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Aging Delays Completion of Head Rotation Cycles in Continuous Gaze Stabilization Exercises despite Putative Healthy Vestibular Function

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Gaze · Aging · Head kinematics · Vestibular · Rehabilitation

Abstract

Introduction: Aging is associated with loss of balance, with falls being one of the leading causes of death among the elderly in the USA. Gaze stabilization exercises (GSE) improve balance control in vestibular populations and could be useful to prevent falls in healthy individuals. However, the extent to which aging affects head kinematics in GSE is unknown. ***Methods:*** Forty-eight younger (n = 25, 24 ± 6 years, 60% female) and older (n = 23, 66 ± 5 years, 56% female) adults completed six 30-s GSE. Participants were asked to maintain gaze fixation on a stationary target while continuously performing head movements in pitch (e.g., vertical) and yaw (e.g., horizontal) directions. The visual target was placed on the wall 1 m or 2 m away or handheld at arm's length. Head kinematics were recorded with an inertial measurement unit placed on the back of the participants' head. ***Results:*** Older adults took significantly more time (e.g., delay) to complete cycles of head rotation in both pitch and yaw compared to younger participants across all GSE. Such delay was further increased during yaw head rotation while fixating gaze of the 1 m target. The average peak velocity (APV) and average angular displacement (AAD), however, were equivalent between groups in all GSE. ***Conclusion:*** Aging leads to the maintenance of head rotation APV and AAD at the expense of delayed cycles of head rotation, suggesting an age-dependent prioritization strategy (e.g., adapt duration first, range second) during continuous head movements. The distance of the visual target and head movement direction influenced elderly performance and should be considered when prescribing GSE to older populations.

Introduction

According to the American Center for Disease Control (CDC), 36,000 adults aging 65 years and older died in 2020 after falls – the leading cause of injury-related death among elderly persons in the USA [1]. In addition to

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deaths, falls were also responsible for 3 million emergency department visits at an annual cost of USD 50 billion when considering 1 million fall-related hospital stays [1]. Even worse, the current proportion of more than 25% of all older adults falling every year is increasing. In fact, the age-adjusted fall death rate for older adults increased by 41% to 78.0 per 100,000 in 2021 [2], with death-related falls expected to continue rising among people aged ≥85 years [3].

Dizziness or vertigo figure among the leading reasons for elderly adults (>65 years) to visit the emergency department in the USA [4, 5], often in the context of a fall [6]. Specifically, vestibular-related falls are associated with hip fractures [7], higher hospital readmission rates [8], head trauma [9], and death [10, 11]. The two most common regions responsible for dizziness and imbalance in the older population involve pathologies of the vestibular end organs or brain (e.g., benign paroxysmal positional vertigo, migraine), either of which disrupts sensorimotor integration (e.g., integrating afference from the eyes and ears) essential for postural stability [12]. Conversely, older adults tend to decrease head velocity and displacement when performing tasks while standing or walking, relying on gaze fixation to improve head stability, which may serve as a protective measure against falls [13]. However, several functional tasks of daily life impose the opposite behavior. That is, standing or walking while continuously moving the head and fixating or negotiating visual targets (e.g., crossing streets, reading signs during a walk). Furthermore, aging is correlated with deterioration of semicircular canal and otolith functions [14, 15], in addition to a decreased ability to integrate sensory signals into perceptual decisions that account for motor delay [16]. Thus, it is not surprising that elderly persons are at a higher risk for fall-related morbidities given their age-related decline in both the integration and sensory processing of the complex vestibular afference across different regions of the cortex that are critical for spatial navigation [17, 18].

Gaze stabilization exercises (GSE) are considered the standard of care for mitigating the troubling symptoms (i.e., oscillopsia, dizziness) and signs (gaze and gait instability) in individuals with vestibular dysfunction [19, 20]. GSE represent a dual task given that one must visually focus on a static or dynamic target while coordinating simultaneous continuous (or transient) repositioning of the head [21]. Completing GSE as part of a rehabilitation program improves gait speed and visual acuity during head rotation, while also reducing postural instability and fall risk [19, 22, 23]. The actual mechanism responsible for such behavioral improvement is unknown and may include optimization of the vestibulo-ocular reflex (VOR) [24]. GSE likely support improved sensorimotor integration based on the repeated exposure to visuo-vestibular stimuli, leading to refinement of the implemented response [21].

In recent years, GSE have been increasingly applied to treat broader clinical populations including people with reports of dizziness despite having normal peripheral vestibular function [25], older adults with mild cognitive impairment [26], and individuals with diagnoses ranging from mild traumatic brain injury to central nervous system impairment such as stroke [19]. Even among children, vestibular rehabilitation has been reported to improve cognition despite concurrent ADHD and vestibular impairment [27]. Moreover, evidence shows that the benefits from exercising the gaze stabilizing systems are not limited to clinical populations and that GSE have the potential to significantly improve walking performance of healthy older adults, translating to greater functional affordance [28]. However, the mechanisms through which older age alone could influence performance in GSE remain widely overlooked, limiting the dissemination of this simple, yet promising strategy to prevent falls among the elderly.

Understanding the extent to which healthy aging affects head kinematics in GSE could lead to identifying age-specific training protocols that may enable personalized fall prevention strategies in this highly vulnerable (aging) population. To that end, this study compared head kinematics of healthy older adults with healthy younger adults engaging in continuous GSE. We hypothesized that, to maintain visual target stabilization, older adults would (1) reduce the average peak velocity (APV) during continuous head rotations, while (2) simultaneously increasing the duration of head rotation cycles.

Materials and Methods

Study Participants

This study recruited a total of 48 participants including younger (n = 25, 24 ± 6 years, 60% female) and older (n = 23, 66 ± 5 years, 56% female) adults with putative healthy vestibular function. Inclusion criteria were (1) age between 18 and 30 years (younger adults) or between 60 and 75 years (older adults); (2) normal or corrected to normal vision (static dynamic visual acuity (DVA) score >80, 20/20 ETDRS chart equivalent),

Table 1. Demographic and clinical characteristics of study participants

	Younger (n = 25)	Older (n = 23)
	mean (±1 SD)	mean (±1 SD)
Sex (male/female)	10/15	10/13
Age, years	24.9 (3.0)	66.7 (3.3)
Height, cm	170 (0.1)	170 (3.3)
Functional		
StVA – LogMAR	−0.09	−0.05
Right DVA – LogMAR	0.21	0.22
Left DVA – LogMAR	0.21	0.22
FGA	29.9 (0.4)	28.2 (2.1)
TUG right, s	6.1 (0.9)	7.0 (0.8)
TUG left, s	6.1 (0.7)	6.9 (0.8)
Gait speed, m/s	1.5 (0.2)	1.5 (0.2)
Physiological		
vHIT right horizontal	0.98 (0.1)	0.97 (0.1)
vHIT right posterior	0.75 (0.2)	0.76 (0.1)
vHIT right anterior	0.85 (0.2)	0.94 (0.2)
vHIT left horizontal	0.93 (0.2)	0.91 (0.1)
vHIT left posterior	0.86 (0.2)	0.93 (0.1)
vHIT left anterior	0.69 (0.1)	0.7 (0.1)
Subjective		
ABC	91.1 (17)	88.7 (20.4)
Headache	46.0 (8.5)	40.7 (5.4)
DHI	2.6 (5.3)	4.0 (6.8)
Beck anxiety	4.2 (5.1)	5.0 (4.4)

Data of younger and older adult participants including sex distribution along with mean age, height, and scores in functional, physiological and subjective outcome measures. Values presented as means ± 1 SD show no statistically significant difference between age groups, nor within groups as per participant sex (e.g., male vs. female). StVA, static visual acuity; DVA, dynamic visual acuity; TUG, timed up and go; FGA, Functional Gait Assessment; ABC, activities-specific balance confidence scale; DHI, the Dizziness Handicap Inventory; vHIT, video-head impulse test.

normal vestibular function (horizontal VOR gain [eye/head velocity] ≥0.80), and the ability to stand and walk independently without assistive devices. Participants were excluded in case of a verified or self-reported history of orthopedic, rheumatological, or neurological conditions interfering with locomotion and/or continuous head rotation (e.g., stiff neck). A history of position dependent dizziness or vertigo (e.g., benign paroxysmal positional vertigo) also encompassed the exclusion criteria. The participants' demographic and clinical characteristics are summarized in Table 1. This study was approved by the Johns Hopkins Institutional Review Board and performed according to the institution's guidelines for safe and ethical research in human subjects. Informed consent was obtained from all subjects and/or their legal guardian(s) prior to data collection.

Experimental Setup

This experiment involved a single testing session. It was carried in a private room (2.5 m × 3 m) with no obstacles between the participants and the wall. A headband containing a single inertial measurement unit (IMU, Shimmer3; Shimmer Research, Dublin, Ireland) was placed on the participants' head for kinematic data acquisition. The IMU rested on the back of their heads at the midline between the eyes. In standing position, participants were asked to perform six 30-s GSE in standardized order from 1 to 6, as described in Table 2. The exercises required active, continuous head rotations while maintaining gaze fixation on the stationary target – a letter "X" marked on paper. The exercises were performed in pitch (vertical) and yaw (horizontal) directions at eye level with the target fixated on the wall 1 m

Table 2. List of continuous GSE

Exercise number	Visual target location	Participant-target distance	Head movement direction (30″)	Assigned exercise name
1	Wall	1 m	Pitch (vertical)	1-m wall fixed pitch
2	Wall	1 m	Yaw (horizontal)	1-m wall fixed yaw
3	Handheld	1 m	Pitch (vertical)	1-m handheld pitch
4	Handheld	1 m	Yaw (horizontal)	1-m handheld yaw
5	Wall	2 m	Pitch (vertical)	2-m wall fixed pitch
6	Wall	2 m	Yaw (horizontal)	2-m wall fixed yaw

GSE, gaze stabilization exercises. The exercises vary in target type (e.g., fixed to the wall or handheld), target distance (e.g., 1 m vs. 2 m), and direction of head movement, e.g., pitch (vertical) or yaw (horizontal). Each continuous GSE require subjects to move their head repeatedly as fast as possible for 30 s.

(GSE 1 and 2) or 2 m (GSE 5 and 6) away, or handheld at arm's length (GSE 3 and 4). Participants were instructed to move at their fastest pace provided the target did not blur.

Outcome Measures

The study outcomes were classified as either functional, physiological, or subjective and are described below, accordingly. Additional information on the outcome measures in this protocol is published elsewhere [29]. As for when the experimental procedures were completed, after the consent form signature, a headband (e.g., IMU) was placed on the participant's head. Then, all participants were assessed with the functional measures in the order as described in the clinical outcomes section. The six GSE were completed in sequence, as presented in Table 2. Kinematic measures were continuously assessed during the performance of all GSE. After that, the headband was removed and the subjective measures were verified, followed by the physiological assessment (e.g., video head impulse test [vHIT]) which completed the session.

Clinical Outcomes – Functional Measures

Dynamic Visual Acuity

The DVA test measures the ability to see clearly during self-generated active head motion, a functional measure of the VOR. The DVA scores were measured using a portable laptop synced with a head motion IMU. A Samsung Galaxy Pro tablet (Seoul, South Korea) was used to present the visual stimuli and record the subjects' visual acuity during head still (static) and yaw head motion (dynamic) acuity scores. Static visual acuity was measured while the subject sat 200 cm from the tablet. Participants were required to distinguish one letter at a time presented on the tablet. The letter was randomly selected from ten optotypes (capital letters C D H K N O S R V Z). Visual acuity during active continuous (sinusoidal) head rotations is scored separately for right (e.g., left visual hemifield) and left (e.g., right visual hemifield) head rotations. Each subject wore a single IMU attached to a headband. This software generates the visual stimulus once the IMU detects a head rotation velocity greater than 120°/s. Raw static and dyanamic visual acuity scores were obtained and ranged from 0 to 100, where 100 indicates no missed optotypes. The raw scores were then converted to the logarithm of the minimal angle resolution (LogMAR) using the formula LogMAR = 1.7 − (visual acuity raw score × 0.02). Possible LogMAR scores ranged from −0.3 to 1.7 (Snellen equivalent of 20/10 to 20/800) with LogMAR of 00 being the Snellen equivalent of 20/20. Lower LogMAR scores (e.g., ≤0) reflect better visual acuity. Corrected DVA scores were then calculated by subtracting static visual acuity from right and left DVA, respectively and are shown in Table 1.

Timed Up and Go

The timed up and go (TUG) task measured each subject's ability to stand from sitting, walk 3 m, and turn 180 degrees before returning to seated position. Task performance was scored by measuring the time between when the back of the participant moved away from the chair after the examiner said "go" to when they were seated in the chair again. Each subject completed two TUG trials, turning right and left, respectively, when they passed the obstacle.

Gait Speed

The Ten Meter Walk Test measured the participants' self-selected comfortable walking speed over a 10 m distance. The subjects started and stopped at least

2 m beyond the 10 m range to ensure the measured gait speed did not include the acceleration or deceleration phases of the locomotion. Their mean gait speed was computed over the 10 m distance.

Functional Gait Assessment

The Functional Gait Assessment (FGA) encompasses 10 unique walking exercises: (1) gait on a level surface, (2) change in gait speed, (3) gait with horizontal head turns, (4) gait with vertical head turns, (5) gait and pivot turn, (6) step over obstacle, (7) gait with narrow base of support, (8) gait with eyes closed, (9) ambulating backwards, and (10) steps. An experienced clinician scored each task between 0 and 3 points, with 0 indicating severe impairment and 3 indicating normal performance. FGA scores less than 22 (30 total) are predictive of falls in older adults [30].

Clinical Outcomes – Physiological Measures

Video Head Impulse Test

The vHIT (ICS Otometrics, Natus Medical Incorporated, Denmark) measures VOR gain (eye velocity/head velocity) during passive head rotation. Subjects were seated 1 m from a stationary visual target in room light. At least 12 passive head rotations were performed in both directions of three planes parallel to the three pairs of semicircular canals: horizontal, right anterior/left posterior, and left anterior/right posterior. Right eye and head velocity were sampled at 220 Hz. vHIT traces were deleted if the eye velocity trace preceded head velocity, if the head velocity was below 100°/s, or if the passive head rotation trace did not match the acceleration profile suggested by the manufacturer.

Clinical Outcomes – Subjective Measures

Dizziness Handicap Inventory

The Dizziness Handicap Inventory (DHI) is a subjective measure, based on a self-report questionnaire that scores the impact of dizziness or unsteadiness on quality of life. The scale consists of 25 items in functional, emotional, and physical domains, with a total score of 0–100. A higher score corresponds with a worse self-perceived level of disability.

Activities-Specific Balance Confidence Scale

The activities-specific balance confidence scale (ABC) is a self-report measure of balance confidence. The subjective measure consists of 16 self-report items in which subjects rate their confidence of not losing balance while performing various daily activities from 0 (no confidence) to 100 (complete confidence). Previous studies suggested that the ABC score is an accurate indicator of fall risk among individuals with vestibular disorders.

Headache Impact Test

The headache impact test measures the impact headaches have on a subject's ability to function in daily life. The scale consists of 6 items in which subjects report how often (e.g., never, rarely, sometimes, very often, or always) headache affects their daily activities. A higher score corresponds with a worse self-perceived level of disability.

Beck Anxiety Inventory

The Beck Anxiety Inventory is a self-report measure of anxiety with 21 items in which subjects rate their anxiety from: not at all (0), mildly (1), moderately (2), and severely (4). The total score is the sum of the 21 items, with a score of 0–21 indicating low anxiety, 22–35 indicating moderate anxiety, and scores above 36 indicating a potentially concerning level of anxiety.

Kinematic Measures

During each exercise, the subject's angular head velocity was recorded using a small (51 mm × 34 mm × 14 mm) MEMS sensor (Shimmer3 IMU; Shimmer Research, Dublin, Ireland) that was securely and comfortably attached to the back of the participant's head using an elastic head band. The data were sampled at 500 Hz and recorded on a built-in micro-SD card. A low-pass Butterworth filter at 50 Hz was applied to the kinematics data, and a high-pass filter with 0.1 Hz cutoff frequency was used to remove gyroscope drift prior to statistical analyses. Kinematic measurements were calculated based on the head angular velocity data, focusing on the dimension aligned with the direction of head motion during the GSE (e.g., yaw in horizontal GSE and pitch in vertical GSE were analyzed, respectively). Specifically, we identified each repetition as the instructed head movement. Each of these "cycles" was defined as the head moving from one end (e.g., right or up) to the other end (e.g., left or down) and back to the initial end. That is, a cycle started when the head reached the farthest angular distance in a given direction for the first time, ending when the head returned to that starting point from the opposite direction. We computed these kinematic measures based on movement cycles: (i) cycle duration: the time duration to complete each cycle. We computed the mean, standard deviation (SD), and coefficient of variation (CV) of cycle duration. For yaw and pitch motions, we computed (ii) APV: the average of the range of rotational peak head velocity reached within the cycle, across multiple cycles. (iii) Average peak velocity SD (APV SD): the SD of the range of peak rotational head velocity in each cycle, across multiple cycles. (iv) Mean of SD: the average of the SD of the peak rotational head velocity computed across all points of the cycle. Average angular displacement (AAD): the average of the range of side-to-side (or up-to-down) head displacement within the cycle, across multiple cycles. (v) Average angular displacement SD (AAD SD): the SD of the range of head angular displacement in each cycle, across multiple cycles. (vi) Mean of SD: the average of the SD of the rotational head angular displacement computed across all points of the cycle. Correlations between measurements were calculated to reveal the patients' head movement patterns.

Statistics

We performed non-parametric paired sample permutation (re-randomization) tests for all comparisons between kinematic and clinical measures from the vestibular patients (pre- and postoperative) and age-matched healthy controls. Specifically, p values were computed for obtaining the test statistics for 2000 randomized rearrangements of the observed data points. We also computed the Pearson correlation coefficients and p values of kinematic and clinical measures using Pearson correlation. To examine whether trends were consistent across exercises, we examined (i) whether correlations are significant ($p < 0.05$) for most exercises and (ii) whether, for all significant correlations, the relationship had the same sign (i.e., correlation were consistently positive/negative across exercises). The presence of a correlation indicated that the performance in a specific GSE was associated with a given clinical outcome measure in either positive or negative fashion – that is, the greater the GSE kinematic measure, the higher the outcome measure, and vice versa, respectively. Throughout the text, values are expressed as mean ± 1 SD and significance is reported at $p < 0.05$. All data processing and statistical tests were performed using MATLAB (The MathWorks, Inc., Natick, MA, USA).

Results

Overview

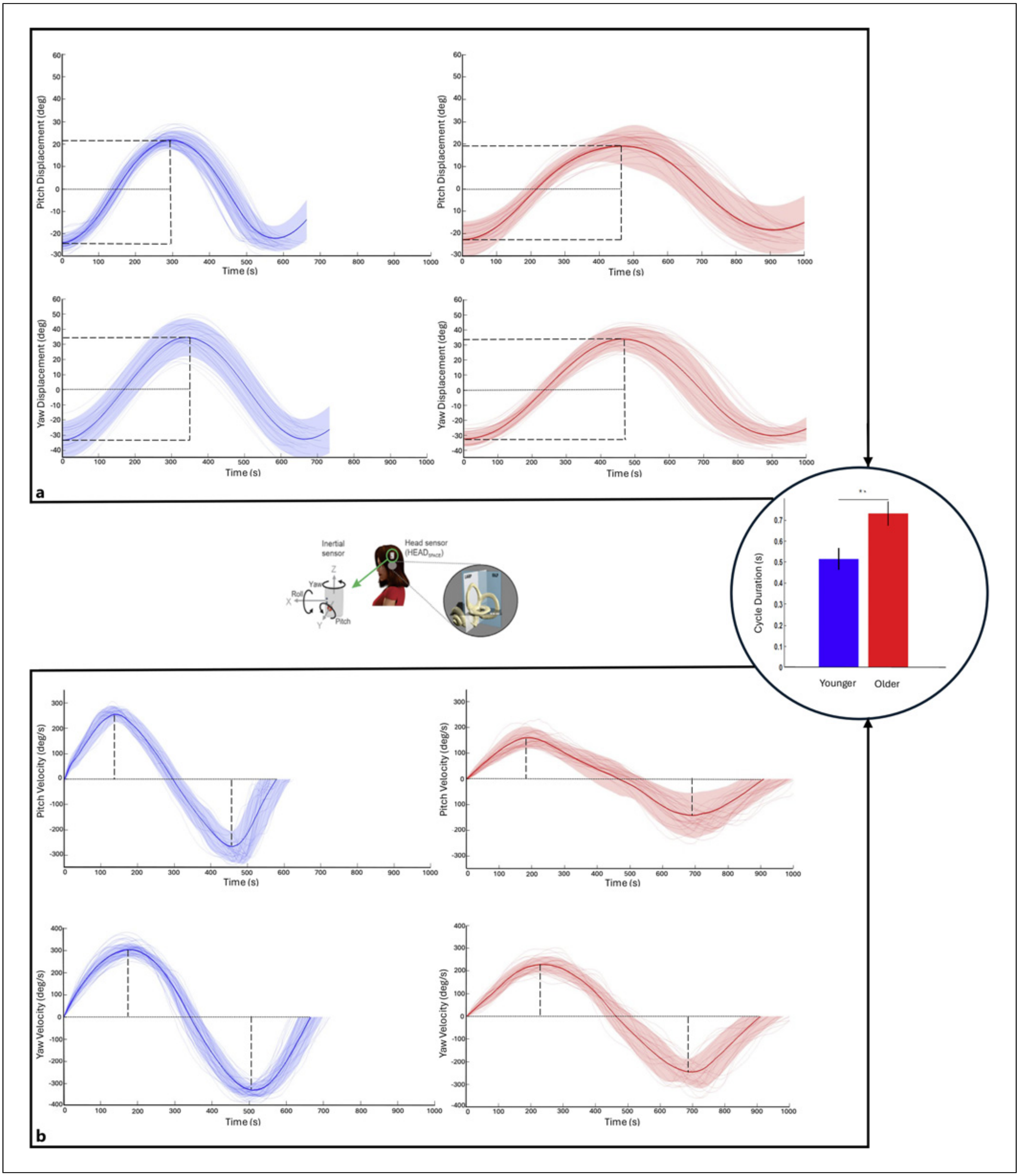
Younger and older participants were mostly equivalent in terms of functional, physiological, and subjective outcome measures (see Table 1). However, analysis of head movement kinematics revealed significant differences between healthy older versus younger adults engaging in continuous GSE. Notably, the mean duration of cycles of head rotation was significantly longer in older adults compared to younger participants across all GSE. Example data traces from one younger participant and one older participant can be seen in Figure 1, where the average cycle durations for younger adults (blue) versus older adults (red) are compared below.

Aging Effects on Head Kinematics

As noted above, healthy older adults implemented longer duration cycles of head rotation compared to that of younger participants during GSE (Fig. 1). Both the AAD and APV of cycles of head rotation, however, were equivalent between the groups despite trends toward greater AAD and reduced APV in older adults. These results suggest that with aging, the angular amplitude and peak velocity of continuous head rotation are maintained at the expense of its increased duration (see online suppl. Fig. 1 for additional information; for all online suppl. material, see https://doi.org/10.1159/000540230). Indeed, as shown in Figure 2, compared to younger participants, older adults significantly delayed the completion of their head rotations (e.g., increased mean cycle duration) while attempting to maintain their gaze on the target as per traditional GSE (see Methods). This strategy was deployed regardless of the distance from the visual target and across all GSE performed. Younger adults also showed significantly higher APV SD and mean of SD than older adults in yaw plane during all GSE in pitch direction (e.g., 1-m wall fixed pitch, 1-m handheld pitch, and 2-m wall fixed pitch, respectively). A summary of the kinematic ranges during the continuous GSE performed by younger and older adults is shown in Table 3 below.

We also performed analyses of the effect of age between same sex groups (e.g., younger female vs. older female) and of the effect of sex between different age groups (e.g., older male vs. older female). As seen in Figure 2, comparisons showed that older males and females took significantly longer to complete head cycles in the 1-m wall fixed yaw exercise compared to younger males and females. Additionally, compared to younger female participants, older female participants also deployed longer cycles of head rotation during the 1-m handheld pitch exercise. No other significant difference was observed between younger versus older male and female participants in respect to AAD, APV, or duration of head rotation.

Finally, we observed significant correlations between head movement kinematics and our standard functional, physiological, and subjective outcome measures. These findings are summarized in Figure 3a (younger) and b (older).



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Correlations between Head Kinematics and Functional Outcomes

In younger adults, the APV in pitch head movement was negatively correlated with the TUG test (right turn), while the FGA only mildly negatively correlated with duration variability (e.g., CV and SD) of head rotation cycles (Fig. 3a, left). No correlations were observed between AAD and functional measures, except for AAD variability negatively correlated with the TUG right and FGA and gait speed positively correlated with AAD mean SD and variability. In older adults, however, weak negative correlations with APV were observed for all functional measures except gait speed and right DVA logMAR score (left visual hemifield), which showed no correlations (Fig. 3b, left). APV and APV variability in pitch and yaw head rotations were correlated with left DVA logMAR scores (right visual hemifield). The latter also correlated with APV mean of SD in yaw. The APV, APV mean of SD, and APV variability were negatively correlated with the TUG in pitch head rotations. The TUG also negatively correlated with the APV variability in yaw GSE. The variability of head cycle duration (e.g., SD and CV) negatively correlated with the FGA, which was also observed for APV in pitch head rotations (Fig. 3b, left). As in younger adults, AAD did not correlate with any functional measures in older participants. AAD mean of SD negatively correlated with left DVA logMAR scores and TUG (right turn) in pitch and yaw and with FGA in pitch. A positive correlation with gait speed was observed in pitch head rotations. As for AAD variability in older adults, it negatively correlated with the FGA in pitch and yaw, with the TUG in pitch, and with left DVA logMAR scores in yaw.

Correlations between Head Kinematics and Physiological Outcomes (vHIT)

In younger adults, APV mean of SD and variability in pitch and yaw GSE negatively correlated with mean vHIT scores in both left and right directions, with the most significant correlations observed in the horizontal plane, bilaterally (Fig. 3a, center). As for the APV, it negatively correlated with left horizontal vHIT gains in yaw and left posterior gains in pitch GSE. Additionally, the APV positively correlated with right posterior vHIT gains in yaw GSE. The CV of cycle duration negatively correlated with vHIT gains, except for the right anterior and left posterior planes. The mean cycle duration yielded a single positive correlation with left horizontal vHIT gains. AAD positively correlated with right posterior vHIT gains in pitch and yaw. AAD mean of SD negatively correlated with right and left horizontal and anterior vHIT gains in pitch. AAD variability negatively correlated with right anterior vHIT gains and left horizontal vHIT gains in pitch, in addition to right horizontal vHIT gains in yaw. In older adults, correlations with mean vHIT scores were more scattered compared to younger adults and with an inverted signal (positive vs. negative, respectively) (Fig. 3b, center). Of the correlations older adults showed between kinematic measures and mean vHIT scores, most occurred in the right horizontal plane (left visual hemifield), mainly in respect to APV and AAD mean of SD. AAD only correlated with left posterior vHIT gains. Older adults also presented correlations between CV of cycle duration and mean right anterior, left horizontal, and posterior vHIT scores. The mean cycle duration yielded a single negative correlation with right posterior vHIT gains.

Correlations between Head Kinematics and Subjective Measures

In younger adults, the ABC showed negative correlations with the CV of cycle duration, the APV mean of SD and variability in pitch, and APV mean of SD in yaw head rotations. The ABC also negatively correlated with AAD mean of SD and variability in pitch (Fig. 3a, right). The DHI was the only subjective measure to show a correlation (negative) with the actual APV, seen in yaw (horizontal) head rotations. The DHI positively correlated with AAD mean of SD in yaw, along with the Beck Anxiety and HIT scores. The latter also positively correlated with AAD mean of SD in pitch. Conversely, in older adults, in addition to negative correlations with APV mean of SD and variability, the ABC showed negative correlations with the APV in pitch and yaw head rotations (Fig. 3b, right). The ABC also correlated with the AAD and mean of SD, but only the first correlation was positive in pitch. The DHI was positively correlated with APV mean of SD and variability in pitch head

Fig. 1. Head rotation cycles. **a** Example range of average angular displacement (AAD) data from one younger (blue) and one older (red) healthy participant tested during continuous gaze stabilization exercises (GSE) with a 1-m wall target in pitch (vertical) and yaw (horizontal) head rotations. **b** Example range of average peak velocity (APV) data from the same younger and older participants. Traces and shades (e.g., blue, red) show the mean and SD of AAD and APV of head rotation, respectively. The center inset shows the position of IMU and planes in which data were recorded. The bar plots show the significantly difference in the mean cycle duration of head rotation between younger and older participants across all GSE.

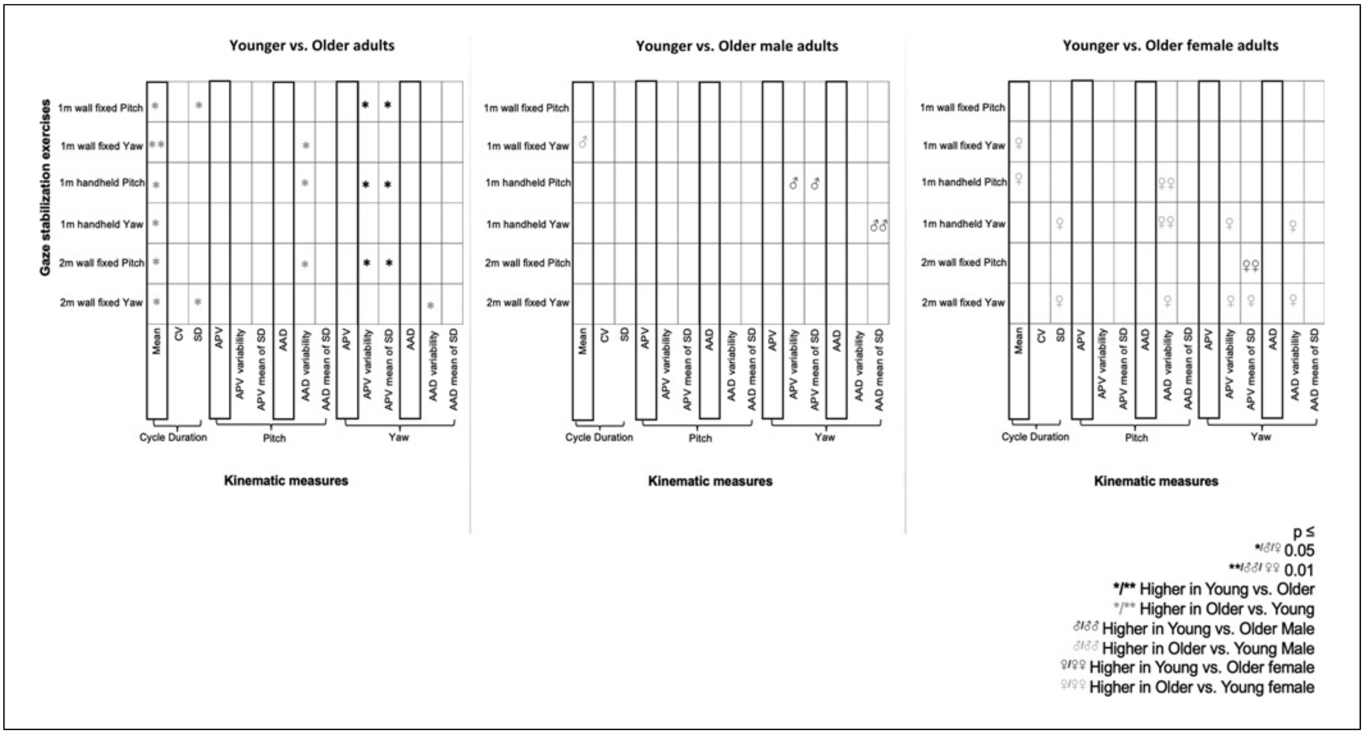

Fig. 2. Healthy aging significantly impacts head kinematics in continuous pitch and yaw movements – comparison of kinematic measures between younger and older participants (left), younger male and older male participants (center), and younger female and older female participants (right). Columns correspond to different kinematic measurements, while rows correspond to the 6 continuous GSE performed. Asterisks, male (circle below diagonal arrow), and female (circle above cross) symbols indicate differences at two significance levels (*, ♂, ♀: 0.05; and **, ♂♂, ♀♀: 0.01). Symbols in black indicate that the first group (e.g., younger) had lager values than the second group (e.g., older). Gray symbols indicated that the first group had smaller values than the second group.

rotations. The DHI also positively correlated with variability of cycle duration. The HIT scores showed positive correlations with APV in pitch and with the AAD in pitch and yaw head rotations.

Altogether, correlation analyses between head kinematics and functional, physiological, and subjective measures showed that vHIT is the most useful clinical tool to inform kinematic behavior in younger adults (e.g., negative correlations). In older participants, however, correlations with vHIT were scattered and overly positive; instead, the functional outcome measures were the most informative correlations between head kinematics and aging.

Discussion

This study investigated the extent to which healthy aging impacts head movement kinematics during six 30-s continuous GSE. Compared to young adults: (1) older participants moved significantly slower (e.g., increased duration of head rotation cycles), while (2) achieving equivalent APV in pitch and yaw head rotations, across all GSE. Additionally, (3) older adults took significantly more time (e.g., delay) to complete cycles of head rotation compared to younger participants in the yaw (horizontal) direction, and (4) while gazing at a target fixed on the wall 1 m away from their standing position. Finally, within group analysis showed that (5) the head kinematics strategies implemented were mostly independent of sex and hence similar between male and female participants in both groups, although women seem to be more prone to age-related adaptations as indicated by increased variability.

Our findings showed that older participants maintained their head cycle AAD and APV equivalent to that of younger participants at the expense of cycle duration. This suggests a prioritization strategy for control of head kinematics in which adaptations to head cycle duration are initially implemented, precluding changes in head cycle APV and ultimately AAD. This hierarchical assumption is further

Table 3. Kinematic ranges during continuous GSE in younger (Y) and older (O) adults

	Kinematic measures	1m wall fixed pitch	1m wall fixed yaw	1m handheld pitch	1m handheld yaw	2m wall fixed pitch	2m wall fixed yaw
Cycles of head rotation	(Y) Mean Duration (s)	0.53 ± 0.20	0.52 ± 0.25	0.56 ± 0.19	0.52 ± 0.17	0.54 ± 0.17	0.52 ± 0.16
	(O) Mean Duration (s)	0.70 ± 0.32 *	0.73 ± 0.27 **	0.72 ± 0.26 *	0.64 ± 0.21 *	0.67 ± 0.26 *	0.67 ± 0.26 *
	(Y) Duration SD	0.06 ± 0.03	0.08 ± 0.07	0.06 ± 0.03	0.06 ± 0.03	0.04 ± 0.02	0.05 ± 0.03
	(O) Duration SD	0.09 ± 0.07 *	0.11 ± 0.06	0.09 ± 0.08	0.08 ± 0.05	0.06 ± 0.05	0.09 ± 0.06 *
	(Y) Duration CV	0.11 ± 0.06	0.15 ± 0.12	0.11 ± 0.06	0.12 ± 0.06	0.08 ± 0.03	0.11 ± 0.07
	(O) Duration CV	0.13 ± 0.08	0.16 ± 0.09	0.11 ± 0.06	0.13 ± 0.05	0.09 ± 0.05	0.13 ± 0.06
Average Peak Velocity (APV)	(Y) Pitch average (deg/s)	320.15 ± 115.38	45.19 ± 32.40	283.99 ± 95.70	39.43 ± 30.08	275.26 ± 89.00	37.06 ± 34.39
	(O) Pitch average (deg/s)	260.32 ± 89.27	30.95 ± 15.53	247.18 ± 88.47	32.46 ± 22.95	259.38 ± 92.72	32.03 ± 18.54
	(Y) Pitch mean of SD	26.00 ± 9.89	11.61 ± 9.37	24.55 ± 11.08	9.70 ± 4.98	20.81 ± 7.20	8.83 ± 4.41
	(O) Pitch mean of SD	29.93 ± 19.53	9.09 ± 3.84	23.15 ± 9.17	9.00 ± 4.32	22.11 ± 9.57	8.44 ± 4.58
	(Y) Pitch variability	43.64 ± 16.70	17.22 ± 12.74	39.50 ± 14.66	13.82 ± 8.84	35.82 ± 14.90	12.76 ± 8.01
	(O) Pitch variability	46.48 ± 21.83	14.21 ± 6.83	37.52 ± 12.44	12.64 ± 6.69	39.70 ± 16.87	12.63 ± 8.17
	(Y) Yaw average (deg/s)	26.28 ± 20.42	447.89 ± 148.82	26.74 ± 15.07	437.60 ± 147.44	24.89 ± 16.74	384.44 ± 125.61
	(O) Yaw average (deg/s)	19.26 ± 11.58	388.25 ± 146.15	22.90 ± 18.31	388.34 ± 129.30	19.04 ± 12.76	371.37 ± 132.58
	(Y) Yaw mean of SD	9.45 ± 5.39	41.52 ± 14.21	8.53 ± 3.68	35.25 ± 14.81	7.50 ± 3.15	29.72 ± 10.88
	(O) Yaw mean of SD	1.95 ± 1.06 *	7.28 ± 2.87	2.12 ± 3.03 *	6.60 ± 2.96	1.86 ± 1.63 *	6.23 ± 2.95
	(Y) Yaw variability	14.80 ± 11.08	81.83 ± 33.10	11.55 ± 5.11	59.87 ± 26.26	11.30 ± 5.23	53.68 ± 20.90
	(O) Yaw variability	8.89 ± 5.71 *	75.85 ± 33.01	8.27 ± 4.15 *	66.12 ± 23.51	8.08 ± 4.54 *	64.90 ± 25.74
Average Angular Displacement (AAD)	(Y) Pitch average (deg)	26.56 ± 11.94	2.88 ± 2.21	25.07 ± 12.15	2.60 ± 1.76	23.58 ± 10.95	2.52 ± 2.40
	(O) Pitch average (deg)	26.94 ± 11.11	2.96 ± 1.75	26.85 ± 10.83	2.84 ± 2.20	27.15 ± 11.69	2.92 ± 1.88
	(Y) Pitch mean of SD	4.58 ± 1.81	4.03 ± 2.46	4.73 ± 2.28	5.03 ± 3.32	3.89 ± 1.52	2.94 ± 1.59
	(O) Pitch mean of SD	5.83 ± 2.56	4.45 ± 2.63	5.26 ± 2.41	4.48 ± 2.64	4.64 ± 1.98	2.88 ± 1.46
	(Y) Pitch variability	3.94 ± 1.31	1.30 ± 0.81	3.33 ± 0.92	1.27 ± 0.67	3.04 ± 0.95	1.12 ± 0.56
	(O) Pitch variability	4.16 ± 1.94	1.89 ± 0.92 *	4.07 ± 1.33 *	1.69 ± 0.98	3.89 ± 1.63 *	1.45 ± 0.78
	(Y) Yaw average (deg)	1.70 ± 1.10	38.33 ± 22.51	1.94 ± 1.02	37.47 ± 17.48	1.75 ± 1.05	32.65 ± 15.90
	(O) Yaw average (deg)	1.67 ± 1.32	43.15 ± 20.54	2.21 ± 2.05	38.90 ± 14.81	1.84 ± 1.77	39.65 ± 16.55
	(Y) Yaw mean of SD	3.08 ± 3.13	6.94 ± 4.91	2.37 ± 2.06	6.89 ± 5.62	1.86 ± 1.05	5.35 ± 2.76
	(O) Yaw mean of SD	1.95 ± 1.06	7.28 ± 2.87	2.12 ± 3.03	6.60 ± 2.96	1.86 ± 1.63	6.23 ± 2.95
	(Y) Yaw variability	1.45 ± 1.39	7.28 ± 3.44	1.19 ± 0.54	5.54 ± 1.75	1.05 ± 0.39	5.10 ± 1.42
	(O) Yaw variability	1.01 ± 0.48	7.75 ± 3.84	0.98 ± 0.50	6.85 ± 3.04	0.94 ± 0.45	6.64 ± 2.62 *

Mean duration of cycles of head rotation, APV in pitch and yaw, and AAD in pitch and yaw indicate the main outcome measures, where mean duration of cycle rotation is the only measure significantly different between groups across all GSE. * $p \leq 0.05$. ** $p \leq 0.01$.

supported by the fact that, while AAD and APV were not significantly different between groups, a trend toward difference was observed in both outcome measures, yet greater in APV. Hence, adaptations in head displacement seem to be secondary to adaptations in head velocity and likely to be deployed in more complex tasks. Such task-based prioritization behaviors are often reported in studies of aging and dual-task locomotion (e.g., posture first vs. posture second strategies) [31] but, to our knowledge, had not been characterized in the context of head kinematics.

Interestingly, in this study, gait speed did not show any correlations with the main head kinematic measures (e.g., mean cycle duration, APV, or AAD). This suggests that despite being a reliable, age-dependent predictor of morbidity and even incident disability [32, 33], gait speed should not be considered the sole factor in determining incident risk among healthy elderly. Conversely, our data showed that older adults with gait speed equivalent to that of younger adults still adapt their head movements (e.g., delayed completion of cycle duration and increased APV deviations) to maintain visual target stabilization while standing. Because variability of the gain of the VOR and vestibular perception has been reported to increase with head velocity [34], it is possible that older adults increased head cycle duration in an attempt to improve the afferent signal (e.g., VOR gain), favor visual perception, and weaken the extent of noise translated to the final motor output (e.g., head rotation). Although such behavior could increase visuospatial awareness, it likely favors visuo-vestibular noise that could result in loss of balance and increase the risk of falls [35]. This assumption is in line with evidence that older adults often fail to perceive loss in motor affordance or to translate that awareness to daily life, hence adopting nonconservative, dangerous locomotor strategies [36].

The efficient integration of visual information facilitates stable postural control and is an essential component of GSE. Aging, however, leads to decline in visual affordance (e.g., processing times) [37], along with visual (increased) and vestibular (decreased) reweighing [38]. Our results, however, showed that static DVA logMAR scores were very similar between groups. This indicates that static acuity assessment, while sensitive to adaptations of visual acuity in response to disease or advanced aging, is not sensitive enough to detect early visuomotor adaptations in healthy older adults. Conversely, negative correlations were observed between dynamic visual acuity logMAR scores and kinematic measures (head cycle APV and variability) in older but not in younger participants and only for leftward head rotations. This further suggests that stabilization of the fixed target in the right visual hemifield was not as efficient, justifying the compensatory kinematic adaptations observed.

Out of all clinical outcome measures, VOR performance (e.g., VOR gains via vHIT) was the most informative about head kinematics among GSE. Nevertheless, VOR performance was widely tied to kinematic internal variability rather than head movement adaptability, expressed as mean values of cycles of head rotations in both groups. In general, correlations between head kinematics and vHIT suggest that the greater the VOR/semicircular canal function, the greater the control (e.g., less APV and cycle duration variability) of head rotation cycles implemented by younger adults. Conversely, in older adults, a trend toward the inversion of such pattern was observed with greater mean vHIT scores associated with lower control (e.g., higher APV and cycle duration variability) of head rotation cycles. This behavior translated to older participants with higher VOR implementing greater APV deviations in both pitch and yaw GSE. This result is consistent with the prior reports that during dual-task while standing, healthy older adults have the capacity to tolerate increases in motor instability (e.g., postural control variability) to better accommodate a parallel visuo-cognitive task (e.g., target fixation) [39]. These adaptations to APV, however, did not translate to significant differences compared to younger adults as opposed to what was seen here for cycle duration. In the context of cycle duration, the increase in visual processing times in older age [37] may further explain the deployment of delayed head rotations as means to prolong visual target stabilization. Increasing cycle duration variability would also be helpful at preventing the expression of visuo-vestibular symptoms (e.g., dizziness), which indeed were not reported by either younger or older study participants.

Regarding the subjective measures in both younger and older adults, the ABC was the most informative, although under different patterns. That is, for younger participants, the ABC negatively correlated with APV SD. In older adults, in addition to negative correlations with APV SD and mean of SD, the ABC showed significant negative correlations with the APV mean in pitch and yaw head rotations. These results suggest that deterioration of range of velocity during controlled gaze fixation first manifests at the variability level (e.g., internal modulation) for as long as this compensatory "young strategy" (e.g., APV modulation) is still effective to maintain the final motor performance. With aging, this initial compensatory strategy would no longer be effective, which in turn would lead to deterioration at the final motor output (e.g., external modulation) along with increased movement variability.

A greater delay in the completion of yaw head rotations was observed in older adults gazing at a 1-m target fixed on the wall. This result suggests that regulating continuous GSE in yaw plane with near targets may be more challenging in terms of sensorimotor integration than pitch motion or doing GSE in either pitch or yaw motion at far target distances. We find this surprising, at least in part, since pitch head rotations impose the simultaneous integration of sensory information from more afferent signals (e.g., 4 vertical canals and the otolith organs) compared to yaw head rotations (e.g., 2 horizontal canals), which in theory should have added complexity to cortical processing. Instead, the greater delay seen in yaw may be associated with the fact that in horizontal head rotations, visual disparity is constantly impacted by facial structures (e.g., nose) which temporarily block one hemifield versus the other, unlike visual fixations in pitch. This transitional hemifield blockage would have caused perceptual deficits such as described in monocular observers to whom facial structures reduce gaze fixation affordance, especially when viewing time is limited [40]. This argument is further supported by evidence that horizontal disparity is the primary driver to effective position (depth) perception [41], while vertical disparity may favor direction perception [42] – less relevant in the context of fixed targets as presented in our

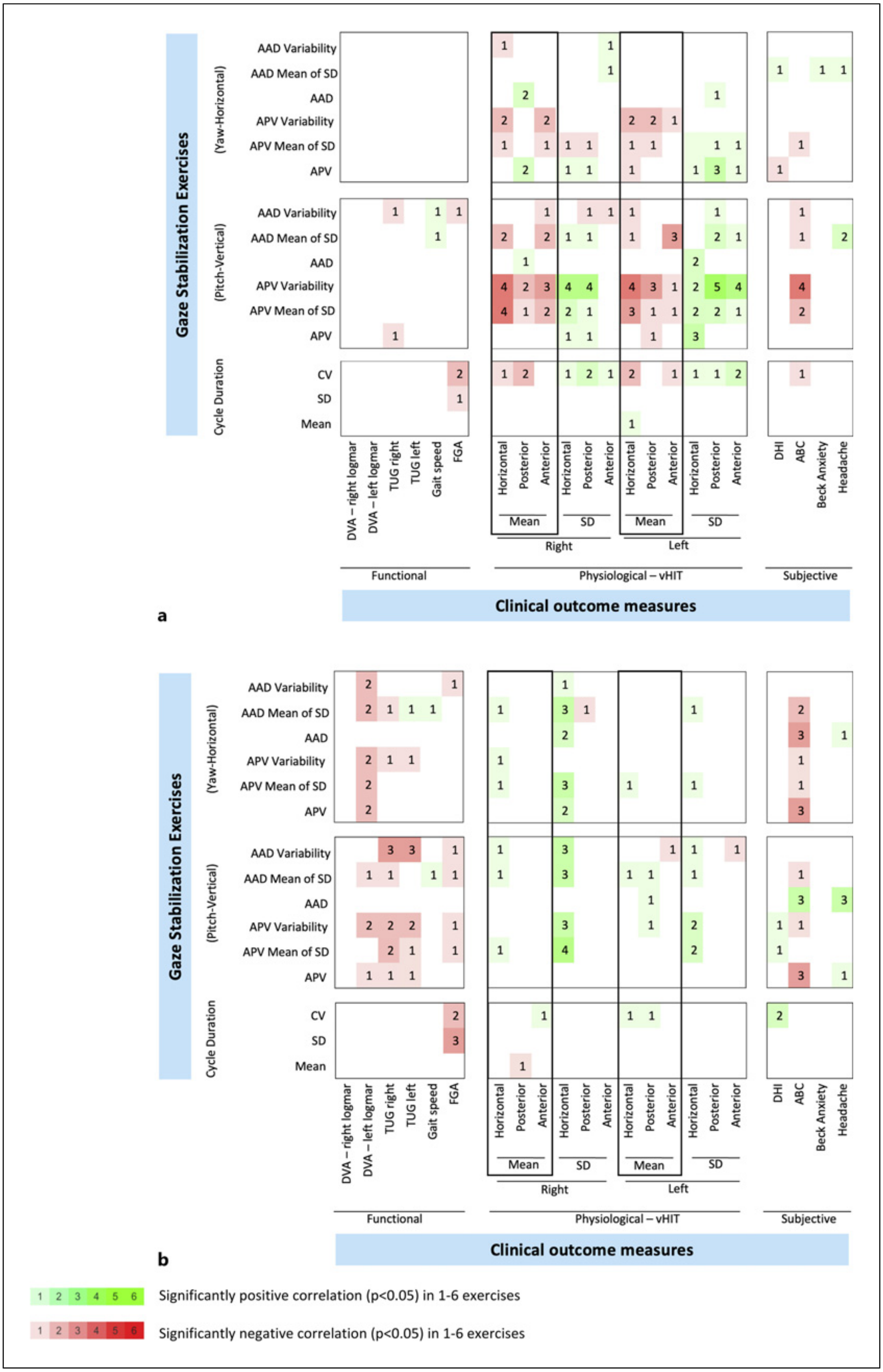

Fig. 3. a Correlations between the kinematic and clinical measures during the 6 continuous gaze stabilization exercises (GSE) performed by younger older adults. **b** Correlations between the kinematic and clinical measures during the 6 continuous gaze stabilization exercises (GSE) performed by older adults. Green and red squares reflect positive and negative correlations, respectively. Brightness and number in the squares indicate the number of exercises (1–6) with a significant correlation ($p < 0.05$).

design. Another potential aspect influencing head cycle duration was cervical joint proprioception, as cervical joint position error tends to increase with aging [43]. Such sensory loss likely leads to less consistent repositioning of the head in respect to visual targets, which based on our results appears to further aggravate sensory integration in yaw versus pitch head rotations during proximal visual target fixations.

Finally, the ability to maintain head rotation AAD and APV equivalent to that of younger participants during GSE while only adapting/modifying movement cycle duration may be associated with the combination of multiple factors. These factors include the presence of efficient vestibular function (normal vHIT) and visual acuity (normal DVA), paired with a locomotor apparatus not affected by disease (healthy older). Additionally, the reduced demand for dynamic balance control in static standing (no gait involved) could have favored the outcomes observed.

This study has some limitations which may affect the generalizability of the results reported. For instance, eye tracking was not used. Although eye tracking should increase our understanding of gaze behavior during GSE, head kinematics are known to be reliable at informing behavioral modifications during GSE in response to sensorimotor integrative conflicts caused by disease [21] or, in our case, aging. Second, it is also possible that our study suffered a selection bias and recruited a sample of highly functional older adults, which may explain some of the equivalency in performance observed between groups. We did attempt to mitigate such confounds by implementing multiple recruitment strategies and using a balanced sample distribution (e.g., size and sex). Moreover, our results are in line with previous research in healthy older adults where participants eventually deployed some behaviors equivalent to those of younger participants [36]. Other relevant aspects which were not controlled in our design were largely due to logistical challenges and include tracking the weight and dimensions of the head, as well as the motor affordance (e.g., strength, recruitment, density) of neck muscles. The first could have influenced, for instance, head movement velocity. The second may have affected, for instance, the range of head rotation. While not controlled, it is unlikely that those aspects significantly affected our results given the consistency in performance within and between groups, along with the fact that some of the exclusion criteria (e.g., orthopedic or rheumatologic conditions precisely including neck stiffness) would have further mitigated such influence. Finally, we did not control for handedness which can play an important role in the control of continuous movement. However, considering that the vast majority (~90%) of the world population is right-handed, it is likely that our sample was mostly composed of right-handed individuals.

Conclusions

In this study, we found that healthy aging alone imposes delays to cycles of continuous head rotations during gaze fixation in standing. We also identified that head kinematic control is further compromised in yaw versus pitch and while fixating near versus far visual targets. These behaviors contribute to loss of balance and the risk of falls while performing daily tasks of similar context. Such risk was further highlighted by the fact that older participants fail to perceive the delayed completion of their head motion control and implement gait speed equivalent to that of younger, optimally functional participants. In this context, it should be noted that unlike the widespread awareness of the benefits of cardiovascular exercise to prevent falls (e.g., hypotension), the potential of GSE to improve balance and prevent injury in the elderly is currently overlooked. Finally, this study suggests that older age should be considered by clinicians prescribing and/or interpreting GSE, which may need to be adapted in respect to both individual affordance and the distance where visual targets are placed.

Statement of Ethics

This study protocol was reviewed and approved by the Johns Hopkins Institutional Review Board, Approval No. 00059430. Written informed consent was obtained from all study participants in accordance with the World Medical Association Declaration of Helsinki.

Conflict of Interest Statement

The authors have no conflict of interest to declare.

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Author Contributions

K.E.C., M.C.S., O.A.Z., and W.H.S. designed the study. W.H.S. and J.L.M. performed the experiments. W.H.S. and O.A.Z. analyzed the data and prepared the figures and tables. W.H.S. and M.C.S. wrote the manuscript with input from J.L.M., O.A.Z., and K.E.C.

Data Availability Statement

The data that support the findings of this study are not publicly available as they contain information that could compromise the privacy of research participants but are available from the corresponding authors (mschube1@jhmi.edu) under the Institutional Research Board approval upon reasonable request.

References

1 CDC) CfDCaP. Older adult fall prevention. CDC; 2023. [Updated September 2022]. https://www.cdc.gov/falls/pdf/CDC-DIP_At-a-Glance_Falls_508.pdf

2 Prevention CFDCa. Deaths from older adult falls. CDC; 2021. https://www.cdc.gov/falls/data/fall-deaths.html

3 Moreland B, Kakara R, Henry A. Trends in nonfatal falls and fall-related injuries among adults aged≥ 65 years: United States, 2012–2018. MMWR Morb Mortal Wkly Rep. 2020;69(27):875–81. https://doi.org/10.15585/mmwr.mm6927a5

4 Souza WH, Grove CR, Gerend PL, Ryan C, Schubert MC. Regional differences in patient-reported outcomes as a proxy of healthcare practices for Americans living with vestibular symptoms. J Vestib Res. 2022;32(6):541–51. https://doi.org/10.3233/VES-220022

5 National hospital ambulatory medical care survey: 2020 emergency department summary tables. 2022.

6 Alyono JC. Vertigo and dizziness: understanding and managing fall risk. Otolaryngol Clin North Am. 2018;51(4):725–40. https://doi.org/10.1016/j.otc.2018.03.003

7 Kristinsdottir EK, Jarnlo G-B, Magnusson M. Asymmetric vestibular function in the elderly might be a significant contributor to hip fractures. Scand J Rehabil Med. 2000;32(2):56–60. https://doi.org/10.1080/003655000750045550

8 Curry SD, Carotenuto A, DeLuna DA, Maar DJ, Huang Y, Samson KK, et al. Higher readmission rates after hip fracture among patients with vestibular disorders. Otol Neurotol. 2021;42(9):e1333–8. https://doi.org/10.1097/MAO.0000000000003277

9 Alrwaily M, Whitney SL. Vestibular rehabilitation of older adults with dizziness. Otolaryngol Clin North Am. 2011;44(2):473–96. https://doi.org/10.1016/j.otc.2011.01.015

10 Bermúdez Rey MC, Clark TK, Wang W, Leeder T, Bian Y, Merfeld DM. Vestibular perceptual thresholds increase above the age of 40. Front Neurol. 2016;7:162. https://doi.org/10.3389/fneur.2016.00162

11 Deems DA, Deems RO, O'Malley BW Jr. Managing challenges in an aging vestibular system: rehabilitation strategies normalize balance function in a cohort of patients up to 99 years. Ear Nose Throat J. 2019;98(1):37–43. https://doi.org/10.1177/0145561318824541

12 Newman-Toker DE, Hsieh Y-H, Camargo JCA, Pelletier AJ, Butchy GT, Edlow JA, editors. Spectrum of dizziness visits to US emergency departments: cross-sectional analysis from a Nationally representative sample. Mayo clinic proceedings. Elsevier; 2008.

13 Cromwell RL, Newton RA, Forrest G. Influence of vision on head stabilization strategies in older adults during walking. J Gerontol A Biol Sci Med Sci. 2002;57(7):M442–8. https://doi.org/10.1093/gerona/57.7.m442

14 Agrawal Y, Zuniga MG, Davalos-Bichara M, Schubert MC, Walston JD, Hughes J, et al. Decline in semicircular canal and otolith function with age. Otol Neurotol. 2012;33(5):832–9. https://doi.org/10.1097/MAO.0b013e3182545061

15 Iwasaki S, Yamasoba T. Dizziness and imbalance in the elderly: age-related decline in the vestibular system. Aging Dis. 2015;6(1):38–47. https://doi.org/10.14336/AD.2014.0128

16 Jones SA, Beierholm U, Meijer D, Noppeney U. Older adults sacrifice response speed to preserve multisensory integration performance. Neurobiol Aging. 2019;84:148–57. https://doi.org/10.1016/j.neurobiolaging.2019.08.017

17 Cullen KE. Vestibular processing during natural self-motion: implications for perception and action. Nat Rev Neurosci. 2019;20(6):346–63. https://doi.org/10.1038/s41583-019-0153-1

18 Giannopulu I. Visuo-vestibular and somesthetic contributions to spatial navigation in children and adults. In: Mobility of visually impaired people: fundamentals and ICT assistive technologies; 2018; p. 201–33.

19 Cole KR, Goodman K, Volland L. Reporting of exercise dose and dosage and outcome measures for gaze stabilisation in the literature: a scoping review. BMJ Open. 2022;12(2):e049560. https://doi.org/10.1136/bmjopen-2021-049560

20 Hall CD, Herdman SJ, Whitney SL, Anson ER, Carender WJ, Hoppes CW, et al. Vestibular rehabilitation for peripheral vestibular hypofunction: an updated clinical practice guideline from the Academy of Neurologic Physical Therapy of the American Physical Therapy Association. J Neurol Phys Ther. 2022;46(2):118–77. https://doi.org/10.1097/NPT.0000000000000382

21 Wang L, Zobeiri OA, Millar JL, Souza Silva W, Schubert MC, Cullen KE. Continuous head motion is a greater motor control challenge than transient head motion in patients with loss of vestibular function. Neurorehabil Neural Repair. 2021;35(10):890–902. https://doi.org/10.1177/15459683211034758

22 Fatima SN, Tanveer F, Shoukat F, Ahmad A, Siddique K. Effects of balance training with and without gaze stabilization exercises on clinical outcomes in elderly patients with chronic dizziness: a randomized controlled trial. J Bodyw Mov Ther. 2022;32:46–50. https://doi.org/10.1016/j.jbmt.2022.05.007

23 Rinaudo CN, Schubert MC, Cremer PD, Figtree WV, Todd CJ, Migliaccio AA. Once-daily incremental vestibular-ocular reflex adaptation training in patients with chronic peripheral vestibular hypofunction: a 1-week randomized controlled study. J Neurol Phys Ther. 2021;45(2):87–100. https://doi.org/10.1097/NPT.0000000000000348

24 Rinaudo CN, Schubert MC, Figtree WV, Cremer PD, Migliaccio AA. Human vestibulo-ocular reflex adaptation reduces when training demand variability increases. J Assoc Res Otolaryngol. 2021;22(2):193–206. https://doi.org/10.1007/s10162-020-00775-y

25 Hall CD, Heusel-Gillig L, Tusa RJ, Herdman SJ. Efficacy of gaze stability exercises in older adults with dizziness. J Neurol Phys Ther. 2010;34(2):64–9. https://doi.org/10.1097/NPT.0b013e3181dde6d8

26 Roh M, Lee E. Effects of gaze stability exercises on cognitive function, dynamic postural ability, balance confidence, and subjective health status in old people with mild cognitive impairment. J Exerc Rehabil. 2019;15(2):270–4. https://doi.org/10.12965/jer.1938026.013

27 Lotfi Y, Rezazadeh N, Moossavi A, Haghgoo HA, Rostami R, Bakhshi E, et al. Preliminary evidence of improved cognitive performance following vestibular rehabilitation in children with combined ADHD (cADHD) and concurrent vestibular impairment. Auris Nasus Larynx. 2017;44(6):700–7. https://doi.org/10.1016/j.anl.2017.01.011

28 Hafström A, Malmström E-M, Terdèn J, Fransson P-A, Magnusson M. Improved balance confidence and stability for elderly after 6 weeks of a multimodal self-administered balance-enhancing exercise program: a randomized single arm crossover study. Gerontol Geriatr Med. 2016;2:2333721416644149. https://doi.org/10.1177/2333721416644149

29 Wang L, Zobeiri OA, Millar JL, Schubert MC, Cullen KE. Head movement kinematics are altered during gaze stability exercises in vestibular schwannoma patients. Sci Rep. 2021;11(1):7139. https://doi.org/10.1038/s41598-021-86533-3

30 Wrisley DM, Kumar NA. Functional gait assessment: concurrent, discriminative, and predictive validity in community-dwelling older adults. Phys Ther. 2010;90(5):761–73. https://doi.org/10.2522/ptj.20090069

31 Peterson DS. Effects of gender on dual-tasking and prioritization in older adults. Gait Posture. 2022;97:104–8. https://doi.org/10.1016/j.gaitpost.2022.07.247

32 Hardy SE, Perera S, Roumani YF, Chandler JM, Studenski SA. Improvement in usual gait speed predicts better survival in older adults. J Am Geriatr Soc. 2007;55(11):1727–34. https://doi.org/10.1111/j.1532-5415.2007.01413.x

33 Perera S, Patel KV, Rosano C, Rubin SM, Satterfield S, Harris T, et al. Gait speed predicts incident disability: a pooled analysis. J Gerontol A Biol Sci Med Sci. 2016;71(1):63–71. https://doi.org/10.1093/gerona/glv126

34 Nouri S, Karmali F. Variability in the vestibulo-ocular reflex and vestibular perception. Neuroscience. 2018;393:350–65. https://doi.org/10.1016/j.neuroscience.2018.08.025

35 Wagner AR, Chaudhari AM, Merfeld DM. Might vestibular "noise" cause subclinical balance impairment and falls? Int J Phys Med Rehabil. 2021;9(Suppl 8):001.

36 Souza Silva W, McFadyen B, Fung J, Lamontagne A. Effects of age on obstacle avoidance while walking and deciphering text versus audio phone messages. Gerontology. 2019;65(5):524–36. https://doi.org/10.1159/000499067

37 Li KZ, Bherer L, Mirelman A, Maidan I, Hausdorff JM. Cognitive involvement in balance, gait and dual-tasking in aging: a focused review from a neuroscience of aging perspective. Front Neurol. 2018;9:913. https://doi.org/10.3389/fneur.2018.00913

38 Koppen M, Ter Horst AC, Medendorp WP. Weighted visual and vestibular cues for spatial updating during passive self-motion. Multisens Res. 2019;32(3):165–78. https://doi.org/10.1163/22134808-20191364

39 Doumas M, Smolders C, Krampe RT. Task prioritization in aging: effects of sensory information on concurrent posture and memory performance. Exp Brain Res. 2008;187(2):275–81. https://doi.org/10.1007/s00221-008-1302-3

40 Good GW, Fogt N, Daum KM, Mitchell GL. Dynamic visual fields of one-eyed observers. Optometry. 2005;76(5):285–92. https://doi.org/10.1016/s1529-1839(05)70311-0

41 Farell B. What's special about horizontal disparity. J Vis. 2023;23(13):4. https://doi.org/10.1167/jov.23.13.4

42 Maekawa T, Kaneko H. Does changing vertical disparity induce horizontal head movement? PLoS One. 2015;10(9):e0137483. https://doi.org/10.1371/journal.pone.0137483

43 Alahmari KA, Reddy RS, Silvian PS, Ahmad I, Kakaraparthi VN, Alam MM. Association of age on cervical joint position error. J Adv Res. 2017;8(3):201–7. https://doi.org/10.1016/j.jare.2017.01.001