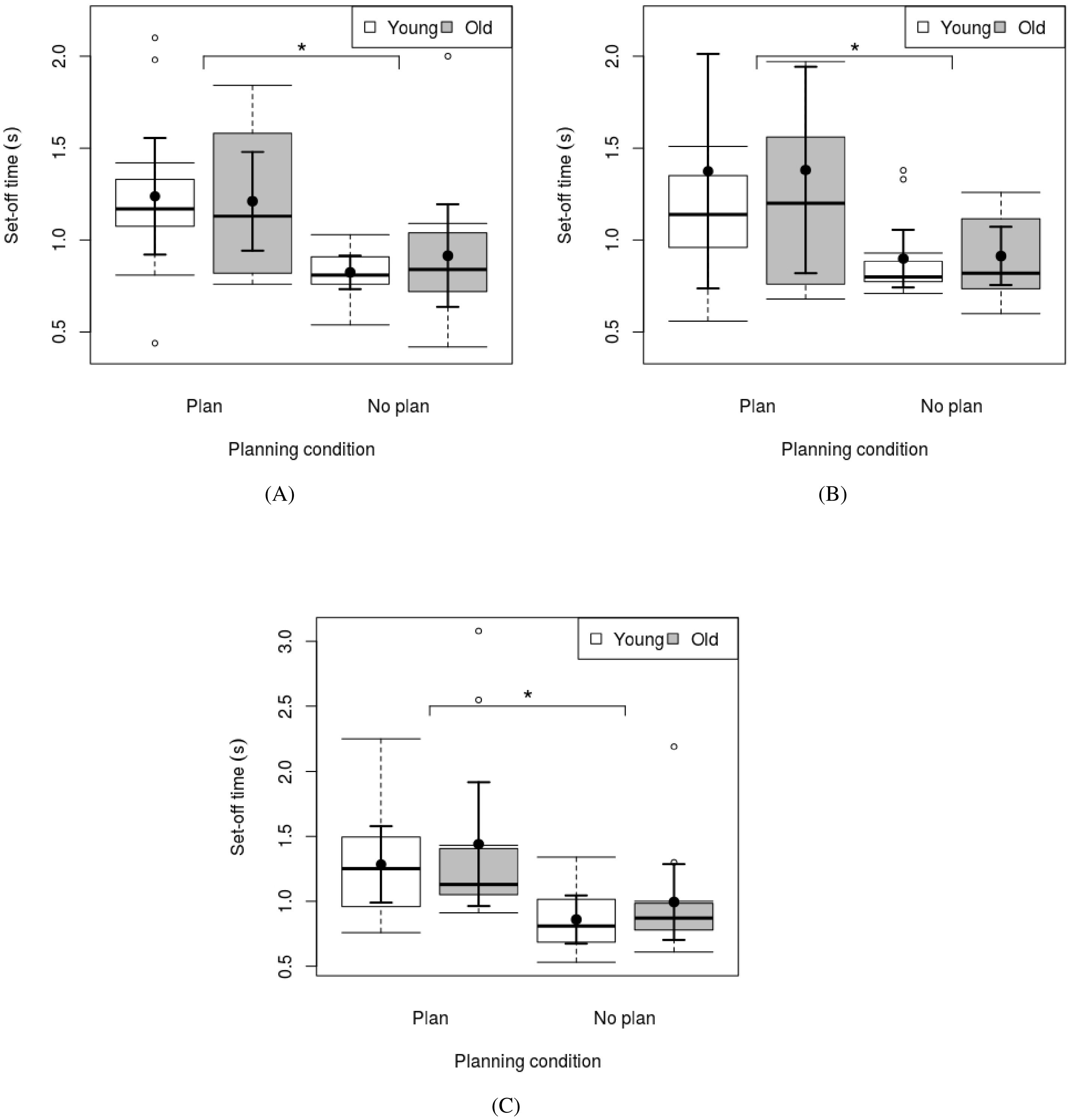
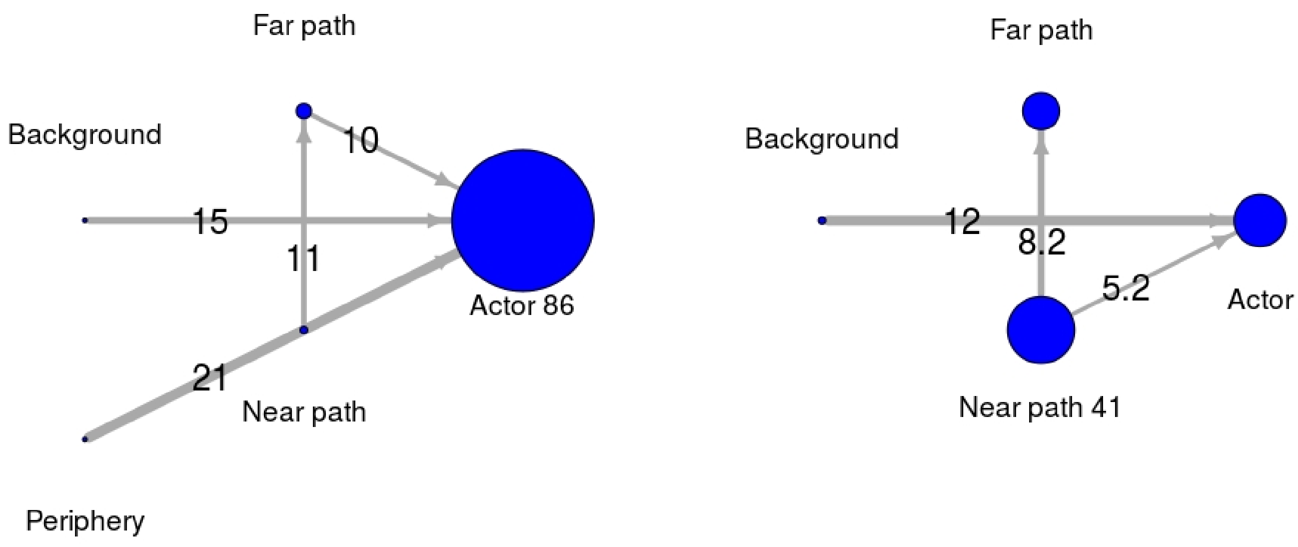
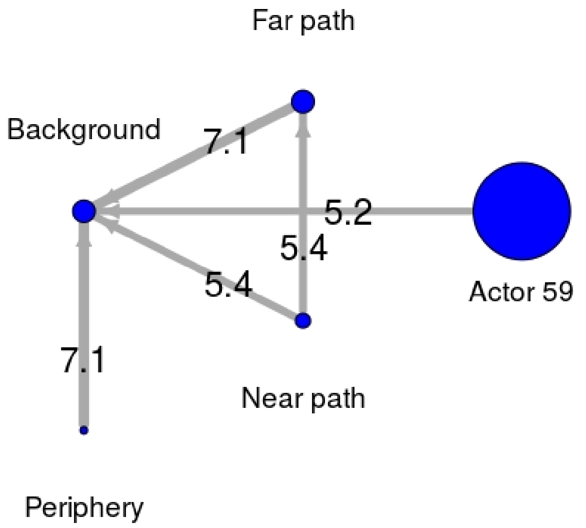


Figure 5: Participant set-off times for PLAN and NO PLAN during A: STAT, B: WALK and C: ABSENT, in young (n=11) and older (n=11) females. Data are presented as means and 95% confidence intervals in bold dots and bars, and medians and lower and upper quartiles with Tukey style whiskers (outliers plotted separately). *Significant difference between conditions.

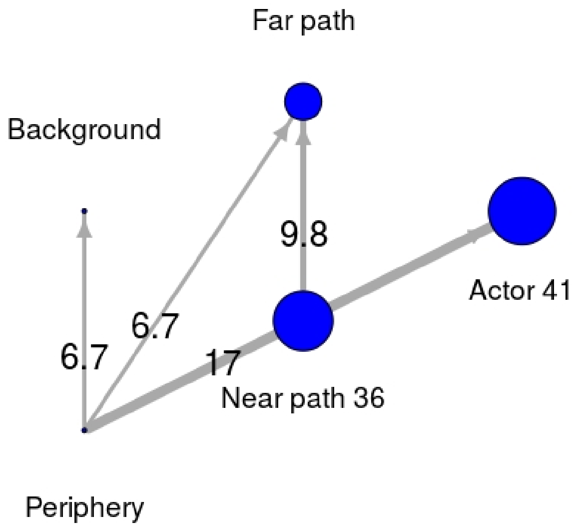


(A) (B)

Figure 6: Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs (presented as percentages) during STAT in A: young (n=11) and B: older (n=11) females. The blue circles denote initial fixations with the corresponding probability displayed underneath. The grey arrows denote transfers between ROIs with the corresponding probability superimposed. The size of the circles and arrows are relative to the magnitude of the probabilities. Only probabilities significantly different from a Gaussian distribution and $>5\%$ are displayed.

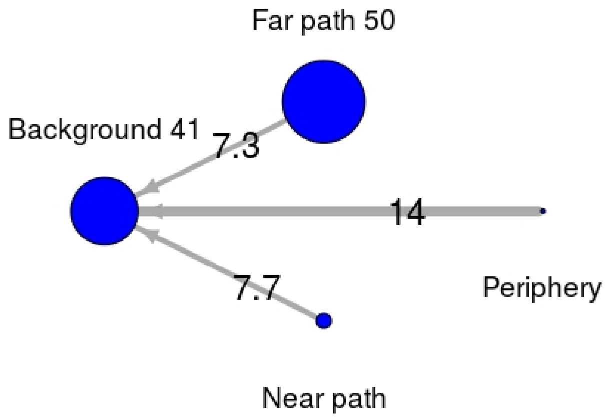


(A)

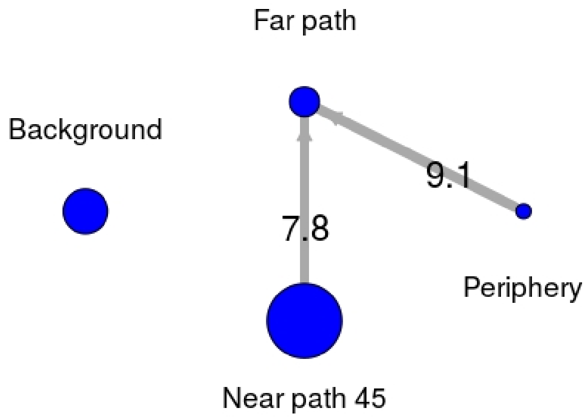


(B)

Figure 7: Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs (presented as percentages) during WALK in A: young (n=11) and B: older (n=11) females. The blue circles denote initial fixations with the corresponding probability displayed underneath. The grey arrows denote transfers between ROIs with the corresponding probability superimposed. The size of the circles and arrows are relative to the magnitude of the probabilities. Only probabilities significantly different from a Gaussian distribution and $>5\%$ are displayed.



(A)



(B)

Figure 8: Probability distributions over the initial ROI fixations and probabilities of transfers between ROIs (presented as percentages) during ABSENT in A: young (n=11) and B: older (n=11) females. The blue circles denote initial fixations with the corresponding probability displayed underneath. The grey arrows denote transfers between ROIs with the corresponding probability superimposed. The size of the circles and arrows are relative to the magnitude of the probabilities. Only probabilities significantly different from a Gaussian distribution and $>5\%$ are displayed.

Appendix E

Conference Slides

EYE MOVEMENTS AFFECT POSTURAL CONTROL IN YOUNG AND OLDER FEMALES

Thomas, N.M., Bampouras, T.M., Donovan, T., Dewhurst, S.
Active Ageing Research Group, UoC (Lancaster, UK)

Introduction

- Vision provides important information for postural control through retinal cues and extraocular position information
- There is growing evidence to suggest eye movements can affect postural control
- However, little research in older individuals

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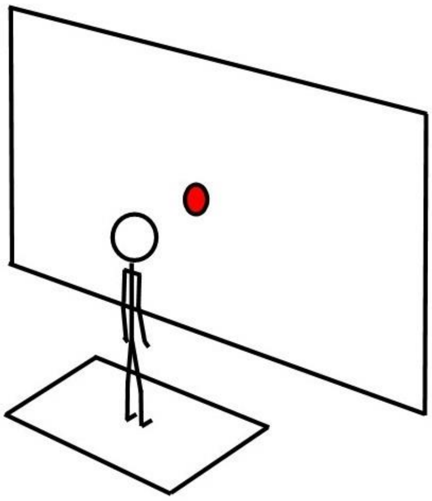
EYE MOVEMENTS AFFECT POSTURAL CONTROL IN YOUNG AND OLDER FEMALES

Thomas, N.M., Bampouras, T.M., Donovan, T., Dewhurst, S.
Active Ageing Research Group, UoC (Lancaster, UK)

Methods

- Stationary gaze fixations and smooth pursuit eye movements in 12 young (26.1±4.9) and 12 older (72.8±6.9 years) females



- Postural sway and gaze errors were compared within conditions and between age groups

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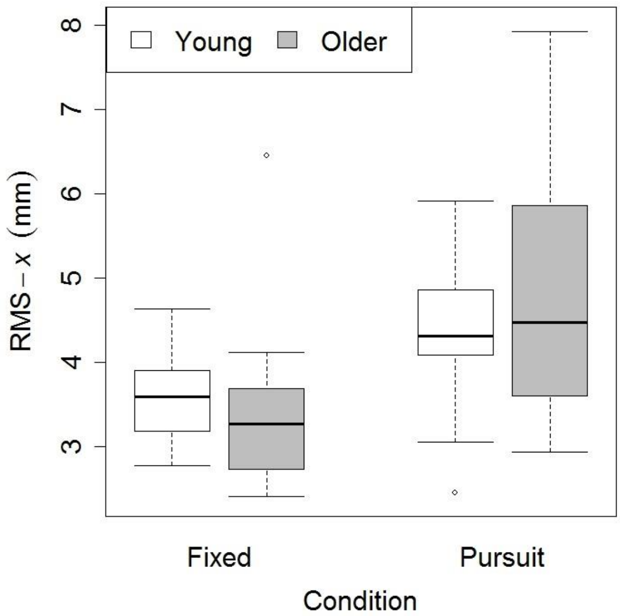
Results



- Smooth pursuits caused increases of postural sway ($p < 0.001$, 30.36%, g_{av} = 0.95)
- No change with age for postural sway or gaze errors

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EYE MOVEMENTS AFFECT POSTURAL CONTROL IN YOUNG AND OLDER FEMALES

Thomas, N.M., Bampouras, T.M., Donovan, T., Dewhurst, S.
Active Ageing Research Group, UoC (Lancaster, UK)

Discussion

- More challenging conditions for interpreting retinal flow and more complex extraocular signals are likely to have increased postural sway

- Declines in posture and gaze control during stance may not be a consequence of healthy ageing

- Future research is needed during locomotion

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Appendix F

Participant information sheet and consent forms

'Visual Contributions to Postural Stability during Stationary Target Fixations, and saccadic and Smooth Pursuit Eye Movements'

Participant Information Sheet

About the study

This research aims to investigate balance in response to a number of different visual scenes. The purpose is to develop our understanding of visual contributions to postural control.

Some questions you may have about the research project:

Why have you asked me to take part and what will I be required to do?
This investigation requires healthy male and female participants aged over 65 years who are free from balance disorders, special susceptibility to motion sickness, or degenerative eye conditions. You will be required to stand upright around 1 metre in front of a projection screen. You will then be asked to observe a total of 13 different visual scenes, including stationary and moving targets with different background environments. Your balance in response to these scenes will be assessed with a force platform, and your 'point of view' observations (where you are looking) will be monitored with eye tracking technology. You will be required to attend the 'Bishops Cross drama studio' at the University of Cumbria Lancaster campus once for testing, which will last around one hour.

What if I do not wish to take part or change my mind during the study?
Your participation in the study is entirely voluntary. You are free to withdraw from the study at any time without having to provide a reason for doing so.

What happens to the research data?
The raw data will be kept in secure storage until it is processed. The data will be purged of all details that could potentially identify you personally and only members of the research team will have access to it. You are free to ask to see your data to ensure you are happy it cannot be used to identify you in any way. Anonymous data will be preserved for no longer than necessary as per institutional guidelines, however you should be aware this period could be indefinite. If you choose to withdraw from the study before its completion date, your data will not be included in the findings of the study and will be securely destroyed. After the completion date, your anonymous data will remain as a part of the findings and cannot be withdrawn.

How will the research be reported?
The findings of the present investigation may be used in part or whole for presentations or publications. At request, you are eligible to receive an overview of the findings, and/or a copy of any presentations or publications produced. No individual will be identified or linked to the data.

How can I find out more information?

Please contact the researcher directly. Neil Thomas, Department of Medical and Sport Sciences, Active Ageing Research Group, Faculty of Health and Science, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. Neil.Thomas@Cumbria.ac.uk. 01524 590910. Alternatively you can send an email to the Active Ageing Research Group account for further communication activeageing@cumbria.ac.uk.

What if I want to complain about the research?
Initially you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint you should contact Professor Diane Cox, Director of Research Office, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. diane.cox@cumbria.ac.uk

'Visual Contributions to Postural Stability during Stationary Target Fixations, and saccadic and Smooth Pursuit Eye Movements'

Participant Information Sheet

About the study

This research aims to investigate balance in response to a number of different visual scenes. The purpose is to develop our understanding of visual contributions to postural control.

Some questions you may have about the research project:

Why have you asked me to take part and what will I be required to do?
This investigation requires healthy male and female participants aged 18 – 35 who are free from from balance disorders, special susceptibility to motion sickness, or degenerative eye conditions. You will be required to stand upright around 1 metre in front of a projection screen. You will then be asked to observe a total of 13 different visual scenes, including stationary and moving targets with different background environments. Your balance in response to these scenes will be assessed with a force platform, and your 'point of view' observations (where you are looking) will be monitored with eye tracking technology. You will be required to attend the 'Bishops Cross drama studio' at the University of Cumbria Lancaster campus once for testing, which will last around one hour.

What if I do not wish to take part or change my mind during the study?
Your participation in the study is entirely voluntary. You are free to withdraw from the study at any time without having to provide a reason for doing so.

What happens to the research data?
The raw data will be kept in secure storage until it is processed. The data will be purged of all details that could potentially identify you personally and only members of the research team will have access to it. You are free to ask to see your data to ensure you are happy it cannot be used to identify you in any way. Anonymous data will be preserved for no longer than necessary as per institutional guidelines, however you should be aware this period could be indefinite. If you choose to withdraw from the study before its completion date, your data will not be included in the findings of the study and will be securely destroyed. After the completion date, your anonymous data will remain as a part of the findings and cannot be withdrawn.

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Please contact the researcher directly. Neil Thomas, Department of Medical and Sport Sciences, Active Ageing Research Group, Faculty of Health and Science, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. Neil.Thomas@Cumbria.ac.uk. 01524 590910. Alternatively you can send an email to the Active Ageing Research Group account for further communication activeageing@cumbria.ac.uk.

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'Visual Contributions to Postural Stability during Stationary Target Fixations, and saccadic and Smooth Pursuit Eye Movements'

Participant Consent Form

Please answer the following questions by circling your responses:

Have you read and understood the information sheet about this study? YES NO

Have you been able to ask questions and had enough information? YES NO

Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO

Do you understand that video obtained from the eye tracking equipment will include your own field of vision and at no point will your face be recorded? YES NO

Your data will be anonymised before being analysed. Do you give permission for members of the research team to have access to your anonymised data? YES NO

Do you understand that anonymised data will be kept for no longer than necessary as per institutional guidelines, however, this period could be indefinite? YES NO

If you leave the study before its completion date, your data will be removed from the findings and securely destroyed.

Do you understand that after the completion date, your anonymised data will remain a part of the findings and cannot be withdrawn? YES NO

Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant:... **Date:**................

Name (block letters):..

Signature of researcher:... **Date:**................

Name (block letters):..

'The effects of eye movements on balance'
Participant Information Sheet

About the study

This research aims to investigate the effects of eye movements on balance. The purpose is to develop our understanding of visual contributions to postural control.

Some questions you may have about the research project:

Why have you asked me to take part and what will I be required to do?
This investigation requires healthy male and female participants between the ages of 18-35 and 60-90 years who are free from balance disorders, special susceptibility to motion sickness, or degenerative eye conditions. You will be required to walk along a 5-10 metre walkway 6 times (with breaks) whilst viewing stationary and moving targets on a projection screen located ahead of you. Your balance in response to these visual scenes (during walking) will be assessed with 3D motion analysis equipment, and your 'point of view' observations (where you are looking) will be monitored with eye tracking technology. You will be required to attend the University "Foro Italico" biomechanics laboratory once for testing, which will last around one hour.

What if I do not wish to take part or change my mind during the study?
Your participation in the study is entirely voluntary. You are free to withdraw from the study at any time without having to provide a reason for doing so.

What happens to the research data?
The raw data will be kept in secure storage until it is processed. The data will be purged of all details that could potentially identify you personally and only members of the research team will have access to it. You are free to ask to see your data to ensure you are happy it cannot be used to identify you in any way. Anonymous data will be preserved for no longer than necessary as per institutional guidelines, however you should be aware this period could be indefinite. If you choose to withdraw from the study before its completion date, your data will not be included in the findings of the study and will be securely destroyed. After the completion date, your anonymous data will remain as a part of the findings and cannot be withdrawn.

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The findings of the present investigation may be used in part or whole for presentations or publications. At request, you are eligible to receive an overview of the findings, and/or a copy of any presentations or publications produced. No individual will be identified or linked to the data.

How can I find out more information?
Please contact the researcher directly. Neil Thomas, Presso Prof. Andrea Macaluso, Dipartimento di Scienze Motorie Umane e della Salute - Movimento Umano e dello Sport, Università di Roma "Foro Italico" Piazza L. de Bosis 6, 00135. Neil.Thomas@Cumbria.ac.uk. +39.3288036.997.

What if I want to complain about the research?
Initially you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint you should contact Prof. Arnaldo Zelli,

Dipartimento di Scienze Motorie Umane e della Salute - Scienze Umane e Sociali, Università di Roma “Foro Italico” Piazza L. de Bosis 6, 00135. arnaldo.zelli@uniroma4.it, +39.0636733.368

University of Cumbria

'The effects of eye movements on balance'

Participant Consent Form

Please answer the following questions by circling your responses:

Have you read and understood the information sheet about this study? YES NO

Have you been able to ask questions and had enough information? YES NO

Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO

Do you understand that video obtained from the eye tracking equipment will include your own field of vision and at no point will your face be recorded? YES NO

Your data will be anonymised before being analysed. Do you give permission for members of the research team to have access to your anonymised data? YES NO

Do you understand that anonymised data will be kept for no longer than necessary as per institutional guidelines, however, this period could be indefinite? YES NO

If you leave the study before its completion date, your data will be removed from the findings and securely destroyed.

Do you understand that after the completion date, your anonymised data will remain a part of the findings and cannot be withdrawn? YES NO

Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant:... **Date:**.................

Name (block letters):...

Signature of researcher:... **Date:**.................

Name (block letters):...

UNIVERSITÀ DEGLI STUDI DI ROMA “FORO ITALICO”

'Gli effetti dei movimenti oculari sull’equilibrio’

Foglio informativo per i partecipanti

Il progetto

La nostra ricerca è volta a studiare gli effetti dei movimenti oculari sull’equilibrio. L’obiettivo è di comprendere come la stimolazione visiva contribuisca al controllo posturale.

Alcune domande che potreste avere riguardo il progetto di ricerca:

Perché mi avete chiesto di prendere parte al progetto e cosa mi si chiede di fare?
Lo studio richiede partecipanti ambosessi in salute di età compresa tra i 18-35 anni e 60-90 anni che non soffrano di disturbi dell’equilibrio, chinetosi (mal di mare, mal d’auto, ecc.), o patologie degenerative dell’occhio. Le sarà richiesto di camminare lungo una passerella di 5-10m per 15 volte (con le dovute pause) fissando oggetti mobili o fissi proiettati su uno schermo di fronte alla pedana. L’andamento della sua camminata, in risposta agli stimoli visivi sullo schermo, sarà registrato tramite strumentazione di analisi del movimento in 3D e il suo “punto di vista” (dove sta guardando) sarà monitorato con tecnologia di tracciamento visuale non invasiva. Le chiederemo di recarsi presso l’Università degli Studi di Roma Foro Italico per sottoporsi al test che durerà circa un’ora.

Cosa succede se non desidero partecipare o cambio idea durante il corso del progetto?
La sua partecipazione è completamente volontaria. E’ libero di ritirarsi dal progetto in qualsiasi momento senza dover fornire giustificazioni.

Cosa accade ai dati acquisiti?
I dati grezzi saranno conservati in modo sicuro fino all’elaborazione finale del progetto. Ogni elemento raccolto sarà reso anonimo e resterà accessibile solo ai membri della ricerca. E’ libero di prendere visione dei propri dati per assicurarsi che non possono essere utilizzati per identificarla in alcun modo. I dati anonimi saranno conservati per il tempo strettamente necessario secondo le linee guida istituzionali (il periodo, al momento, è indefinito). Se sceglie di abbandonare il progetto prima del termine, i suoi dati saranno cancellati e non inclusi nell’elaborato. Al termine dello studio, i suoi dati resi anonimi costituiranno parte integrante del progetto e non potranno essere ritirati.

Come sarà utilizzato il progetto di ricerca?
I risultati del progetto saranno utilizzati come presentazioni o pubblicazioni. Su richiesta, è libero di richiedere l’elaborazione finale dei dati e/o una copia delle presentazioni o pubblicazioni. Nessun partecipante potrà essere identificato tramite i dati raccolti.

Come posso trovare maggiori informazioni?
Si prega di contattare direttamente i membri del progetto di ricerca: Neil Thomas, presso Prof. Andrea Macaluso, Dipartimento di Scienze Motorie Umane e della Salute -

Movimento Umano e dello Sport, Università di Roma "Foro Italico" Piazza L. de Bosis 6, 00135. Neil.Thomas@Cumbria.ac.uk. +39.3288036.997.

Come posso fare un reclamo?

Inizialmente può fare riferimento direttamente ai ricercatori. Per un reclamo formale rivolgersi a: Prof. Arnaldo Zelli, Dipartimento di Scienze Motorie Umane e della Salute - Scienze Umane e Sociali, Università di Roma "Foro Italico" Piazza L. de Bosis 6, 00135. arnaldo.zelli@uniroma4.it, +39.0636733.368

UNIVERSITÀ DEGLI STUDI DI ROMA "FORO ITALICO"

'Gli effetti dei Movimenti Oculari sull'Equilibrio'

Modulo di consenso

Rispondere alle seguenti domande cerchiando la risposta desiderata:

Ha letto e compreso tutte le informazioni riguardo il progetto? SI NO

E' stato in grado di rispondere alle domande precedentemente sottoposte? SI NO

Sa che è libero di abbandonare il progetto in qualsiasi momento e senza dover dare spiegazioni? SI NO

E' al corrente che il video ottenuto dal dispositivo di localizzazione visuale registrerà il suo campo visivo ma che non apparirà mai il suo volto? SI NO

I suoi dati saranno resi anonimi prima di procedere con l'analisi. Autorizza i gestori del progetto ad avere accesso ai suoi dati resi anonimi? SI NO

Sa che i dati resi anonimi saranno conservati per il tempo strettamente necessario come da linee guida istituzionali? (Questo periodo è, al momento, indefinito) SI NO

Se abbandona il progetto prima del termine, I suoi dati saranno rimossi dalla ricerca e cancellati in modo sicuro.

E' al corrente che, dopo la data di completamento della ricerca, i dati anonimi faranno parte dei risultati e non possono essere ritirati? SI NO

Si prega di firmare per prendere parte al progetto, dopo aver ottenuto sufficienti informazioni in merito:

Firma del partecipante:... **Data:**......................................

Nome (in maiuscolo):..

Firma del responsabile progetto:... **Date:**....................................

Nome (in maiuscolo):..

'Dynamic balance, eye movements and gaze allocation'

Participant Information Sheet

About the study

This research aims to investigate the effects of eye movements on balance and gaze strategies. The purpose is to develop understanding of visual contributions to postural control.

Some questions you may have about the research project:

Why have you asked me to take part and what will I be required to do?

This investigation requires healthy male and female participants between the ages 18-35 and 65-90 years who are free from balance disorders and degenerative eye conditions. You will be required to stand still and walk forward for 4 metres in a university waiting room, whilst viewing a member of the research team who will also stand still and walk. There will be around 5-10 short trials, with breaks, and you will be required to attend the University of Cumbria once for testing which will last around an hour. Your balance during the trials will be assessed with small acceleration measuring devices, and your 'point of view' observations (where you are looking) will be monitored with eye tracking technology.

What if I do not wish to take part or change my mind during the study?

Your participation in the study is entirely voluntary. You are free to withdraw from the study at any time without having to provide a reason for doing so.

What happens to the research data?

The raw data will be kept in secure storage until it is processed. The data will be purged of all details that could potentially identify you personally and only members of the research team will have access to it. You are free to ask to see your data to ensure you are happy it cannot be used to identify you in any way. Anonymous data will be preserved for no longer than necessary as per institutional guidelines, however you should be aware this period could be indefinite. If you choose to withdraw from the study before its completion date, your data will not be included in the findings of the study and will be securely destroyed. After the completion date, your anonymous data will remain as a part of the findings and cannot be withdrawn.

How will the research be reported?

The findings of the present investigation may be used in part or whole for presentations or publications. At request, you are eligible to receive an overview of the findings, and/or a copy of any presentations or publications produced. No individual will be identified or linked to the data.

How can I find out more information?

Please contact the researcher directly. Neil Thomas, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD, neil.thomas@uni.cumbria.ac.uk

What if I want to complain about the research?

Initially you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint you should contact Prof. Diane Cox, Director of Research Office, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD, diane.cox@cumbria.ac.uk

'Dynamic balance, eye movements and gaze allocation'

Participant Consent Form

Please answer the following questions by circling your responses:

Have you read and understood the information sheet about this study?
YES NO

Have you been able to ask questions and had enough information?
YES NO

Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal?
YES NO

Do you understand that video obtained from the eye tracking equipment will include your own field of vision and at no point will your face be recorded?
YES NO

Your data will be anonymised before being analysed. Do you give permission for members of the research team to have access to your anonymised data?
YES NO

Do you understand that anonymised data will be kept for no longer than necessary as per institutional guidelines, however, this period could be indefinite?
YES NO

If you leave the study before its completion date, your data will be removed from the findings and securely destroyed.

Do you understand that after the completion date, your anonymised data will remain a part of the findings and cannot be withdrawn?
YES NO

Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant:.. **Date:**.................

Name (block letters):...

Signature of researcher:.. **Date:**.................

Name (block letters):...

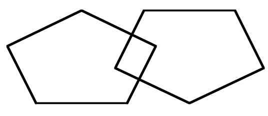
Appendix G

Mini mental status examination

Mini-Mental State Examination (MMSE)

Patient's Name: ____ Date: ______________

Instructions: Score one point for each correct response within each question or activity.

Maximum Score	Patient's Score	Questions
5		"What is the year? Season? Date? Day? Month?"
5		"Where are we now? State? County? Town/city? Hospital? Floor?"
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible.
5		"I would like you to count backward from 100 by sevens." (93, 86, 79, 72, 65, …) Alternative: "Spell WORLD backwards." (D-L-R-O-W)
3		"Earlier I told you the names of three things. Can you tell me what those were?"
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		"Repeat the phrase: 'No ifs, ands, or buts.'"
3		"Take the paper in your right hand, fold it in half, and put it on the floor." (The examiner gives the patient a piece of blank paper.)
1		"Please read this and do what it says." (Written instruction is "Close your eyes.")
1		"Make up and write a sentence about anything." (This sentence must contain a noun and a verb.)
1		"Please copy this picture." (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

Appendix H

Snellen chart

Visual Acuity Chart - Approximate Snellen Scale

For Educational Purposes Only

20/200	E	200 ft	61 m
20/100	H N	100 ft	30.5
20/70	D F N	70 ft	21.3 m
20/50	P T X Z	50 ft	15.2 m
20/40	U Z D T F	40 ft	12.2 m
20/30	D F N P T H	30 ft	9.1 m
20/20	P H U N T D Z	20 ft	6.1 m
20/15	N P X T Z F H	15 ft	4.6 m

Bibliography

Abrams, R. A., Meyer, D. E. and Kornblum, S. (1989), 'Speed and accuracy of saccadic eye movements: characteristics of impulse variability in the oculomotor system.', *Journal of Experimental Psychology: Human Perception and Performance* **15**(3), 529.

Aguiar, S. A., Polastri, P. F., Godoi, D., Moraes, R., Barela, J. A. and Rodrigues, S. T. (2015), 'Effects of saccadic eye movements on postural control in older adults.', *Psychology & Neuroscience* **8**(1), 19–27.

Allison, L. K., Kiemel, T. and Jeka, J. J. (2006), 'Multisensory reweighting of vision and touch is intact in healthy and fall-prone older adults', *Experimental brain research* **175**(2), 342–352.

Ambrose, A. F., Paul, G. and Hausdorff, J. M. (2013), 'Risk factors for falls among older adults: a review of the literature', *Maturitas* **75**(1), 51–61.

Baloh, R. W., Ying, S. H. and Jacobson, K. M. (2003), 'A longitudinal study of gait and balance dysfunction in normal older people', *Archives of neurology* **60**(6), 835–839.

Barre, A. and Armand, S. (2014), 'Biomechanical ToolKit: Open-source framework to visualize and process biomechanical data', *Computer methods and programs in biomedicine* **114**(1), 80–87.

Bauby, C. E. and Kuo, A. D. (2000), 'Active control of lateral balance in human walking', *Journal of biomechanics* **33**(11), 1433–1440.

Berard, J. R., Fung, J., McFadyen, B. J. and Lamontagne, A. (2009), 'Aging affects the ability to use optic flow in the control of heading during locomotion', *Experimental brain research* **194**(2), 183–190.

Billino, J., Bremmer, F. and Gegenfurtner, K. R. (2008), 'Differential aging of motion processing mechanisms: Evidence against general perceptual decline', *Vision Research* **48**(10), 1254 – 1261.

Birmingham, E., Bischof, W. F. and Kingstone, A. (2008), 'Gaze selection in complex social scenes', *Visual Cognition* **16**(2-3), 341–355.

Boccignone, G. (2015), 'Advanced statistical methods for eye movement analysis and modeling: A gentle introduction', *arXiv preprint arXiv:1506.07194* .

Bonnet, C. T. and Baudry, S. (2016), 'Active vision task and postural control in healthy, young adults: Synergy and probably not duality', *Gait & Posture* **48**, 57–63.

Borg, O., Casanova, R. and Bootsma, R. J. (2015), 'Reading from a Head-Fixed Display during Walking: Adverse Effects of Gaze Stabilization Mechanisms', *PloS one* **10**(6), e0129902.

Borger, L., Whitney, S., Redfern, M. and Furman, J. (1998), 'The influence of dynamic visual environments on postural sway in the elderly.', *Journal of vestibular research: equilibrium & orientation* **9**(3), 197–205.

Brach, J. S., Berlin, J. E., VanSwearingen, J. M., Newman, A. B. and Studenski, S. A. (2005), 'Too much or too little step width variability is associated with a fall history in older persons who walk at or near normal gait speed', *Journal of neuroengineering and rehabilitation* **2**(21), 1.

Bronstein, A. (1986), 'Suppression of visually evoked postural responses', *Experimental brain research* **63**(3), 655–658.

Brunner, L. C., Eshilian-Oates, L. and Kuo, T. Y. (2003), 'Hip fractures in adults.', *American family physician* **67**(3), 537–542.

Bugnariu, N. and Fung, J. (2007), 'Aging and selective sensorimotor strategies in the regulation of upright balance', *Journal of neuroengineering and rehabilitation* **4**(1), 1.

Bötzel, K., Marti, F. M., Rodríguez, M. C., Plate, A. and Vicente, A. O. (2016), 'Gait recording with inertial sensors – How to determine initial and terminal contact', *Journal of Biomechanics* **49**(3), 332 – 337.

Chapman, G. and Hollands, M. (2006), 'Evidence for a link between changes to gaze behaviour and risk of falling in older adults during adaptive locomotion', *Gait & Posture* **24**(3), 288–294.

Coutrot, A., Hsiao, J. H. and Chan, A. B. (2017), 'Scanpath modeling and classification with hidden Markov models', *Behavior Research Methods* .

DeAngelis, G. and Angelaki, D. (2012), Visual-vestibular integration for self-motion perception, *in* M. Murray and M. Wallace, eds, 'The Oxford Handbook of Innovation', The Nueral Basis of Multisensory Processes, Boca Raton, FL.

Di Fabio, R., Alongkot Emasithi, J. G. and Paul, S. (2001), 'Suppression of the vertical vestibulo-ocular reflex in older persons at risk of falling', *Acta Oto-Laryngologica* **121**(6), 707–714.

Dichgans, J. and Brandt, T. (1978), Visual-vestibular interaction: Effects on self-motion perception and postural control, *in* 'Perception', Springer, pp. 755–804.

Dijkstra, T., Schöner, G. and Gielen, C. (1994), 'Temporal stability of the action-perception cycle for postural control in a moving visual environment', *Experimental Brain Research* **97**(3), 477–486.

Dingwell, J., Cusumano, J., Cavanagh, P. and Sternad, D. (2001), 'Local dynamic stability versus kinematic variability of continuous overground and treadmill walking', *Journal of biomechanical engineering* **123**(1), 27–32.

Donaldson, I. (2000), 'The functions of the proprioceptors of the eye muscles', *Philosophical Transactions of the Royal Society B: Biological Sciences* **355**(1404), 1685–1754.

Dowiasch, S., Marx, S., Einhäuser, W. and Bremmer, F. (2015), 'Effects of aging on eye movements in the real world', *Frontiers in Human Neuroscience* **9**, 46.

Duffy, C. J. and Wurtz, R. H. (1991), 'Sensitivity of MST neurons to optic flow stimuli. II. Mechanisms of response selectivity revealed by small-field stimuli', *Journal of neurophysiology* **65**(6), 1346–1359.

Eikema, D., Hatzitaki, V., Konstantakos, V. and Papaxanthis, C. (2013), 'Elderly adults delay proprioceptive reweighting during the anticipation of collision avoidance when standing', *Neuroscience* **234**, 22–30.

Fluckiger, M. and Baumberger, B. (1988), 'The perception of an optical flow projected on the ground surface.', *Perception* .

Foulsham, T., Walker, E. and Kingstone, A. (2011), 'The where, what and when of gaze allocation in the lab and the natural environment', *Vision Research* **51**(17), 1920 – 1931.

Franz, J. R., Francis, C. A., Allen, M. S., O'Connor, S. M. and Thelen, D. G. (2015), 'Advanced age brings a greater reliance on visual feedback to maintain balance during walking', *Human movement science* **40**, 381–392.

Gibson, J. J. (1950), *The perception of the visual world.*, Houghton Mifflin, Boston.

Gibson, J. J., Olum, P. and Rosenblatt, F. (1955), 'Parallax and perspective during aircraft landings', *The American journal of psychology* pp. 372–385.

Giveans, M. R., Yoshida, K., Bardy, B., Riley, M. and Stoffregen, T. A. (2011), 'Postural sway and the amplitude of horizontal eye movements', *Ecological Psychology* **23**(4), 247–266.

Glasauer, S., Schneider, E., Jahn, K., Strupp, M. and Brandt, T. (2005), 'How the eyes move the body', *Neurology* **65**(8), 1291–1293.

Guerraz, M. and Bronstein, A. (2008), 'Ocular versus extraocular control of posture and equilibrium', *Neurophysiologie Clinique/Clinical Neurophysiology* **38**(6), 391–398.

Hallet, P. E. (1986), Eye movements, *in* K. R. Boff, L. Kaufman and J. P. Thomas, eds, 'Handbook of human perception and performance', Wiley, New York, pp. 10.1–10.112.

Han, B. I., Song, H. S. and Kim, J. S. (2011), 'Vestibular Rehabilitation Therapy: Review of Indications, Mechanisms, and Key Exercises', *Journal of Clinical Neurology (Seoul, Korea)* **7**(4), 184–196.

Higuchi, T. (2013), 'Visuomotor Control of Human Adaptive Locomotion: Understanding the Anticipatory Nature', *Frontiers in Psychology* **4**, 277.

Hollands, M. A., Marple-Horvat, D. E., Henkes, S. and Rowan, A. K. (1995), 'Human eye movements during visually guided stepping', *Journal of Motor Behavior* **27**(2), 155–163.

Hollman, J. H., Brey, R. H., Bang, T. J. and Kaufman, K. R. (2007), 'Does walking in a virtual environment induce unstable gait?: An examination of vertical ground reaction forces', *Gait & Posture* **26**(2), 289–294.

Hollman, J. H., Childs, K. B., McNeil, M. L., Mueller, A. C., Quilter, C. M. and Youdas, J. W. (2010), 'Number of strides required for reliable measurements of pace, rhythm and variability parameters of gait during normal and dual task walking in older individuals', *Gait & posture* **32**(1), 23–28.

Huisinga, J. M., Mancini, M., St. George, R. J. and Horak, F. B. (2013), 'Accelerometry Reveals Differences in Gait Variability Between Patients with Multiple Sclerosis and Healthy Controls', *Annals of Biomedical Engineering* **41**(8), 1670–1679.

Irwin, D. E. (1991), 'Information integration across saccadic eye movements', *Cognitive psychology* **23**(3), 420–456.

Itoh, N. and Fukuda, T. (2002), 'Comparative Study of Eye Movements in Extent of Central and Peripheral Vision and Use by Young and Elderly Walkers', *Perceptual and Motor Skills* **94**(3_suppl), 1283–1291.

Jeka, J., Allison, L., Saffer, M., Zhang, Y., Carver, S. and Kiemel, T. (2006), 'Sensory reweighting with translational visual stimuli in young and elderly adults: the role of state-dependent noise', *Experimental brain research* **174**(3), 517–527.

Jeka, J. J., Allison, L. K. and Kiemel, T. (2010), 'The dynamics of visual reweighting in healthy and fall-prone older adults', *Journal of motor behavior* **42**(4), 197–208.

Jeka, J. J., Oie, K. S. and Kiemel, T. (2008), 'Asymmetric adaptation with functional advantage in human sensorimotor control', *Experimental brain research* **191**(4), 453–463.

Kim, J.-W., Eom, G.-M., Kim, C.-S., Kim, D.-H., Lee, J.-H., Park, B. K. and Hong, J. (2010), 'Sex differences in the postural sway characteristics of young and elderly subjects during quiet natural standing', *Geriatrics & gerontology international* **10**(2), 191–198.

Knox, P. C., Davidson, J. H. and Anderson, D. (2005), 'Age-related changes in smooth pursuit initiation', *Experimental brain research* **165**(1), 1–7.

Kowler, E. (2011), 'Eye movements: The past 25years', *Vision research* **51**(13), 1457–1483.

Kullback, S., Kupperman, M. and Ku, H. H. (1962), 'Tests for Contingency Tables and Marltov Chains', *Technometrics* **4**(4), 573–608.

Lakens, D. (2013), 'Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs', *Frontiers in psychology* **4**, 863.

Lappe, M. and Hoffmann, K. (2000), 'Optic flow and Eye Movements', *International review of neurobiology* **44**, 29–47.

Laurens, J., Awai, L., Bockisch, C., Hegemann, S., van Hedel, H., Dietz, V. and Straumann, D. (2010), 'Visual contribution to postural stability: interaction between target fixation or tracking and static or dynamic large-field stimulus', *Gait & posture* **31**(1), 37–41.

Lee, D. and Lishman, J. (1975), 'Visual proprioceptive control of stance.', *Journal of human movement studies* .

Legrand, A., Mazars, K. D., Lazzareschi, J., Lemoine, C., Olivier, I., Barra, J. and Bucci, M. P. (2013), 'Differing effects of prosaccades and antisaccades on postural stability', *Experimental brain research* **227**(3), 397–405.

Lestienne, F., Soechting, J. and Berthoz, A. (1977), 'Postural readjustments induced by linear motion of visual scenes', *Experimental Brain Research* **28**(3-4), 363–384.

Lewis, R. F., Zee, D. S., Gaymard, B. M. and Guthrie, B. L. (1994), 'Extraocular muscle proprioception functions in the control of ocular alignment and eye movement conjugacy', *Journal of neurophysiology* **72**(2), 1028–1031.

Li, C., Layman, A. J., Geary, R., Anson, E., Carey, J. P., Ferrucci, L. and Agrawal, Y. (2015), 'Epidemiology of Vestibulo-Ocular Reflex Function: Data From the Baltimore Longitudinal Study of Aging', *Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology* **36**(2), 267.

Lin, D., Seol, H., Nussbaum, M. A. and Madigan, M. L. (2008), 'Reliability of COP-based postural sway measures and age-related differences', *Gait & posture* **28**(2), 337–342.

Lindemann, U., Najafi, B., Zijlstra, W., Hauer, K., Muche, R., Becker, C. and Aminian, K. (2008), 'Distance to achieve steady state walking speed in frail elderly persons', *Gait & posture* **27**(1), 91–96.

Logan, D., Ivanenko, Y. P., Kiemel, T., Cappellini, G., Sylos-Labini, F., Lacquaniti, F. and Jeka, J. J. (2014), 'Function dictates the phase dependence of vision during human locomotion', *Journal of neurophysiology* **112**(1), 165–180.

Logan, D., Kiemel, T., Dominici, N., Cappellini, G., Ivanenko, Y., Lacquaniti, F. and Jeka, J. J. (2010), 'The many roles of vision during walking', *Experimental brain research* **206**(3), 337–350.

Manckoundia, P., Mourey, F., Pfitzenmeyer, P., Van Hoecke, J. and Pérennou, D. (2007), 'Is backward disequilibrium in the elderly caused by an abnormal perception of verticality? A pilot study', *Clinical neurophysiology* **118**(4), 786–793.

Marigold, D. S. and Patla, A. E. (2008), 'Visual information from the lower visual field is important for walking across multi-surface terrain', *Experimental Brain Research* **188**(1), 23–31.

Maslivec, A., Bampouras, T. M. and Dewhurst, S. (2017), 'Head flexion and different walking speeds do not affect gait stability in older females', *Human Movement Science* **55**(Supplement C), 87–93.

Matheron, E., Yang, Q., Delpit-Baraut, V., Dailly, O. and Kapoula, Z. (2016), 'Active ocular vergence improves postural control in elderly as close viewing distance with or without a single cognitive task', *Neuroscience Letters* **610**, 24 – 29.

Mays, L. E. (1984), 'Neural control of vergence eye movements: convergence and divergence neurons in midbrain', *Journal of Neurophysiology* **51**(5), 1091–1108.

McAndrew, P. M., Dingwell, J. B. and Wilken, J. M. (2010), 'Walking variability during continuous pseudo-random oscillations of the support surface and visual field', *Journal of biomechanics* **43**(8), 1470–1475.

Melzer, I., Benjuya, N. and Kaplanski, J. (2001), 'Age-related changes of postural control: effect of cognitive tasks', *Gerontology* **47**(4), 189–194.

Moschner, C. and Baloh, R. W. (1994), 'Age-related changes in visual tracking', *Journal of Gerontology* **49**(5), 235–238.

Nagai, K., Yamada, M., Uemura, K., Yamada, Y., Ichihashi, N. and Tsuboyama, T. (2011), 'Differences in muscle coactivation during postural control between healthy older and young adults', *Archives of gerontology and geriatrics* **53**(3), 338–343.

Nashner, L. and Berthoz, A. (1978), 'Visual contribution to rapid motor responses during postural control', *Brain research* **150**(2), 403–407.

NICE (2013), 'Falls in older people: assessing risk and prevention'. **URL:** *https://www.nice.org.uk/guidance/cg161/chapter/introduction*

Orendurff, M. S., Schoen, J. A., Bernatz, G. C. and Segal, A. D. (2008), 'How humans walk: bout duration, steps per bout, and rest duration', *Journal of rehabilitation research and development* **45**(7), 1077–1090.

Owings, T. M. and Grabiner, M. D. (2004), 'Variability of step kinematics in young and older adults', *Gait & posture* **20**(1), 26–29.

Page, W. K. and Duffy, C. J. (1999), 'MST neuronal responses to heading direction during pursuit eye movements', *Journal of neurophysiology* **81**(2), 596–610.

Paige, G. (1991), 'Senescence of human visual-vestibular interactions. 1. Vestibulo-ocular reflex and adaptive plasticity with aging.', *Journal of vestibular research: equilibrium & orientation* **2**(2), 133–151.

Paquette, C. and Fung, J. (2011), 'Old age affects gaze and postural coordination', *Gait & posture* **33**(2), 227–232.

Paquette, M. R. and Vallis, L. A. (2010), 'Age-related kinematic changes in late visual-cueing during obstacle circumvention', *Experimental Brain Research* **203**(3), 563–574.

Paterson, K. L., Lythgo, N. D. and Hill, K. D. (2009), 'Gait variability in younger and older adult women is altered by overground walking protocol', *Age and ageing* **38**(6), 745–748.

Patla, A. E. (1997), 'Understanding the roles of vision in the control of human locomotion', *Gait & Posture* **5**(1), 54–69.

Patla, A. E. and Vickers, J. N. (2003), 'How far ahead do we look when required to step on specific locations in the travel path during locomotion?', *Experimental brain research* **148**(1), 133–138.

Paulus, W., Straube, A. and Brandt, T. (1984), 'Visual stabilization of posture', *Brain* **107**(4), 1143–1163.

Peirce, J. W. (2007), 'PsychoPy—psychophysics software in Python', *Journal of neuroscience methods* **162**(1), 8–13.

Peterka, R., Black, F. and Schoenhoff, M. (1990), 'Age-related changes in human vestibulo-ocular reflexes: sinusoidal rotation and caloric tests', *J Vestib Res* **1**(1), 49–59.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G. and Myklebust, B. M. (1996), 'Measures of postural steadiness: differences between healthy young and elderly adults', *Biomedical Engineering, IEEE Transactions on* **43**(9), 956–966.

Rebula, J. R., Ojeda, L. V., Adamczyk, P. G. and Kuo, A. D. (2013), 'Measurement of foot placement and its variability with inertial sensors', *Gait & Posture* **38**(4), 974 – 980.

Rocchi, L., Chiari, L. and Cappello, A. (2004), 'Feature selection of stabilometric parameters based on principal component analysis', *Medical and Biological Engineering and Computing* **42**(1), 71–79.

Rodrigues, S. T., Aguiar, S. A., Polastri, P. F., Godoi, D., Moraes, R. and Barela, J. A. (2013), 'Effects of saccadic eye movements on postural control stabilization', *Motriz: Revista de Educação Física* **19**(3), 614–619.

Rodrigues, S. T., Polastri, P. F., Carvalho, J. C., Barela, J. A., Moraes, R. and Barbieri, F. A. (2015), 'Saccadic and smooth pursuit eye movements attenuate postural sway similarly', *Neuroscience letters* **584**, 292–295.

Ross, R. G., Olincy, A., Harris, J. G., Radant, A., Adler, L. E., Compagnon, N. and Freedman, R. (1999), 'The effects of age on a smooth pursuit tracking task in adults with schizophrenia and normal subjects', *Biological psychiatry* **46**(3), 383–391.

Rougier, P. and Garin, M. (2007), 'Performing saccadic eye movements or blinking improves postural control', *Motor Control* **11**(3), 213.

Royden, C. S., Crowell, J. A. and Banks, M. S. (1994), 'Estimating heading during eye movements', *Vision Research* **34**(23), 3197–3214.

Sato, H. and Maitland, M. E. (2008), 'Relationship between forward trunk lean during walking and musculoskeletal functions for females', *Journal of Mechanics in Medicine and Biology* **8**(04), 459–471.

Schaafsma, S. and Duysens, J. (1996), 'Neurons in the ventral intraparietal area of awake macaque monkey closely resemble neurons in the dorsal part of the medial superior temporal area in their responses to optic flow patterns', *Journal of Neurophysiology* **76**(6), 4056–4068.

Schellenbach, M., Lövdén, M., Verrel, J., Krüger, A. and Lindenberger, U. (2010), 'Adult age differences in familiarization to treadmill walking within virtual environments', *Gait & posture* **31**(3), 295–299.

Schulmann, D. L., Godfrey, B. and Fisher, A. G. (1987), 'Effect of eye movements on dynamic equilibrium', *Physical therapy* **67**(7), 1054–1057.

Sharpe, J. and Sylvester, T. (1978), 'Effect of aging on horizontal smooth pursuit.', *Investigative ophthalmology & visual science* **17**(5), 465–468.

Spooner, J. W., Sakala, S. M. and Baloh, R. W. (1980), 'Effect of aging on eye tracking', *Archives of Neurology* **37**(9), 575–576.

Sprague, W. W., Cooper, E. A., Reissier, S., Yellapragada, B. and Banks, M. S. (2016), 'The natural statistics of blur', *Journal of Vision* **16**(10).

Stoffregen, T. A. (1985), 'Flow structure versus retinal location in the optical control of stance.', *Journal of Experimental Psychology: Human Perception and Performance* **11**(5), 554.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T., Hove, P. and Oullier, O. (2007), 'Postural sway and the frequency of horizontal eye movements', *Motor Control* **11**(1), 86.

Stoffregen, T. A., Bardy, B. G., Bonnet, C. T. and Pagulayan, R. J. (2006), 'Postural stabilization of visually guided eye movements', *Ecological Psychology* **18**(3), 191–222.

Sturnieks, D., St George, R. and Lord, S. (2008), 'Balance disorders in the elderly', *Neurophysiologie Clinique/Clinical Neurophysiology* **38**(6), 467–478.

Sundermier, L., Woollacott, M. H., Jensen, J. L. and Moore, S. (1996), 'Postural sensitivity to visual flow in aging adults with and without balance problems', *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences* **51**(2), 45–52.

Tadin, D. and Blake, R. (2005), 'Motion perception getting better with age?', *Neuron* **45**(3), 325–327.

Thier, P. and Ilg, U. J. (2005), 'The neural basis of smooth-pursuit eye movements', *Current opinion in neurobiology* **15**(6), 645–652.

Thomas, N. M., Bampouras, T. M., Donovan, T. and Dewhurst, S. (2016), 'Eye Movements Affect Postural Control in Young and Older Females', *Frontiers in Aging Neuroscience* **8**, 216.

Uiga, L., Cheng, K. C., Wilson, M. R., Masters, R. S. and Capio, C. M. (2015), 'Acquiring visual information for locomotion by older adults: A systematic review', *Behavior, Energy Overload and Brain Health: From Science to Society* **20**(Supplement C), 24–34.

UN (2013), 'World population ageing'.
URL: *http://www.un.org/*

Underwood, G., Phelps, N., Wright, C., van Loon, E. and Galpin, A. (2005), 'Eye fixation scanpaths of younger and older drivers in a hazard perception task.', *Ophthalmic & physiological optics : the journal of the British College of Ophthalmic Opticians (Optometrists)* **25**(4), 346–356.

Ustinova, K. and Perkins, J. (2011), 'Gaze and viewing angle influence visual stabilization of upright posture', *Brain and behavior* **1**(1), 19–25.

Wade, M. G., Lindquist, R., Taylor, J. R. and Treat-Jacobson, D. (1995), 'Optical flow, spatial orientation, and the control of posture in the elderly', *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* **50**(1), 51–54.

Wapner, S. and Witkin, H. A. (1950), 'The role of visual factors in the maintenance of body-balance', *The American journal of psychology* **63**(3), 385–408.

Warren, W. H., Blackwell, A. W. and Morris, M. W. (1989), 'Age differences in perceiving the direction of self-motion from optical flow', *Journal of gerontology* **44**(5), 147–153.

Warren, W. H. and Hannon, D. J. (1990), 'Eye movements and optical flow', *J Opt Soc Am A* **7**(1), 160–169.

Warren, W. H., Kay, B. A. and Yilmaz, E. H. (1996), 'Visual control of posture during walking: functional specificity.', *Journal of Experimental Psychology: Human Perception and Performance* **22**(4), 818–838.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P. and Sahuc, S. (2001), 'Optic flow is used to control human walking', *Nat Neurosci* **4**(2), 213–216.

Winter, D. A. (1995), 'Human balance and posture control during standing and walking', *Gait & posture* **3**(4), 193–214.

Winter, D. A. (2009), *Biomechanics and Motor Control of Human Movement*, John Wiley Sons, New Jersey.

Wolfson, L., Whipple, R., Derby, C. A., Amerman, P. and Nashner, L. (1994), 'Gender differences in the balance of healthy elderly as demonstrated by dynamic posturography', *Journal of gerontology* **49**(4), 160–167.

Yeh, T. T., Cluff, T. and Balasubramaniam, R. (2014), 'Visual Reliance for Balance Control in Older Adults Persists When Visual Information Is Disrupted by Artificial Feedback Delays', *PLoS ONE* **9**(3), 1–9.

Young, W. R. and Hollands, M. A. (2010), 'Can telling older adults where to look reduce falls? evidence for a causal link between inappropriate visual sampling and suboptimal stepping performance', *Experimental Brain Research* **204**(1), 103–113.

Young, W. R. and Williams, A. (2015), 'How fear of falling can increase fall-risk in older adults: Applying psychological theory to practical observations', *Gait & Posture* **41**(1), 7–12.

Young, W. R., Wing, A. M. and Hollands, M. A. (2012), 'Influences of State Anxiety on Gaze Behavior and Stepping Accuracy in Older Adults During Adaptive Locomotion', *The Journals of Gerontology: Series B* **67B**(1), 43–51.

Zeni, J., Richards, J. and Higginson, J. (2008), 'Two simple methods for determining gait events during treadmill and overground walking using kinematic data', *Gait & posture* **27**(4), 710–714.

Zeuwts, L., Vansteenkiste, P., Deconinck, F., van Maarseveen, M., Savelsbergh, G., Cardon, G. and Lenoir, M. (2016), 'Is gaze behaviour in a laboratory context similar to that in real-life? A study in bicyclists', *Transportation Research Part F: Traffic Psychology and Behaviour* **43**(Supplement C), 131–140.

Zhang, T., Heuer, H. W. and Britten, K. H. (2004), 'Parietal area VIP neuronal responses to heading stimuli are encoded in head-centered coordinates', *Neuron* **42**(6), 993–1001.

Zietz, D. and Hollands (2009), 'Gaze behavior of young and older adults during stair walking', *Journal of Motor Behavior* **41**(4), 357–366. PMID: 19508962.