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Visual field dependence, sensorimotor function and falls in community dwelling older people

ERIKA M. PLINER[1] | NATALIE HEZEL[2] | STEPHEN R. LORD[3]

[1] Mechanical Engineering, University of Utah, Salt Lake City, Utah, USA
[2] Geriatric Center, Heidelberg University Hospital, Heidelberg, Germany
[3] NeuRA, University of New South Wales, Sydney, NSW, Australia

Correspondence to: Professor Stephen Lord
NeuRA, 139 Barker Street, Randwick, N.S.W, 2031, Australia
Phone: 61 2 93991061
email: s.lord@neura.edu.au
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HIGHLIGHTS

- About one quarter of older community dwelling people have visual field dependence
- Ankle weakness and increased postural sway are associated with visual field dependence
- Participants with visual field dependence have a high incidence of falls and injurious falls
- Addressing excessive dependence on visual information may help prevent falls in older people

ABBREVIATIONS

IRRs	Incidence rate ratios
non-VFD	Non-visually field dependence
OR	Odds ratio
PPA	Physiological Profile Assessment
RVT	Roll Vection Test
SD	Standard deviation
SRT	Simple reaction time
VFD	Visual field dependence

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BACKGROUND: Moving visual fields can have strong destabilising effects on balance, particularly when visually perceived motion does not correspond to postural movements. This study investigated relationships between visual field dependence and sensorimotor function and falls in older people.
AIM: To determine whether sensorimotor function deficits are associated with visual field dependence (VFD), and whether VFD is a risk factor for falls and fall-related injuries in older community living people.
METHOD: 684 community-dwelling adults aged 75 years and older undertook a roll vection test (i.e. attempted to align a rod to the vertical while exposed to a rotating visual field). Participants also underwent a series of sensorimotor function tests and were followed up for falls for 12 months with monthly questionnaires.
RESULTS: 131 (24%) participants aligned the rod in the roll vection test > 6.5º from the vertical and were categorised as being VFD. More women than men were VFD and participants with VFD had reduced lower limb strength, increased sway in a test reliant on vestibular function (standing on a foam mat with eyes closed), and poorer dynamic stability. Participants with VFD also experienced significantly more falls and injurious falls in the follow-up period compared to participants without VFD when adjusting for age, sex and a composite physiological fall risk score.
CONCLUSION: VFD may be associated with reduced muscle strength and impaired vestibular function in older people. As VFD was identified as an independent risk factor for falls, incorporating strategies to address this condition may improve the efficacy of fall prevention interventions for older people.

KEYWORDS: Visual field dependence | Accidental falls | Balance | Muscle strength | Vestibular function | Aged

INTRODUCTION

Falls are devastating, widespread, costly and increasing across the globe [1]. One-third of older people experience at least one fall each year, and 37.7 million falls require medical attention annually, globally [1]. Falls can result in hip fractures, disability and premature nursing home admissions, presenting a serious threat to quality of life and independence [1]. Reducing falls in older adults is therefore an urgent health care issue.

Numerous studies have documented impairments in sensory, motor, and cognitive systems, which play crucial roles in maintaining balance, can increase the risk of falls in older people [2,3]. In addition, there is some evidence that an increased reliance on vision to maintain balance and orientation in space, known as visual field dependence (VFD) [4], may also predispose older people to falls [5-7]. People are exposed to moving visual fields in everyday life and this exposure is increasing with the rise of immersive and augmented environments for entertainment and training activities [8]. This increases the need to understand and adequately characterize VFD due to visual fields having strong destabilising effects on balance and lead to lower limb muscle stiffening [9], postural changes [10], disequilibrium and motion sickness [11,12]. VFD varies considerably among individuals [13,14] with women [12,13,14] and older adults [15] displaying greater VFD than men and younger adults, respectively.

Individuals with vestibular deficits are more VFD than healthy adults [10,11], and it has been suggested age-related reductions in proprioception and vestibular function contribute to the increased prevalence of VFD observed in older adults[6]. However, to date, no studies have directly contrasted sensorimotor capabilities in those with and without VFD. Three studies simulating a moving visual field have shown visual field dependence is associated with falls in older people [5-7]. However, these studies have limitations in that they recruited their samples from select settings (such as falls clinics or retirement villages), included only moderate-sized samples, did not monitor falls prospectively, and/or did not include injurious falls as a study outcome.

Further study is required involving a comprehensive battery of sensorimotor function (sensory acuity, strength, processing speed, and balance assessments), and a rigorous falls follow-up procedure to elucidate why certain older people are VFD, and if VFD predisposes older people to falls. We therefore conducted a large prospective cohort study to determine whether older community living people with VFD have sensorimotor function deficits and are at increased risk of falls and fall-related injuries. Our primary hypotheses were that VFD would be associated with multiple sensorimotor function measures, and people with VFD would experience more falls and injurious falls than people without VFD. In addition, based on pervious findings [12-15], we hypothesised that women would be more VFD than men and that the older participants would be more VFD than the younger participants.

METHODS

Participants and Recruitment

This study comprises a secondary analysis from a randomised controlled trial that investigated multifactorial fall prevention interventions [16]. Participants in the extensive intervention group received individualized interventions comprising exercise and strategies for maximizing vision and sensation; the minimal intervention group received brief advice; and the control group received no intervention. The study population comprised community-dwelling adults aged 75 years and older living in northern Sydney, Australia who were randomly drawn from a health insurance company membership database. Participants were excluded from the study if they had minimal English language skills, were blind, had Parkinson's disease or a Short Portable Mental Status Questionnaire score less than 7 [17]. To recruit as representative sample of older people as possible, transport was provided for those who could not make their own way to the falls assessment clinic to maximize participation rates of older people with mobility limitations. Of the 2,468 people initially contacted, 684 (238 men, 446 women) aged 75 to 98 (mean ± standard deviation 80.4 ±4.5) met the above study inclusion criteria and agreed to participate. Each participant provided written, informed consent. Characteristics of the sample are presented in Table 1 (TABLE 1). Ethical approval was granted by the Human Research Ethics Committee, University of New South Wales.

Visual Field Dependence

Visual field dependence was assessed with a Roll Vection Test (RVT) [18] which assesses perception of vertical under a visually challenging condition. The RVT apparatus consisted of a dome (opened umbrella), 125 cm in diameter, with 8 alternating black and white triangular panels that restricted the participant's visual field to 130 degrees. The dome was mounted horizontally with a bracket onto an adjustable stand via the central shaft of the dome. During the test the dome was rotated by a motor connected to the shaft via sprockets and a belt drive. An axle ran through the shaft and attached to a smaller flat white disc (21 cm diameter, subtending 32 degrees of visual angle) such that the rotation of the dome was uncoupled from the rotation of the disc. The disc extended out from the inner surface of the dome to about level with its rim. The white disc was marked with a straight black line across its centre. The participant stood directly in front of the disc, with the height of the axis of rotation (of the dome and disc) adjusted to eye level. The distance between the disc and the participants' nasal dorsums was approximately 15 cm. At the start of the test the white disc was rotated so that the black line was offset by 26° from vertical (Figure 1). The rotating dome was chosen as the test apparatus, as the high contrast, physical nature of the stimulus when rotated at 16 rpm induces maximal body in the direction of rolling stimuli (18).

Participants were instructed to focus on the centre of the static small white disc while the dome rotated counter-clockwise at 96 degrees sec^{-1} (16 rpm) for 30 seconds. At the end of the 30 second trial, and while the dome was still rotating, each participant was instructed to rotate the white disc until the black line was perceived to be vertical. The angular error from true vertical of the black strip on the small disc was measured for each trial using a digital spirit level (accurate to 0.1°). Participants performed six trials, three with the black line on the disc tilted in the direction of the roll and three with the line on the disc tilted in the opposite direction of the roll. The test measure comprised the mean deviation in degrees from vertical measured over the 6 trials and was recorded as the overall angular error (continuous variable). Based on previous research addressing VFD and fall risk [6], participants with angular errors ≥ 6.5° were categorized as being visually field dependence (VFD) and participants with angular errors < 6.5° were categorized as being non-visually field dependent (non-VFD). The RVT stimulus was too destabilizing for some participants to stand without a risk of falling (43 participants). These participants were given the RVT sample mean score plus three standard deviations ($\bar{x}$ + 3s) of able participants. To not disadvantage participants that scored higher than the $\bar{x}$ + 3s (9 participants), these participants were also give a score of the $\bar{x}$ + 3s.

Table 1. Prevalence of major medical conditions, medication use, participation in physical activity, and mobility and ADL limitations in the

study population.

Condition	Number	(%)
Medical conditions		
Poor vision	171	*25.0*
Stroke	48	*7.0*
Lower limb arthritis	283	*41.4*
Diabetes	46	*6.7*
Incontinence	103	*15.1*
Depression	70	*10.2*
Health rated as fair or poor	60	*8.7*
Medication use		
Four plus medications	377	*55.1*
Cardiovascular system medications	477	*69.7*
Psychoactive medications	105	*15.3*
Musculoskeletal system medications	161	*23.5*
Physical activity		
Planned walks < once per week	306	*44.7*
Physical activity < 1 hour / day	201	*29.4*
Limited in climbing stairs	43	*6.3*
Mobility and ADL limitations		
Used a walking aid	115	*16.8*
Difficulty with home maintenance	416	*61.3*
Difficulty with housework	222	*32.8*
Difficulty cooking	106	*15.5*
Difficulty shopping	101	*14.8*
Difficulty dressing	16	*2.3*

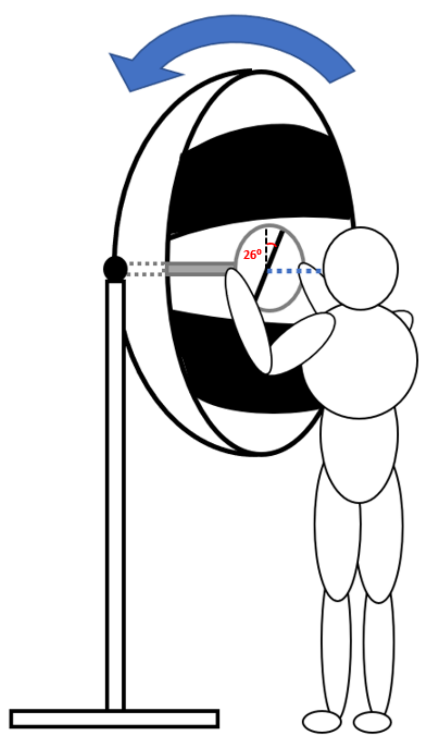

Figure 1. The roll vection apparatus. The participant stood directly in front of the disc, with the height of the axis of rotation (of the dome and disc) adjusted to eye level. The distance between the disc and the participants' nasal dorsums was approximately 15 cm.

Sensorimotor function assessments

Participants completed vision, peripheral sensation, reaction time, muscle strength and balance tests [19,20,21]. High contrast visual acuity was assessed using a logMAR chart at a test distance of 3 m [20]. Edge contrast sensitivity was assessed using the Melbourne Edge Test [22] with participants wearing their near-vision lens correction as appropriate. Depth perception was measured using a Howard-Dohlman depth perception apparatus [23]. Peripheral sensation was assessed with tests of proprioception, tactile sensation and vibration. Proprioception was measured using a lower limb-matching task [19]. Errors were recorded using a protractor inscribed on a vertical clear acrylic sheet (60 cm x 60 cm x 1 cm) placed between the legs. Tactile sensitivity was measured at the lateral malleolus using a Semmes-Weinstein aesthesiometer [24]. Vibration sense at the tibial tuberosity of the knee was measured using a vibrator that produced a 200 Hz vibration of varying intensity under load [19]. The average maximal voluntary strength of the knee extensor, knee flexor and ankle dorsiflexor muscle groups in the participant' dominant (stronger) leg was measured under isometric conditions in a seated position [19]. Simple reaction time (SRT) was assessed in milliseconds with participants seated using a light as the stimulus and a finger-press and a foot-press as the response [19]. Participants had 5 practice trials and 10 test trials, and the average of the 10 test trials was the test measure. Postural sway was measured using a swaymeter that measured displacement of the body at the level of the waist [19]. Testing was performed with participants standing on the floor and on a foam rubber mat (60 cm x 60 cm x 15 cm thick) with eyes open and eyes closed. This test of sway has been shown to have good test-retest reliability as well as good convergent validity with force place measurements [25]. Leaning balance was assessed using the coordinated stability test, a balance test that requires participants to adjust their balance in a steady and coordinated manner when near the limits of their base of support [21].

Weighted scores for five of the above tests: visual contrast sensitivity, lower-limb proprioception, knee extension strength, reaction time, and sway on the foam rubber surface were combined into a composite fall risk score, with higher scores greater than 1.5 indicative of elevated fall risk [7]. This composite physiological profile assessment (PPA) fall risk score has been found to be predictive of falls in multiple large prospective studies undertaken in older people [19].

Falls Surveillance

Participants who met the inclusion criteria for the intervention (i.e. had at least one physiological risk factor for falls) (n=620) were monitored for falls for 12 months using monthly fall calendars. Falls were defined as "events that resulted in a person coming to rest unintentionally on the ground or other lower level, not as the result of a major intrinsic event or an overwhelming hazard" [26]. Injurious falls were defined as falls that resulted in bruises, strains, cuts and abrasions, back pain, and fractures. When a fall occurred, specific details about fall injuries were obtained from telephone interviews. If fall calendars were not returned at the end of each month, further contact was made by telephone interview. Prospective fall data was assessed for 586 participants who completed 2-12 months of fall calendar follow-up (excluding 34 participants with incomplete follow-up).

Statistical analysis

For continuous variables with right skewed distributions, logs or square root transformations were applied before analysis. An independent t-test was performed to compare the mean roll vection scores between men and women. An ANOVA was performed to compare the mean roll vection scores across three age groups (75-79, 80-84, and 85+ years old) with roll vection as the dependent variable and age group as the independent variable. A Hochberg post hoc analysis was performed if roll vection was found to differ significantly between age groups.

Binary logistic regression was used to calculate univariate odds ratios (95% confidence intervals) for VFD with the sensorimotor function test measures converted into z-scores (i.e. standard deviations for the sample) to allow comparison of the strength of the odds ratios among the sensorimotor function measures. Stepwise binary logistic regression was then used to identify independent and significant predictors of VFD. The standardised odds ratios are presented to provide an indication of the relative importance of each variable in explaining the variance in the dependent variable. Age and sex were then included in the regression model, to assess whether these measures were additional significant predictors of VFD, or adjusted the odds ratios of the sensorimotor function measures.

Finally, incidence rate ratios (IRRs) were calculated using negative binomial regression models to compare the rate of falling in the group with VFD with the group without VFD, while adjusting for intervention group (as the intervention aimed to reduce fall rates), age, sex and fall risk scores. These models estimate the number of occurrences of an event such as falls that has Poisson variation with overdispersion and can allow for variable follow-up periods. The data were analysed using STATA 14 (Stata Corp., College Station, TX) and SPSS for Windows (SPSS Inc., Chicago, IL).

RESULTS

Roll vection associations with age and sex

The mean (SD) roll vection score for the sample was 4.8° (SD=3.9°), and women had significantly higher roll vection scores than men; 5.5º (SD=4.1°) and 3.5° (SD=3.1°) respectively ($t_{1,682}$=6.85; p<0.001). Adults aged 75-79, 80-84, and 85+ years had mean roll vection scores of 4.7 (SD=3.8), 4.6 (SD=3.9), and 5.6 (SD=4.1) 80-84 years respectively (F2,681=3.22, p=0.042). Post-hoc tests revealed mean scores for adults aged 85+ years were significantly higher than those for those aged 75-79 years (p=0.044) and those aged 80-84 years (p=0.048).

Sensorimotor Function and Visual Field Dependence

Table 2 shows the mean scores plus standard deviations for the sensorimotor function test measures for the VFD and non-VFD groups (TABLE 2). The univariate ORs revealed the VFD group performed significantly worse than the non VFD group in the three strength measures and the sway on foam with eyes closed and the coordinated stability balance measures. None of the visual, peripheral sensation or reaction time test measure scores were associated with VFD (Table 2).

Two variables (ankle dorsiflexion strength and sway on foam with eyes closed) were included in the final stepwise logistic regression model for predicting VFD. In this model, each standard deviation decrease in ankle flexion strength reduced the odds of being VFD by 17% (OR=0.83, 95%CI=0.68-0.99) and each standard deviation increase in sway increased the odds of being VFD by 28% (OR=1.28, 95%CI=1.07-1.53) – Nagelkerke r^2=0.034. When age and sex were also included in the regression model, the odds ratios were as follows: ankle dorsiflexion strength (OR=1.03, 95%CI=0.81-1.30), sway on foam with eyes closed (OR=1.36, 95%CI=1.12-1.64), age (OR=1.00, 95%CI=0.96-1.05), and sex (OR=2.38, 95%CI=1.45-3.90) – Nagelkerke r^2=0.061.

Table 2. Physiological function measures: VFD – non-VFD comparisons.

Factor	VFD N = 158	Non-VFD N = 526	OR (95% CI)
Isometric strength (kg)			
Knee extension	24.9 (11.6)	27.9 (12.5)	0.79 (0.66 – 0.94)*
Knee flexion	14.3 (6.3)	15.6 (6.6)	0.80 (0.67 – 0.96)*
Ankle dorsiflexion	6.3 (3.1)	7.3 (3.7)	0.77 (0.64 – 0.92)*
Simple reaction time (ms)	280 (55)	273 (47)	1.14 (0.96 – 1.36)
Peripheral sensation			
Vibration sense (microns+)	40.7 (28.5)	38.9 (26.0)	1.04 (0.87 – 1.24)
Proprioception (°error)	2.2 (1.5)	2.1 (1.4)	1.04 (0.87 – 1.25)
Light touch (lg_{10} 0.1mg)	0.44 (0.05)	0.44 (0.05)	0.97 (0.81 – 1.16)
Vision			
Depth perception (cm error)	31.7 (39.9)	27.1 (35.8)	1.13 (0.95 – 1.35)
Contrast sensitivity (dB)	18.6 (2.5)	18.8 (2.4)	0.97 (0.81 – 1.15)
Visual acuity (MAR#)	1.27 (0.50)	1.28 (0.59)	1.03 (0.86 – 1.23)
Postural Sway (mm^)			
Firm surface/eyes open	532 (420 – 643)	435 (400-469)	1.17 (0.98 – 1.41)
Firm surface/eyes closed	665 (553 – 777)	574 (522-625)	1.09 (0.92 – 1.31)
Compliant surface/eyes open	1664 (1470 – [illegible]	1456 (1358-1555)	1.18 (0.99 – 1.41)
Compliant surface/eyes closed	4446 (3956 – [illegible]	3543 (3303-3784)	1.35 (1.14 – 1.60)**
Coordinated stability task (errors)	10.4 (10.0)	7.8 (7.8)	1.33 (1.11 – 1.59)**

Results presented as mean ± 95% confidence interval, mean (SD). †Univariate odds ratios (95% confidence limits) were calculated with measures converted into standard deviations for the sample. For example, each 1 SD increase in ankle dorsiflexion strength reduced the odds of falling by 23%.
* $p < 0.05$, ** $p < 0.005$, *** $p < 0.001$.
+ Peak to peak displacement 2of the vibrator tip under load
# Minimum angle resolvable in minutes or arc
^ Product of maximal sagittal and lateral sway in 30s trials (square mm)
High scores in the visual acuity, depth perception, proprioception, light touch, vibration sense, reaction time, sway and co-ordinated stability tests and low scores in the visual contrast sensitivity and muscle strength tests indicate worse performance.
Sixty-eight participants were not able to perform the sway test on the foam mat with eyes open and 162 participants were not able to perform the sway test on the foam mat with eyes closed. These participants were given the sway test sample mean scores plus three standard deviations ($\bar{x}$+3s) of able participants. To not disadvantage participants that scored higher than the $\bar{x}$+3s, these participants were also give a score of the $\bar{x}$+3s.

Visual Field Dependence and Falls

Of the 586 participants with falls follow-up data, 309 (52.7%) did not fall, 146 (24.9%) fell once, 72 (12.3%) fell twice, 31 (5.3%) fell three times, and 28 (4.8%) fell four or more times. Three hundred and sixty-seven participants had no injurious falls, 143 (24.4%) had one injurious fall, 54 (9.2%) had two injurious falls, 18 (3.1%) had three injurious falls and four (0.7%) had four of more injurious falls. The multivariate negative binomial analysis revealed VFD increased both the rate of falls (1.37, 95%CI=1.07-1.77), and injurious falls (1.36, 95%CI=1.03-1.78) when adjusting for group allocation, age, sex and fall risk scores (TABLE 3).

Table 3. Incident ratios.

	Fall rate	**Injurious fall rate**
	IRR (95% CI)	IRR (95% CI)
Visual Field Dependence[a]	1.37 (1.07-1.77)	1.36 (1.03-1.78)
PPA Fall Risk Score[b]	1.23 (1.10-1.37)	1.21 (1.07-1.36)
Age[c]	1.01 (0.99-1.04)	1.02 (0.99-1.05)
Sex[d]	0.92 (0.73-1.17)	1.51 (1.14-2.00)
Group[e]	0.99 (0.86-1.13)	0.96 (0.83-1.11)

ORs expressed as:
a) Visually field dependent vs not visually field dependent
b) SD increase in PPA Fall Risk Score
c) Increased age in years
d) Female vs male sex
e) Minimal and extensive intervention vs control (reference category)

DISCUSSION

Our findings, in general, supported our hypotheses. We found multiple lower limb strength and balance measures were associated with VFD, and of these, reduced ankle dorsiflexion strength and increased sway on a foam mat with eyes closed were significant and independent predictors of VFD when contrasting the sensorimotor function measures alone. VFD was more common in women compared with men and in older participants compared with their younger counterparts. Participants with VFD experienced more falls and injurious falls in a follow-up period of 12 months, independent of age sex, and physiological fall risk.

The findings that women and those aged 85+ years had the greatest VFD agrees with previous studies that have found women [12,13,14] and older adults [15] to be less stable during upright stance when exposed to moving visual fields. These consistent findings may partially explain why fall and fall injury rates increase with age and are often higher in women than men in samples drawn from community settings [27,28].

Reduced ankle dorsiflexion strength and increased sway on the foam mat with eyes closed were identified as significant and independent predictors of VFD when only the sensorimotor function measures were included as possible predictors in the first step of the binary stepwise logistic regression model. It has been reported that older people with reduced muscle strength are less able to control their balance when reliable vision input is removed (i.e. with eyes closed) [29]. This may also be the case when weaker individuals are exposed to moving visual stimuli, and manifest in the current study by a lateral body tilt in the direction of the rolling stimulus and subsequent increased error in perceiving the true vertical. The inclusion of sex in the next step of the binary logistic regression analysis greatly reduced the OR for ankle dorsiflexion strength. This suggests that the relationship between ankle dorsiflexion strength and VFD was likely driven by women being both significantly more likely to be VFD and significantly weaker than men; i.e. the mean ankle dorsiflexion score for women was 5.6 kg (SD=2.5) whereas the mean ankle dorsiflexion score for men was 9.8 kg (SD=3.7) – $t_{1,682}$ = 16.82, p<0.001.

The finding that sway on the foam with eyes closed was the balance measure most predictive of VFD provides indirect evidence that reduced vestibular function contributes to VFD, as this test is conducted in a situation in which vestibular sense is unaltered, and the other relevant sensory inputs are either removed (eye closure) or compromised by the compliant surface (somatosensory inputs and lower limb proprioception) [3,30]. Further research could assess this association more directly with diagnostic tests of vestibular function including otolithic integrity [31].

Regarding the other measures included as possible predictors of VFD, the coordinated stability test is a functional measure of dynamic balance with correlates spanning strength in multiple lower limb muscle groups, simple reaction time and sway on firm and compliant surfaces [21]. Therefore, it is possible this relationship between coordinated stability and VFD may be bi-directional, or simply correlational, rather than mechanistic, in nature. No visual of peripheral sensation measures were associated with VFD suggesting these sensory modalities do not contribute to the ability to accurately perceive the vertical under a visually challenging condition. Further, despite the significant associations revealed, much of the variance in VFD was unexplained in the multiple logistic regression model. This indicates VFD is only weakly associated with the included predictors and other complementary variables are required to better elucidate why some older people are VFD.

We found participants with VFD experienced more falls and more injurious falls than participants without VFD independent of age, sex and an index of physiological fall risk. These findings build on previous research conducted in falls clinics and retirement villages that found older people with VFD report more retrospective falls than people without VFD [5-7]. It is possible that visual perturbations to balance control are harder to detect than perturbations induced by trips and slips where distinct, immediate sensory information is provided [32]. This lack of an immediate cue may explain why older people with VFD have an increased risk of suffering an injury after a fall, in that they may not be able to initiate adequate protective responses to lessen the impact of a fall.

Strengths of this study include the large sample, the broad range of sensorimotor function measures and the prospective follow-up for falls. Certain study limitations are acknowledged. We did not include a direct vestibular measure and did not assess ground reaction forces with force plates to assess sway and changes in body position. In addition, the optic flow stimulus was restricted to roll vection and findings may vary when exposing participants to alternative moving visual fields such as linear expansion or linear contraction optic flow stimuli. Future studies may benefit from increasing sensitivity in testing measures (e.g. using motion capture systems and force plates) to better understand underlining mechanisms of VFD. Finally, as with our previous studies addressing instability, poor mobility and falls, we have taken a "physiological" rather than "disease-oriented" approach to evaluating factors associated with VFD. This approach maintains that functional consequences of both clinical and subclinical disease will be manifest in reduced sensorimotor abilities [2,19,33]. Never-the-less, we acknowledge that documentation of certain medical conditions and medication use and assessments of frailty may have provided additional insight into factors underlying VFD.

CONCLUSION

In conclusion, multiple lower limb strength and balance measures were associated with VFD, and increased sway on foam with eyes closed remained a significant predictor of VFD when adjusting for age and sex. Participants with VFD experienced more falls and injurious falls in a follow-up period of 12 months, independent of age, sex and physiological fall risk. These findings have clinical applications, in that they indicate moving visual stimuli may predispose older people to falls. Therefore, advice with respect to being cautious when exposed to complex dynamic visual situations, such as virtual reality and augmented environments and when walking in crowds or when travelling on busses and trains while standing, may merit inclusion in fall prevention counselling and education programs for older people.

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