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Sensorimotor and cognitive factors associated with the age-related increase of visual field dependence: a cross-sectional study

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Abstract Reliance on the visual frame of reference for spatial orientation (or visual field dependence) has been reported to increase with age. This has implications on old adults' daily living tasks as it affects stability, attention, and adaptation capacities. However, the nature and underlying mechanisms of this increase are not well defined. We investigated sensorimotor and cognitive factors possibly associated with increased visual field dependence in old age, by considering functions that are both known to degrade with age and important for spatial orientation and sensorimotor control: reliance on the (somatosensory-based) egocentric frame of reference, visual fixation stability, and attentional processing of complex visual scenes (useful field of view, UFOV). Twenty young, 18 middle-aged, and 20 old adults completed a visual examination, three tests of visual field dependence (RFT, RDT, and GEFT), a test of egocentric dependence (subjective vertical estimation with the body erect and tilted at 70°), a visual fixation task, and a test of visual attentional processing (UFOV®). Increased visual field dependence with age was associated with reduced egocentric dependence, visual fixation stability, and visual attentional processing. In addition, visual fixation instability and reduced UFOV were correlated. Results of middle-aged adults fell between those of the young and old, revealing the progressive nature of the age effects we evaluated. We discuss results in terms of reference frame selection with respect to ageing as well as visual and non-visual information processing. Inter-individual differences amongst old adults are highlighted and discussed with respect to the functionality of increased visual field dependence.

Keywords Ageing · Frames of reference · Visual field dependence–independence · Egocentric referencing · Visual fixation instability · Useful field of view

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Introduction

Spatial orientation is the assessment of one's own and/or other objects' position, orientation, and movement, and involves information processing for both cognitive and sensorimotor operations. When interacting with their environment, humans select appropriate frames of reference for spatial orientation depending on the challenge of the setting and/or the task. Our ability to routinely perceive and control our spatial orientation is based on the functional alignment of egocentric reference frame axes (Fourre et al. 2009; Isableu et al. 2009, 2010) either on directions within a gravito-inertial field or on surrogates of the direction of gravity, e.g., axes within the visual frame of reference (walls, ground, ceiling). Depending on the task-specific inertial-acceleration constraints and demands (Isableu et al. 2009), axes of the body's different coordinate systems can be advantageously exploited, each in association with distinct frames of reference (Fourre et al. 2009; Guerraz et al. 1998a, b; Guerraz et al. 2000; Pagano and Turvey 1995). When the body's sensory systems do not register an acceleration pattern, frames of reference are highly congruent and redundant. This means that different frames of reference could be used for spatial orientation in an equally efficient manner according to the principle of vicariance (or interchangeability) (Reuchlin 1978), leading thereby to large inter-individual differences.

Robust differences amongst individuals have been demonstrated in frame of reference selection for certain spatial tasks indicating the existence of "perceptual styles," whereby an individual expresses a stable preference over time to exploit one mode of spatial referencing amongst others. Witkin and colleagues (Witkin et al. 1962; Witkin et al. 1954) proposed to rank individuals' perceptual style along a continuum from visual field independence to dependence. They further theorized these perceptual styles as the operation of a differentiation in perceptivo-cognitive functioning (global vs. analytic), extending beyond spatial orientation (Witkin et al. 1954). A perceiver is considered more or less visual field dependent, i.e., using the visual field as a frame of reference for spatial orientation, based on his/her ability to consider or ignore, respectively, misleading, distracting, or conflicting contextual visual information; or, more generally, the ability of a subject to dissociate an element from its context and reuse it in a different one.

Research has revealed that visual field dependence affects attention, perceptual response time, accident involvement (Bailleux et al. 1990; Mihal and Barrett 1976; Yan 2010), postural strategies (Isableu et al. 1997; Isableu et al. 1998, 2003), and adaptation and sensory reweighting (Brady et al. 2012; Gueguen et al. 2012; Isableu et al. 2010; Viel et al. 2010). Enhanced probability of fall is also observed in young and healthy subjects under difficult stance conditions when confronted to perturbing visual information (Isableu et al. 2010; Streepey et al. 2007). Furthermore, visual field-dependent individuals are more sensitive to peripheral visual information, such as motion and orientation cues (Amblard et al. 1985; Isableu et al. 1998; Streepey et al. 2007). A shift towards greater visual field dependence has been reported in old adults (Eikema et al. 2012; Kobayashi et al. 2002; Marendaz 1984; Markus 1971; Panek et al. 1978; Poulain et al. 2004; Schwatz and Karp 1967; Slaboda et al. 2011). However, the determinants leading to this age-related shift in frame of reference selection have not been well defined. Visual field dependence is associated with higher risk for old adults in daily living tasks due to its attentional and sensorimotor implications. Motor control in itself is more attentionally demanding with age, requiring additional cognitive resources (Seidler et al. 2010). Studies have shown that greater visual field dependence in old adults is associated with postural equilibrium alterations, increasing risk of fall (Eikema et al. 2012; Jamet et al. 2004; Lord and Webster 1990) and leads to more difficulty to perform dual tasks (Maylor and Wing 1996). Moreover, the implication of adaptation and sensory re-weighting difficulties for old adults (Bugnariu and Fung 2007; Eikema et al. 2012; Eikema et al. 2013; Slaboda et al. 2011; Slaboda and Keshner 2012) means risk is even greater under sensory perturbation (e.g. walking on uneven terrain) or while in unfamiliar environments where vision in necessary to guide action. Identifying and understanding frame of reference selection with age can help predict performance, adaptation capability in new tasks/environments and provide guidelines for the design of new training procedures for old adults in order to preserve/regain autonomy. In the present study, we investigated factors possibly associated with increased visual field dependence in old age, by considering functions that are both known to degrade with age and important for spatial orientation and sensorimotor control: reliance on the egocentric frame of reference, visual fixation stability, and divided and selective attention for processing peripheral visual information (useful field of view, UFOV).

The weighting of visual information for postural (Borger et al. 1999; Bugnariu and Fung 2007; Jamet et al. 2004; Poulain and Giraudet 2008; Slaboda et al. 2011; Straube et al. 1988) and locomotor (Berard et al. 2011) tasks has been shown to increase with age, affecting old adults' stability. Several studies have attributed the upweighting of visual input in old adults to greater somatosensory and vestibular age-related deficits (Judge et al. 1995; Manchester et al. 1989). These latter inputs are used to construct and update one's internal models, leading to a dynamic internal representation of the body in space which combines efferent and afferent information and resolves sensory ambiguities (Cullen et al. 2011; McIntyre et al. 1998; Merfeld et al. 1999). This dynamic, internal representation or body schema (De Vignemont 2010; Morasso and Sanguineti 1995; Paillard 1999) is the basis of the egocentric, as opposed to the visual, frame of reference. It has been shown that internal models modulate the perception of the vertical (Barra et al. 2010), taking into account one's perception of the body's longitudinal (*Z*) axis, or "idiotropic vector" (Mittelstaedt 1983). Body verticality perception has been investigated in young and old adults (Barbieri et al. 2010; Schwatz and Karp 1967) to examine the evolution of egocentric spatial orientation with age. These studies demonstrated alterations of the body schema with age, possibly due to somatosensory deficits (Boisgontier and Nougier 2013; Deshpande and Patla 2005; Shaffer and Harrison 2007; Woollacott 1993). However, the relationship between increased visual field dependence and reduced egocentric referencing has not been investigated directly in old adults.

Oculomotor signals contribute to perceptual knowledge and sensorimotor control for egocentric referencing, as they participate in the kinematic proprioceptive chain linking the eye to the foot (Roll and Roll 1988). Moreover, experiments on fixation tasks have revealed the role of eye position signals for head location perception (Lewald and Ehrenstein 2000), while studies using prisms have uncovered the role of oculomotor signals for postural control (Kapoula and Lê 2006). The tiny eye movements involved in gaze fixation maintain a centrally viewed point in focus and keep peripheral visual information salient. The ability to maintain stable eye position may thus affect the exploitation of the egocentric frame of reference as well as visual information processing. Simulated fixation instability in healthy adults, by inducing retinal slips, has revealed the importance of oculomotor stability on complex tasks requiring peripheral visual information gathering (Macedo et al. 2008). Furthermore, it has been reported in previous studies that peripheral visual cues are mainly involved in balance control in children as well as adults (Assaiante and Amblard 1995; Assaiante et al. 2005) and limitations in peripheral perception affect stability in old adults (Manchester et al. 1989). Visual fixation stability is therefore important for both visual information processing and for its somatosensory contribution and inherently impacts equilibrium and spatial orientation of the whole body. Although it is known that oculomotor control is affected by age (Paige 1994; Pelak 2010), there is a discrepancy in the literature with regard to ageing on visual fixation stability. While some reports indicate greater instability with age (Hotson and Steinke 1988; Pelak 2010; Sekuler and Ball 1986), other studies have found no (Crossland et al. 2008; Kosnik et al. 1987; Shallo-Hoffmann et al. 1990) or limited (Herishanu and Sharpe 1981) age effects.

Considering the importance of peripheral visual information processing for spatial orientation and the oculomotor consequences of reduction in this ability, we deemed pertinent the evaluation of peripheral visual information processing within our study. With old age, degradation of the peripheral visual field has been documented (Jaffe et al. 1986). What is more marked, however, and more detrimental for old adults, is the shrinking of the attentional visual field, or useful field of view (UFOV) (Ball et al. 1990; Edwards et al. 2006; Matas et al. 2014; Sekuler et al. 2000). UFOV reduction with age has implications on daily living tasks, including driving (Ball et al. 1993; Owsley et al. 1998) as it implies both visual sensory and cognitive decline (Wood and Owsley 2013). UFOV testing assesses speed of visual processing for detection and localization of central and peripheral targets under conditions of divided visual attention and in the presence and absence of visual clutter. In addition, age-related UFOV shrinkage has been revealed in manual (Beurskens and Bock 2012) and locomotor tasks (Reed-Jones et al. 2014). Changes in oculomotor behavior have been observed with UFOV decline in old adults. Scialfa and colleagues (1987) have proposed a model whereby old adults take smaller samples of a visual scene and scan these more slowly than young adults. Visual search studies have also revealed that old adults make more (Scialfa et al. 1994) as well as illicit (Beurskens and Bock 2012) saccades to compensate UFOV shrinkage.

In the present paper, we seek to establish whether the greater reliance on the visual frame of reference with age is linked to a reduced reliance on the egocentric, somatosensory-based, frame of reference (or egocentric dependence). In this context, examining visual fixation stability can help elucidate the contribution of this basic oculomotor function to egocentric spatial orientation with age. In addition, evaluating the UFOV could reveal links between the visual and somatosensory contribution of the eyes for spatial orientation with age, considering that visual attention and peripheral visual information processing ability is already known to correlate with perceptual style (Goodenough et al. 1987; Isableu et al.

1998; Yan 2010). A visual examination was also included in our study to ensure that our data were not biased due to deficits in or age effects on certain visual functions. Poor visual acuity (Lord et al. 1991), contrast sensitivity, and stereopsis (Lord and Menz 2000) have been identified as factors affecting postural stability under challenging situations for old adults as well as risk factors for falls, though there is some discrepancy between studies for the latter (Ambrose et al. 2013).

We chose a cross sectional design involving young, middle-aged, and old adults, in order to better understand the increasing reliance on the visual frame of reference with age. In cognitive and behavioral research studies, middle-aged adults are often not included or are classified as old adults as often as they are classified as young. Reports have identified an increase in visual field dependence during middle age (Lee and Pollack 1978; Panek et al. 1978; Poulain et al. 2004). However, factors or mechanisms related to this increase were not investigated or were inconclusive (Lee and Pollack 1978, 1980). Sensory changes are known to occur in middle age, most notably the onset of presbyopia, affecting perceivers' ability to focus on near distances. Proprioceptive acuity has also been shown to decrease from young to middle-aged adulthood (Goble 2010; Hurley et al. 1998) and degradation of the vestibular system also occurs around middle-age (Sloane et al. 1989). Changes in cognitive function are less well defined. Hence, in this study, we were interested in observing how frames of reference are used for spatial orientation in middle-age and what factors may contribute to specific reference frame selection.

Our primary hypothesis was twofold. We supposed increased visual field dependence with age to be correlated to reduced egocentric dependence. Furthermore, a diminished reliance on the egocentric frame of reference should be associated with greater visual fixation instability, supporting the idea that greater visual field dependence and reduced egocentric dependence with age may be partly due to enhanced uncertainty within the eye–foot proprioceptive chain, leading to neglect of somatosensory inputs. Our secondary hypothesis considered that UFOV reduction with age leads to increased eye movements to gather spatial referencing information. These movements may contribute to increasing noise in the proprioceptive chain as well, and weakening proprioceptive self-referencing would constitute an additional factor leading to upweighting the visual frame of reference. We therefore expected UFOV reduction to correlate with visual fixation instability (noisier oculomotor signal) as well as visual field dependence. Finally, we expected middle-aged adults' behavior to fall between that of young and old adults revealing a progressive evolution in the parameters evaluated.

Methods

Participants

A total of 58 volunteers participated in the study. They were divided into three age groups: 20 young adults (YA, 10 males, 10 females, age 31.7±6.4 years), 18 middle-aged adults, (MA, 7 males, 11 females, age 51.5±5.6 years), and 20 old adults (OA, 10 males, 10 females, age 74.1±3.7 years). Participants were free of visual, neurological, musculoskeletal, cardiovascular, and vestibular impairments. They all had a binocular visual acuity of at least 0.10 logMAR with normal or corrected to normal vision. Participants wearing glasses were fully adapted to their lenses. The experimenters verified that differences in visual acuity between the refractive correction worn and optimal correction were under 0.10 logMAR. Visual equipment was kept during the visual field and egocentric dependence tests; optimal refractive correction was worn for all other examinations for best corrected visual acuity. Cognitive function was checked with the Mini Mental Status Examination (MMSE). Scores below 25 warranted exclusion. Old adults lived in the community and reported having a fairly active lifestyle. All volunteers were informed of the different test procedures and provided written consent to participate. All tests were performed with the approval of the local ethics committee in accordance with the Declaration of Helsinki.

Visual examination, visual fixation instability, and UFOV evaluation were grouped into an experimental session of 1.5 h. A second experimental session of the same duration was performed to evaluate visual field and egocentric dependence. Experimental sessions were randomized for all participants and spaced apart by 1 week on average.

Visual examination

Four standard tests were completed: binocular visual acuity, binocular contrast sensitivity, stereoscopic acuity, and monocular visual field. Visual acuity, i.e., fine detail perception, was measured using the ETDRS© chart at 100 % contrast. The evaluation was performed binocularly at a viewing distance of 3 m. Binocular contrast sensitivity was assessed using the Pelli-Robson chart (Pelli et al. 1988) at a medium spatial frequency of 3 cycles/°. For MA and OA, the chart was viewed with an addition of 0.75 δ to avoid blurry vision due to the loss of accommodation capacity. The test was performed at a distance of 1 m. Stereoscopic acuity, i.e., 3D perception, was evaluated using the Fly and Wirt Points vectograms of the Titmus Test. Participants viewed the vectograms as they would read a book, at a distance of 40 cm. The participants wore their optimal refractive correction with an addition of 2.5 δ and polarized glasses. The Fly test is a gross assessment of 3D perception, while the Wirt Points test measures the stereoscopic threshold. Monocular visual fields were evaluated via kinetic microperimetry (MP1©, Nidek Technologies, Padova, Italy). A target was displayed centrally (a white cross, subtending 2°× 1° and projected at a simulated distance of 5 m) and calibrated to the visual acuity of the participant on the microperimeter. A 10-dB, size III target (0.43°) moved from one of 8 cardinal positions at 20° eccentricity towards the centre at a speed of 1.5°/s. The measurement was made monocularly for each eye, the other one being covered during the evaluation. Participants fixated the central cross and had to respond once they perceived the peripheral stimulus. A map of visual field was thus obtained for each eye in order to check there were no major deficits in the perception of peripheral visual information.

Visual field and egocentric dependence

Visual field dependence was evaluated with the group embedded figures test (GEFT), the rod-and-frame test (RFT), and the rod-and-disc test (RDT). Egocentric dependence was evaluated with a subjective vertical estimation task under two postural conditions, referred to here as the rod-and-body test (RBT).

To evaluate the cognitive component of visual field dependence, all participants completed a validated French version of the GEFT (Oltman et al. 1971). This assessment of visual field dependence is commonly used in studies of ageing perceptual style and occasionally alongside visual search paradigms. The test was administered individually, under and with strictly identical conditions and instructions. Participants were asked to find and manually trace hidden forms embedded within complex figures. Two parts were scored, each composed of 9 figures and participants had 5 min to complete each part. Scores indicate the number of missed or incorrect items out of the 18. Higher scores therefore denote greater reliance on the visual frame of reference. Visual field-dependent participants have a global rather than analytic approach in perceiving and thus have greater difficulty in finding the embedded figures. The visual field dependence reported using this test involves more elaborate cognitive processing than in the subjective vertical tests (RFT and RDT). The GEFT paradigm also comes close to the UFOV 2 and 3 subtests of divided and selective visual attention by tapping into the cognitive component of visual processing.

All participants also performed three tests of subjective vertical estimation: the RFT, RDT, and RBT. The RFT and RDT reveal the degree of visual field dependence by assessing the effect of a tilted frame and rotating disc, i.e., the contribution of static and dynamic visual cues, respectively, on subjective vertical estimation. The RBT reveals the degree of egocentric dependence by assessing the contribution of body orientation cues in subjective vertical estimation. The participant's task was to rotate a rod towards the vertical. To limit the duration of the experimental session and thus avoid fatigue, the participants were instructed to respond as quickly as possible, but without compromising accuracy. Response time has been shown to be unrelated to performance on the RFT (Bagust et al. 2013). Procedure and instructions described by Oltman (1968) were followed for the RFT and adapted for the RDT and RBT. Three examples of the vertical were given: visual vertical (wall ridges or door frames), gravitational vertical (space rocket or plumb line), and postural vertical (erect body).

A computerized program was developed for each test using Python software and stimuli were projected (768× 1024 dpi) on a 1 m^2 screen. The stimuli were a white rod centered within a white tilted square frame (RFT), within a rotating disc composed of white dots (RDT) or on its own (RBT) on a black background. The rod was anti-aliased to smoothen its outline. Participants could rotate the rod around its centre in clockwise or counterclockwise directions using a keyboard's left and right arrow keys. The adjustment precision was 0.2°. A noisy black and white screen appeared for 2 s after each trial to avoid any residual image of the previous trial. Participants viewed the stimuli binocularly, wearing their usual visual equipment, at a distance of 60 cm. The tests were performed with the lights off in a black, window-less room. In addition, participants viewed the stimuli through a black 80-cm Ø tube, fixed onto an adjustable-in-height table, in order to avoid any peripheral visual cues. The table also served to align the centre of the rod with the participant's cyclopean eye.

The angular size of the frame (RFT), the disc (RDT), and the rod (RBT) were 28° of visual angle. For the RFT and RDT, the rod was slightly smaller, subtending 18.9° of visual angle. The frame and disc were respectively tilted at 18° and rotated at 30°/s, clockwise (+) or counterclockwise (−) in order to produce a maximal visual perturbation effect (Bringoux et al. 2009; Dichgans et al. 1972; Zoccolotti et al. 1993). The rod's initial orientation was ±18° in all three tests. The rod was tilted independently of the frame in the RFT and of the disc rotation direction in the RDT, giving rise to four orientation combination conditions in each of the two tests. (For the RBT, only two orientation conditions exist as the rod is the only stimulus).

For the RFT and RDT, a head and chinrest was fixed onto the table in order to keep the head vertical, and thus prevent the use of vestibular and somatosensory cues. In addition, participants sat at the edge of a stool and legs extended with only heels touching the ground in order to minimize somatosensory inputs from the rest of the body. For the RBT, participants stood upright with legs hip width apart, either with the body erect (BE) or with the body tilted (BT) at hip level, i.e., aligned or misaligned with gravity. For the BT condition, they were instructed to tilt their head and trunk laterally, so as to obtain an angle of 70° between the head and the vertical in order to ensure the production of an Aubert or A effect. The A effect denotes an underestimation of the body/vertical angle, which would be mainly of somatosensory origin (Anastasopoulos et al. 1999; Kaptein and Van Gisbergen 2004; Yardley 1990), whereby the perception of the vertical is attracted towards the body's *Z* axis. Due to the observed symmetry in subjective vertical estimation with respect to tilt side (Van Beuzekom et al. 2001), participants were free to choose their preferred tilt side and kept it throughout the test. Visual controls were made using a protractor placed at the base of the skull to ensure the minimum angle between the head and the true vertical was obtained before each trial. Body tilt was maintained 10 s before each trial to familiarize with the body posture. At the end of each trial, participants stood upright for 10 s to prevent fatigue. Figure 1 illustrates the apparatus, postural conditions, and stimuli used for the subjective vertical estimation tests.

Five trials were performed for each orientation condition in all subjective vertical estimation tests. A total of 20 trials for the RFT and for the RDT, and 10 trials for the RBT were randomized within each test. Subjects were given no feedback about their performance. Error of subjective vertical estimation was scored in degrees of deviation from vertical. Mean absolute errors were calculated across trials and conditions for each test. Larger errors in subjective vertical estimation while perturbed by a tilted frame or rotating disc indicate greater visual field dependence. Greater egocentric dependence means that the somatosensory cues of body orientation have a bigger influence on subjective vertical estimation. Individuals with smaller errors with the body erect and larger errors when the body is tilted (greater A effect), therefore, rely on the egocentric frame of reference. The difference between errors in the BT and the BE condition was hence calculated and used in our analyses, larger values indicating greater egocentric dependence and reliance on somatosensory cues of body orientation for vertical estimation.

Visual fixation instability

Visual fixation instability (VFI) was assessed as a basic measure of oculomotor control. VFI was evaluated using the same apparatus as for visual field evaluation. The microperimeter has a spatial and temporal resolution of 0.1° and 25 Hz, respectively. Measurements were made monocularly for each eye, with the other one covered. Participants were instructed to fixate a centrally displayed cross during 30 s. Eye positions were recorded by tracking a retinal landmark and the data treated to remove blinks. VFI was quantified by calculating a bivariate contour ellipse area (BCEA, expressed in minarc^2) encompassing 68 % of fixation points. The BCEA is the 2D analogue of standard deviation. Consequently, large BCEA values are an indication of greater fixation instability. Binocular BCEA was considered that of the better eye.

Useful field of view

All participants performed the useful field of view test (UFOV®; Visual Awareness Research Group, Inc). The UFOV is defined as the visual field area over which information can be acquired in a brief glance without

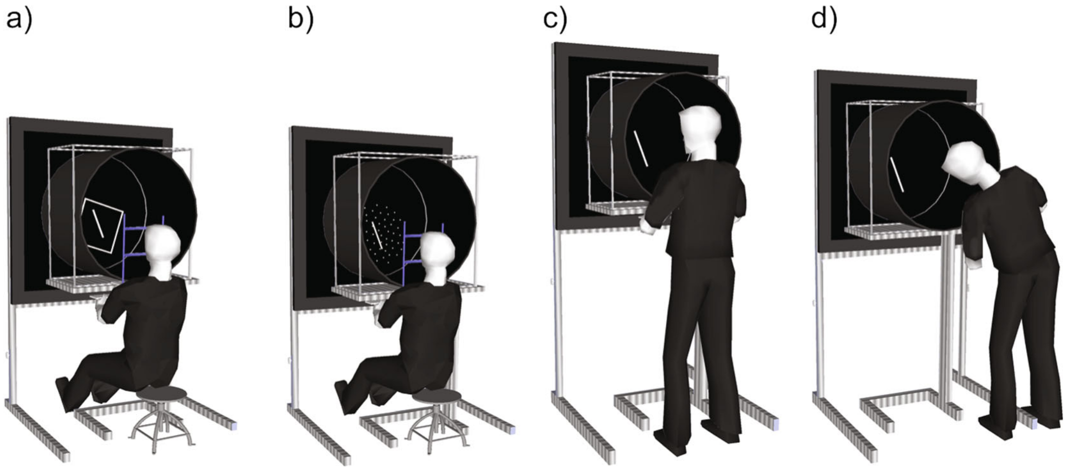

Fig. 1 Illustration of apparatus, postural conditions and stimuli used for the subjective vertical estimation tests. Stimuli were back-projected onto a screen. A table, adjustable in height, held a black optic tube through which participants viewed the stimuli in order to reduce peripheral visual cues. For the rod-and-frame test (RFT) (**a**) and rod-and-disc test (RDT) (**b**), a head and chinrest was attached onto the table to keep the head fixed. Visual stimuli were a white tilted rod within a white tilted frame and within a disc of white dots for the two tests, respectively. The table was raised as appropriate for the rod-and-body test during the body erect (RBT BE) (**c**) and body tilted (RBT BT) (**d**) postural conditions so as the centre of the rod was centered on participants' cyclopean eye

eye or head movements. We used the three-subtest version of the test (Edwards et al. 2005). UFOV 1 required subjects to identify a central target presented in a fixation box. UFOV 2 assesses divided attention capabilities. It requires central target identification and simultaneous localization of a peripheral target. UFOV 3 assesses selective attention capabilities. It includes the first two subtest tasks; only the peripheral target is embedded amongst 47 distracters. Peripheral targets were presented at 15° eccentricity for the UFOV 2 and UFOV 3 subtests. Participants performed the test in the dark, sitting at a distance of 35 cm from a 19-in monitor. They wore their optimal refractive correction and MA and OA had an addition of +3.00 δ to avoid blurry vision due to accommodation loss. Measurements were made binocularly, and the head was not fixed but participants were instructed not to move and keep their gaze on the fixation box. The subtests were presented in their respective order: UFOV 1, then UFOV 2, then UFOV 3. Five practice trials were preformed prior to each subtest. In each subtest, targets were presented at brief display durations (16.67–500 ms) following a double staircase protocol. The display duration at which each subtest can be performed accurately 75 % of the time was measured. Thus, scores for each subtest could range from 16.67 to 500 ms, indicating the visual processing speed associated to each task. We were interested in the UFOV 2 and 3 subtests as measures of peripheral visual processing ability and attention.

Data analysis

Statistical analysis

To evaluate age group effect, one-way analyses of variance (ANOVAs) were performed for all tests except for the UFOV where a 3 (age group)×2 (subtest) repeated measures ANOVA was performed. The partial eta squared (η^2) was used to determine effect strengths. Tukey's honest significant difference (HSD) test ($p<0.05$) was used for post hoc comparisons. Pearson correlations were performed between visual field dependence tests (RFT, RDT, and GEFT) to certify that our measurements were robust with respect to the literature. Correlations were also used to evaluate the relationship between VFI, UFOV, and measures of visual field and egocentric dependence. For all these simple linear correlations, we examined the sign of the regression equation and R^2 values were used to determine correlation strength, significance being $p<0.01$.

Results

Control of visual and cognitive functions

Results of visual functions' measurements are summarized in Table 1 for each age group. The visual field maps determined for each eye revealed no impairment

Table 1 Summary of visual functions assessed for each age group

Age group	Visual acuity (logMAR)	Contrast sensitivity (log)	Titmus stereotest	
			Fly (mm)	Wirt points (in)
YA	−0.22±0.07	1.97±0.07	36±9	41±2
MA	−0.17±0.06*	1.95±0	38±5	38±28
OA	−0.12±0.06*†	1.91±0.12	34±8	34±48

*Significant difference with YA

† Significant difference with MA

in any of the participants. Although there was an age effect on visual acuity ($F(2, 55)=13.93$, $p=0.000$; $\eta^2=0.34$), it should be mentioned that the average visual acuity of the OA group was −0.12 logMAR (12/10), which is considered as good vision. The observed difference between the visual acuities of YA and OA is 0.1 logMAR, i.e., one line on the chart. We thus deemed this difference negligible in the context of our study. There were no significant differences between age groups on any of the other measures of visual function.

The mini-mental state estimation was used to screen for cognitive frailty, all subjects achieved scores of 27 out of 30, or higher.

Visual field dependence increases with age

Mean scores and standard deviations on the measures of visual field dependence, i.e., the GEFT, RFT, and RDT, are summarized in Table 2. Results confirm reports in the literature of increased visual field dependence with old age. The ANOVAs performed for each test revealed a significant main effect of age group (GEFT: F (2, 55)=27.66, $p=0.000$; $\eta^2=0.50$; RFT: F (2, 55)=22.64, $p=0.000$, $\eta^2=0.45$; RDT: F (2, 55)=17.89, $p=0.000$; $\eta^2=0.39$). Post hoc analysis for each test indicated a significant difference between all age groups on the GEFT and RDT, and between YA and OA and between MA and OA on the RFT ($p<0.05$).

Egocentric dependence decreases with age

Mean scores and standard deviations of absolute error on the RBT BE, RBT BT, and mean difference between BT and BE errors for each age group are also presented in Table 2. In this test, only body orientation can provide information for spatial orientation; therefore, larger errors in the BE condition, and smaller errors in the BT condition (reduced A effect), reveal a misjudgment of body orientation perception. The ANOVA performed on the difference of errors revealed a significant age group effect ($F(2, 55)=13.24$, $p=0.000$; $\eta^2=0.33$). Post hoc analysis indicated a significantly lower reliance on the egocentric frame of reference for the OA compared to YA and MA ($p<0.05$).

Relationship between visual field and egocentric dependence

Mean errors on each test of visual field and egocentric dependence are presented in Fig. 2a. Prior to examining the contribution of egocentric referencing on reliance on visual field dependence, we ensured the robustness of the link between the standard visual field dependence tests, i.e., RFT, RDT, and GEFT, with respect to the literature. We observed that larger errors on the RFT correlated positively with larger errors on the RDT ($R^2=$

Table 2 Summary of visual field and egocentric dependence tests for each age group

Age group	GEFT (number of missed items)	RFT absolute error (°)	RDT absolute error (°)	RBT absolute error (°)		
				BE[a]	BT[a]	BT-BE
YA	1±1	2.1±0.8	1.9±0.8	1.1±0.6	15.5±5.7	14.5±5.8
MA	8±6*	3.0±1.6	3.3±1.6*	1.7±0.8	12.6±5.5	10.9±5.5
OA	12±5*†	7.0±3.8*†	4.9±2.0*†	1.9±1.9*	8.5±3.2*	6.0±4.3*†

*Significant difference with YA

† Significant difference with MA

[a] A 3 (age group)×2 (postural condition) repeated measures ANOVA was performed on z-scores (to account for scale differences) of the RBT BE and BT adjustment errors. Tukey's HSD on the posture*age group interaction ($F(2, 55)=14.27$, $p=0.000$, $\eta^2=0.34$) revealed the significant differences presented

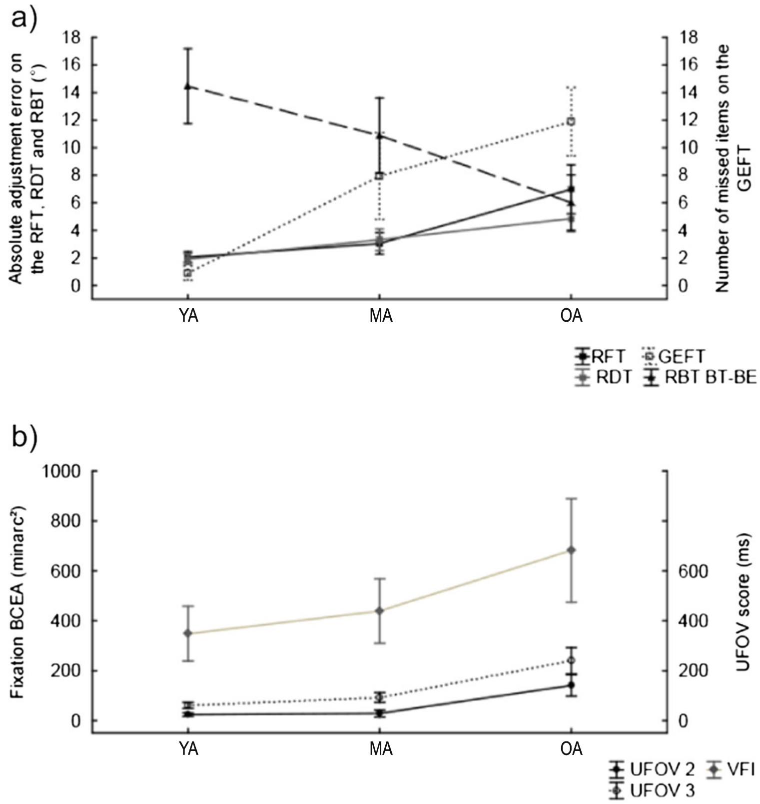

Fig. 2 Scores for each age group on all assessments—means with 95 % confidence intervals. **a** Adjustment error on the RFT and RDT, error difference between the RBT tests (BT-BE) and GEFT scores; **b** visual fixation bivariate contour ellipse area (BCEA) and UFOV 2 and UFOV 3. For the RFT, RDT, and GEFT scores, larger mean values indicate greater visual field dependence. For RBT data, larger mean values indicate greater egocentric dependence. For VFI and UFOV data, larger values indicate greater visual fixation instability and longer processing times (reduced UFOV), respectively

0.51, p=0.000). Similarly, significant positive correlations were found between the GEFT scores and RFT (R^2=0.40, p=0.000) as well as RDT (R^2=0.56, p=0.000). The respective strengths of these relationships are consistent with the literature (Isableu et al. 1998; Wachtel 1972).

We subsequently performed correlation analyses between the RBT and all visual field dependence tests. Significant negative correlations were found between the RBT and RFT (R^2=0.28, p=0.000), RDT (R^2=0.33, p=0.000), and GEFT (R^2=0. 32, p=0.000), indicating that increased visual field dependence is linked to reduced reliance on the egocentric frame of reference.

Visual fixation instability and useful field of view

VFI and UFOV mean scores and standard deviations are summarized in Table 3 and illustrated in Fig. 2b. A one-way ANOVA revealed a significant age group effect on fixation BCEAs (F(2, 55)=5.54, p=0.006; η^2=0.17). Post hoc analysis indicated that OA present significantly larger BCEAs, i.e. a larger fixation area compared to YA (p <0.05). In addition, with the repeated measures ANOVA on UFOV 2 and UFOV 3, we found significant effects of age group (F(2, 55)=48.63, p=0.000; η^2=0.64), subtest (F(1, 55)=43.85, p=0.000; η^2=0.44) and the interaction group*subtest (F(2, 55)=3.28, p=0.045; η^2=0.11). OA required significantly longer processing speeds compared to YA and MA for each test (p<0.05). We observed positive correlations between VFI and UFOV 2 (R^2=0.23, p=0.000) and UFOV 3 (R^2=0.15, p=0.003), i.e., as fixation area increases, so does the display duration necessary in order to complete each attention task in the UFOV test.

Correlations between measures of visual and egocentric dependence with visual fixation instability and useful field of view

We ultimately analyzed visual field and egocentric dependence tests with respect to VFI and UFOV. We explored the relationship of visual fixation instability and spatial orientation (both visual and egocentric referencing) by correlating VFI with all subjective vertical estimation tasks. As illustrated in Fig. 3, significant correlations were found, positive between VFI and both

Table 3 Summary of visual fixation instability (VFI) and useful field of view (UFOV) assessment for each age group

Age group	Fixation BCEA (minarc^2)	UFOV 1 (ms)	UFOV 2 (ms)	UFOV 3 (ms)
YA	347.91±234.47	16.9±0.7	23.9±14.3	60.7±26.2
MA	438.93±258.76	16.7±0	28.6±27.5	92.8±39.7
OA	682.46±443.46*	25.4±25.1	140.8±91.0*†	239.5±111.9*†

*Significant difference with YA

†Significant difference with MA

RFT (R^2=0.28, p=0.000) and RDT (R^2=0.25, p=0.000), and negative between VFI and RBT (R^2=0.20, p=0.000). Finally, in order to understand the effect of peripheral visual information attention and processing deficits on reliance on the visual frame of reference, UFOV 2 and UFOV 3 were correlated with measures of visual field dependence (Fig. 4). GEFT performance correlated positively and significantly with both UFOV 2 (R^2=0.30, p=0.000) and UFOV 3 (R^2=0.36, p=0.000). The trend was similar for the positive correlations between the RFT and UFOV 2 (R^2=0.39, p=0.000) and UFOV 3 (R^2=0.36, p=0.000), as well as between the RDT and UFOV 2 (R^2=0.20, p=0.000) and UFOV 3 (R^2=0.27, p=0.000).

Discussion

The current study explored possible factors contributing to visual field dependence in old age by evaluating egocentric dependence, visual fixation instability (VFI), and useful field of view (UFOV) across adulthood. To our knowledge, this is the first cross-sectional study examining these parameters as well as their interrelationships in the context of ageing. We performed a battery of spatial orientation, oculomotor, and cognitive tests on a sample population of young, middle-aged, and old adults. We proceed to discuss results in terms of frame of reference selection with respect to ageing as this implies processing of visual and non-visual orientation, position, and motion cues for perceptual and interactive sensorimotor tasks of daily living. We shall also emphasize the significance of middle-aged adults' data in terms of frame of reference shifting with age and conclude with future perspectives in this field of research.

1. Age effect on frame of reference selection

   We performed three tests of visual field dependence and an assessment of egocentric dependence in all three age groups. Taken together, results of these assessments reveal that not only do individuals show greater reliance on the visual frame of reference with age, but that this process is accompanied by a lower reliance on the egocentric frame of reference. Scores on the RFT, RDT, and GEFT (Table 2) confirmed the age-related increase in visual field dependence reported in the literature (Eikema et al. 2012; Kobayashi et al. 2002; Matheson et al. 1998; Panek et al. 1978; Schwatz

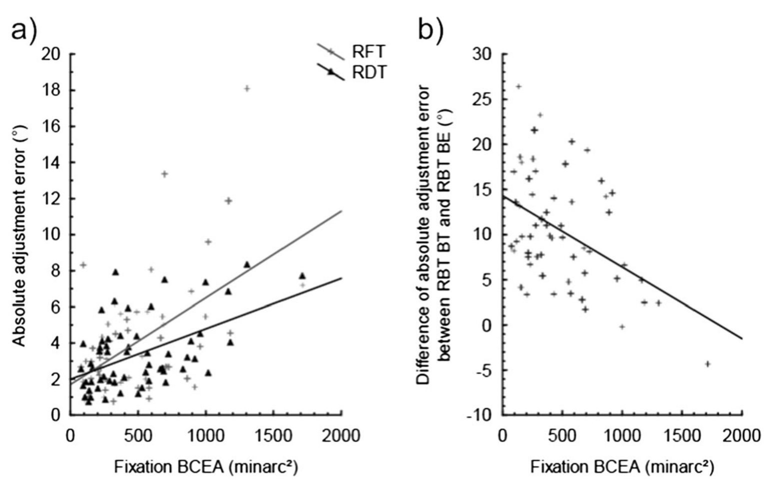

Fig. 3 Relationship of visual fixation instability (VFI) with subjective vertical estimation tests. **a** VFI correlation with the RFT and the RDT; **b** VFI correlation with the RBT (BT-BE error)

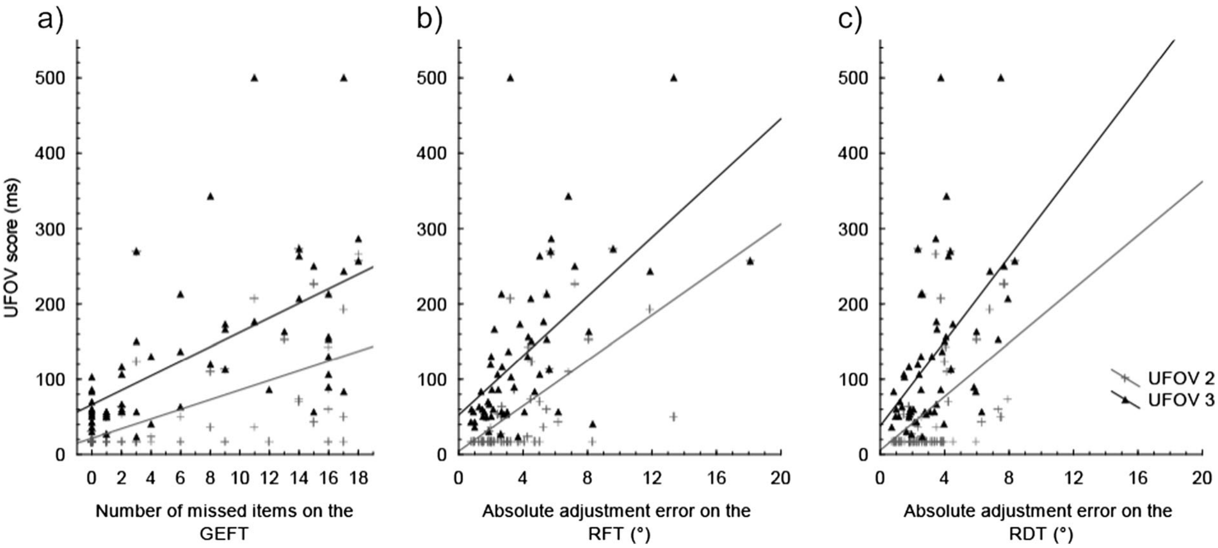

Fig. 4 Relationship of useful field of view (UFOV) subtests 2 and 3 with visual field dependence tests. a UFOV 2 and 3 correlations with the GEFT; b UFOV 2 and 3 correlations with the RFT; c UFOV 2 and 3 correlations with the RDT

and Karp 1967; Slaboda et al. 2011). In agreement with studies examining egocentric referencing in old adults (Barbieri et al. 2010; Schwatz and Karp 1967), we found egocentric dependence decreasing with age (Table 2). This is evidenced in old adults by larger adjustment errors in the RBT body erect (BE) postural condition, but mainly, by smaller errors in the body tilt (BT) condition, i.e., a reduction of the somatosensory-based A effect. Our study is the first investigation, to our knowledge, revealing a reduction of the A effect in the frontal plane with age, but more importantly the first directly linking an increase of visual with a decrease of egocentric reference frame reliance.

The positive correlation between UFOV and scores on the RFT, RDT, and GEFT (Fig. 4) confirm the role of visuospatial as well as divided and selective attention in visual field dependence (Goodenough et al. 1987; Yan 2010). It is well known that UFOV decreases with age, revealing reduced speed of information processing, inability to ignore distracters and inability to divide attention (Owsley et al. 1991). Our data agree with studies of psychological differentiation attributing visual field independence with resistance to distraction (Bednarek and Orzechowski 2008). These authors point out that visual field independence (analytic reality perception) may imply efficient functioning of selective attention whereas visual field-dependent individuals have less efficient attention mechanisms, which reduce stimulation (thus reinforcing specific cognitive preferences). Other studies have also reported declines in cognitive processes in old adults, including slower information processing (Salthouse 2000) and reduced visual attention inhibition (Connelly and Hasher 1993; Sweeney et al. 2001). Our results support the hypothesis that increased visual field dependence with age relates to both sensory and cognitive decline. In addition, UFOV assessment is associated with driving cessation, unsafe driving, and crash risk amongst old adults as it implies both visual sensory abilities and higher order attentional skills for old adults (Ball et al. 1993, 2006; Goode et al. 1998; Mathias and Lucas 2009; Owsley et al. 1991, 1998; Wood et al. 2012)—although there is some ambiguity with respect to the UFOV test's validity as a predictor of safe driving (Aksan et al. 2012; Emerson et al. 2012). Our data are in agreement with older studies relating perceptual style and selective attention/visual search in the context of driving performance and crash risk (Guerrier et al. 1999; McKnight and McKnight 1999; Mihal and Barrett 1976). Indeed, Barrett and Thornton (1968) have pointed out that visual field dependence and automobile accident involvement show similar trends with age.

The inter-individual variability in visual field dependence amongst old adults should be pointed out. In our study, greater visual field dependence is associated with reduced ability to exploit somatosensory information, visual fixation stability, and useful field of view. Moreover, inter-individual variability of VFI and UFOV was larger amongst old adults than within the other age groups (Table 3). Studies have shown that more visual field-dependent old adults are at higher risk of falls (Lord and Webster 1990) and that sedentary old adults are also more visual field dependent than their more active age- and education-matched counterparts (Karp 1967; Markus and Nielsen 1973; Rotella and Bunker 1978). The ageing factor may thus give a different dimension to visual field dependence/independence. Greater visual field dependence amongst old adults may signify an *over-reliance* on visual information, regardless of the appropriateness of using the visual frame of reference, i.e., visual cues are consistently considered more reliable than non-visual existent cues. We hypothesize that age-related deficits may induce this over-reliance on visual information in more affected old adults. The literature makes no distinction between visual field dependence due to vicariance and visual field dependence due to age-related deficits as sensory and cognitive processes are either not examined or not investigated with respect to spatial orientation. However, it is important to distinguish the two cases. The latter would mean that not only is shifting reliance from the visual to another, more appropriate frame of reference more difficult (Bugnariu and Fung 2007; Eikema et al. 2012, 2013; Slaboda et al. 2011; Slaboda and Keshner 2012), but also that the visual frame of reference is not exploited in an optimal manner due to age effects. The correlations between visual field dependence and the other assessments support this idea: on the one hand, reduced visual fixation stability and useful field of view affect how visual information is perceived and processed; on the other, the diminished attention capacity (measured through the UFOV test) and reliability of egocentric cues (revealed via the RBT and weakened oculomotor control in the fixation task) make it more difficult to dynamically switch from one reference frame to another.

2. Proprioceptive neglect within the profile of visual field dependence

Preferential selection of the visual as opposed to the egocentric frame of reference may be linked to a neglect of sorts, or difficulty to integrate the sensory inputs tied to the egocentric frame of reference in old adults. In adults as well as in adolescents (Isableu et al. 2003; Viel et al. 2009), this neglect appears to correspond to a difficulty in integrating proprioceptive inputs and allocating attentional sensorimotor resources to coordinate systems of non-visual frames of reference. The RBT scores revealed that old adults (and to a lesser degree middle-aged adults, but still more than young adults) have trouble exploiting body-based inputs in the absence of visual information. The subjective vertical cannot be built without the mediation of the egocentric perception of one's body position relative to gravity (Anastasopoulos et al. 1999; Luyat et al. 1997; Mittelstaedt 1983; Yardley 1990). This leads us to consider that the *Z* body axis does not provide salient enough information for old adults. More specifically, somatosensation is known to contribute to the sense of verticality (Barbieri et al. 2008) and be affected by age (Shaffer and Harrison 2007). The somatosensory origin of the A effect has been established by observing the systematic disappearance of the A effect depending on the body region and extent of somatosensory neglect in deafferented (Yardley 1990), hemiaesthetic and paraplegic patients (Anastasopoulos et al. 1999; Barra et al. 2010). We therefore infer that the somatosensory contribution for spatial orientation is reduced with age. Moreover, somatosensory information processing requires the integration of signals from all the joints and muscles involved in a given movement or posture maintenance. Such information processing is therefore more complex for old adults as it increases the demand of attentional resources.

Contrary to older reports (Crossland et al. 2008; Kosnik et al. 1987; Shallo-Hoffmann et al. 1990), we observed greater oculomotor instability in the old adult group while fixating a target. Studies have shown that extra-retinal signals provide afferent and efferent input contributing to gaze direction information (Roll et al. 1991), spatial orientation (Lewald and Ehrenstein 2000), the control of posture (Guerraz and Bronstein 2008; Kapoula and Lê 2006; Roll and Roll 1988; Strupp et al. 2003; Wolsley et al. 1996), and locomotion (Royden et al. 1992). Indeed, these inputs are linked to the neck and ankle proprioceptive signals, thus participating in a "proprioceptive chain" (Roll and Roll

1988). The positive correlation we found between decreased visual fixation stability and egocentric dependence (Fig. 3b) is consistent with these studies, which ultimately suggest that extra-retinal information contributes to the construction of a body reference system (Roll et al. 1989). We suggest that visual fixation instability adds noise to the chain of body proprioceptive information. In addition, visual fixation instability was also positively correlated with greater visual field dependence (Fig. 3a).

Taken together, our results support the concept of proprioceptive neglect, or more generally, neglect of somatosensory input, as a main cause of over-reliance on visual frame of reference and increased visual field dependence in old adults. Somatosensory inputs convey noise, while age effects on higher-order capacities render the processing of proprioceptive-chain information more uncertain. Reliance on the visual frame of reference is thus reinforced, as, in comparison, visual input is considered less ambiguous.

3. Peripheral visual information and visual field dependence

For the RFT and RDT tasks, one must ignore peripheral visual information (the tilted frame and rotating disc) in order to accurately align the rod to vertical. In the UFOV 2 and 3 subtests, the scores depend on the individuals' capacity to accurately identify elements in both central and peripheral visual fields (and inhibit distracters in UFOV3). At first view, there would appear to be a certain paradox in that individuals who take into account the peripheral visual information for spatial orientation (visual field dependent) are also those who have difficulty processing peripheral visual information in the UFOV tests. Our correlations of visual field dependence tests to the two UFOV subtests (Fig. 4) imply that for more visual field-dependent participants, peripheral visual information is not only disorienting, as it adds information that is hard to ignore, but also distracting, as it adds noise. It is important, however, to highlight the very short timescale of the UFOV test. While it is reasonable to deduce that peripheral visual information processing is negatively affected by ageing, the limited display duration on the UFOV test, is a moderating factor on such a statement as various higher order processes come into play. Furthermore, it should be pointed out, that UFOV 3 is not only a test assessing inhibition of distracters, attention, and processing in the *peripheral* visual field, but is in itself also a more difficult, cognitively demanding task. Research has revealed visual processing impairments in old adults when attentional load is increased in *central* tasks as well (Russell et al. 2013). It should be noted therefore that, with age, cognitive load affects perception in a general manner. The UFOV 2 and 3 subtests may be paralleled to dual tasks, with concurrent exercises in the central and peripheral visual fields. Given the limited timescale, older and more visual field-dependent perceivers prioritize the central over the peripheral task. The higher display durations required, however, to accomplish the UFOV subtests reveal that these participants are sensitive to peripheral visual cues, taking them into account nevertheless, just as in the visual field dependence test paradigms. Studies examining coordination strategies for segmental stabilization have also shown that visual field-dependent individuals are more sensitive to peripheral visual cues for both static (Isableu et al. 1998, 2010) and dynamic (Assaiante and Amblard 1992, 1993) balance. The shared variance between visual field dependence and UFOV thus supports the fact that these tests examine both temporal and spatial visual processing ability in addition to attention capacity. These functions are particularly relevant for old adults' daily living tasks and sensorimotor control in general in order to preserve autonomy.

Patients with peripheral field loss increase their eye movements to obtain more samples of their limited visual environment (Li et al. 2002). During visual search, old adults make more (Scialfa et al. 1994) as well as illicit (Beurskens and Bock 2012) saccades to compensate UFOV shrinkage. Considering such oculomotor consequences of limiting peripheral visual information processing, we may suggest that visual fixation instability (which implies fine control of very small movements) may indeed be partly attributed to UFOV reduction with age. The alternative hypothesis, however, may also be valid, positing that visual fixation instability may actually lead to a reduction of the UFOV. Since visual fixation instability affects peripheral visual information perception as well (Macedo et al. 2008; Murakami et al. 2006), VFI due to age could engender reduced peripheral information processing capacities, thus shrinking the UFOV. Taking together the correlations of visual fixation instability with both UFOV and visual field dependence, we may suggest that visual fixation instability is linked to greater reliance on the visual frame of reference not only in terms of noisy extra-retinal input (as discussed further above), but also in terms of the noisy visual input it implies.

4. Middle-aged group: evidence of progressive shift in reference frame selection

   Given the implications of greater reliance on the visual frame of reference of old adults mentioned in the above sections, examining possible associated sensorimotor and/or cognitive factors across adulthood can help illuminate the process of this shift in reference frame selection with age. Seeing as we did not obtain an even distribution of ages in our population sample from young to old adults, correlations were not performed with respect to age, but ANOVAs with respect to age groups. Trends revealed the middle-aged adult group responses on all assessments as falling between those of young and old adults, as seen in Fig. 2. Our results cannot argue in favor of linear or non-linear change with age, but this is outside the scope of our study. What our data do suggest, however, is that inter-individual variability increases in middle age and onto old age and that cognitive and sensorimotor decline does not occur "out of the blue" past a certain age. Indeed, certain cognitive functions are known to decline by middle age (Salthouse 2009), as does sensory/sensorimotor performance when additional attentional resources are required (Boisgontier et al. 2012; Jamet et al. 2007; Lindenberger et al. 2000; Sekuler et al. 2000). More importantly, we have further evidence that visual field dependence increases from young to middle-aged adulthood. The correlations we found with egocentric dependence, visual fixation instability, and UFOV show that these factors, also evolving with age, contribute to a certain extent towards this shift in reference frame selection. Post hoc analysis of our data revealed significant differences between all three age groups only on the GEFT and RDT (Table 2). Lee and Pollack 1980) suggest that in middle age, there is evidence of perceptual-cognitive issues that lead to greater visual field dependence with old age. In addition, dynamic visual stimuli have been shown to be more discriminating than static ones between fallers and non-fallers amongst old adults (Lord and Webster 1990). It could be that sensitivity to dynamic visual cues (in addition to cognitive capacity mentioned above) is more prone to ageing effects.

   It should also be mentioned that studies involving visual tasks may obtain biased results for middle-aged adults due to the increased distance required for accommodation caused by the onset of presbyopia (Sekuler et al. 2000), thus revealing more old-adult-like behavior. In the current study, we controlled for this by providing trial frames with increased lens additions to middle-aged and old adults according to the distance of our visual examinations, notably, for the UFOV assessment.

5. Limitations of our experiments and future perspectives

   A critical appraisal of our study must consider the relative strengths of certain correlations. It should be pointed out that we explain only part of the variance of each test as related to visual field dependence/independence. It is this shared variance, however, that is systematically found in sensorimotor control—field dependence/independence correlations, which can affect the adaptation capability of individuals to select and appropriately shift their reliance on different frames of reference (Isableu et al. 1998, 2010; Slaboda and Keshner 2012). The unevenness in our correlations is also due to important inter-individual variability in test responses. In particular for visual fixation instability and useful field of view, variability was high between participants (especially amongst old adults, see Table 3).Variability in UFOV scores has been previously reported in the literature (Edwards et al. 2006). With this in mind, the substantial inter-individual variability warrants caution when generalizing the statement that UFOV degrades with age, even though this decline is significant. Moreover, Beurskens and Bock (2012) suggest UFOV reduction with age is due to central declines. It is possible that cognitive capacities differed amongst our old adult participants (these differences being too fine to be identified via the MMSE cognitive control test). We have already reported the important implication of central processing mechanisms within the profile of visual field dependence. Had we obtained a larger population of old adults, a clustering analysis may have allowed us to partition participants and revealed to a greater degree the association between increased visual field dependence between old adults and reduced UFOV and visual fixation stability. It is also important to be cautious when interpreting correlations between visual field dependence tests and other measures as the shared variance between a test of visual field dependence and the separate variable may not be the same as that shared between different measures of visual field dependence (Wachtel 1972). However, we can have confidence in our results given that the examined variables correlated significantly to all three of our visual dependence tests (GEFT, RFT, and RDT).

Finally, our study has uncovered a reduction in the visual processing and somatosensory contributions to increased visual field dependence with age which may be taken into account in future intervention programs for frailer old adults. We would like to highlight that although it has been established that rigid reliance on the visual frame of reference is a risk factor for old adults, this spatial referencing shift need not be perilous. The main issue of increased visual field dependence is the implication of reduced adaptive and attentional capacities, both of which may be improved with appropriate training. Sensory reweighting (and ultimately learning to identify and utilize more appropriate frames of reference with respect to task constraints) has been shown to improve with time and/or practice in both young (Brady et al. 2012) and old adults (Doumas and Krampe 2010; Eikema et al. 2013; Jeka et al. 2006), while physical activity in general ameliorates both cognitive and physical capabilities affected by age (Seidler et al. 2010) and, in particular, preserves visuospatial functions (Shay and Roth 1992). Furthermore, taking visual field dependence into account in rehabilitation programs for sedentary old adults can lead to optimizing the use of the visual frame of reference, rendering visual field dependence more functional—as is done for young adults (Yan 2010) and Parkinson's patients (Azulay et al. 2006). This can also be done by improving the functionality of factors associated with visual field dependence. Visual fixation stability (Kosnik et al. 1986), divided and selective attention (Ball et al. 1988; Richards et al. 2006; Sekuler and Ball 1986) and processing of complex dynamic scenes (Legault et al. 2013) can be increased with training. Egocentric referencing may also be boosted and thus reduce the perpetual higher weight of visual input, by improving vestibular and somatosensory acuity with appropriate practice (Gauchard et al. 2001; Pavlou et al. 2011; Verschueren et al. 2002).

It is important therefore to be able to distinguish reliance on the visual frame of reference as a preferred spatial referencing mode or as a constraint associated with other age-affected factors in old adults. Training programs for the latter group would thus serve not only to reduce the noise associated with non-visual (or confounding visual) cues but also improve old adults' capacity to distinguish exploitable signal from noise in all available sensory information.

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