

Lighting Impacts on Gaze Behaviors in Older Adults during the Mobility Standardized Test in Virtual Reality

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Abstract

Changes in gaze coordination in older adults have been associated with worse mobility and previous research has investigated whether altering gaze behaviors could improve gait. However, most studies examining gaze behaviors in older adults have been conducted in well-lit laboratory settings. Reduced lighting is known to affect gait and increase fall risk, but the effect of lighting on gaze behaviors has not received much attention to date. In this study, we used a newly developed virtual reality navigation paradigm (Mobility Standardized Test or MOST) to assess gaze behaviors and the associated eye, head, and body movements while navigating through mazes in different light levels in young ($n = 14$) and older adults ($n = 20$). Both groups showed slower walking speed, gaze directed downward, reduced look-ahead distance, and more extensive visual scanning with the eyes and head in dim light. Older adults were more impacted in dim light, showing significantly slower speed, further increased downward gaze, and reduced head movements when scanning compared to the young adults. This study provides insight into how lighting impacts gaze behaviors in visually healthy young and older adults and establishes normative data for comparison with similar behavior in populations with vision loss.

Introduction

Vision is arguably the most important sense for navigating through complex spaces, allowing us to plan paths and detect features or obstacles from a distance (Patla, 1991, Patla, 1998, Patla et al., 1991). However, most of what is known about this process comes from controlled laboratory tasks that only approximate the demands of real-world navigation. As individuals age, how they use vision while walking begins to change. For example, older adults, particularly those with a history of falls, look more at the ground than young adults (Zukowski et al., 2021, Mak et al., 2026, Uiga et al., 2015). When navigating multiple obstacles in series, older adults fixate on upcoming obstacles sooner, indicating a need for a longer planning time (Chapman and Hollands, 2006, Domínguez-Zamora et al., 2020). These changes in gaze behaviors are associated with changing gait metrics such as increased spatiotemporal variability and more obstacle collisions (Chapman and Hollands, 2006, Domínguez-Zamora et al., 2020, Mak et al., 2026). Previous literature suggests that these gaze alterations could be a contributing factor to declining gait and that training better gaze strategies may improve gait (Mak et al., 2025, Young and Hollands, 2010). However, because this body of work is drawn almost entirely from laboratory settings, it remains unclear how well these gaze-gait relationships translate to more visually and physically demanding conditions of the real world (Uiga et al., 2015).

Real-world environments are typically exposed to changing light levels. Lighting is known to impact gait behaviors, yet its importance is often overlooked. In older adults, reduced lighting leads to more cautious movement, including slower speed (Figueiro et al., 2011, Kesler et al., 2005), reduced foot clearance (Choi et al., 2014), and increased variability (Figueiro et al., 2011, Huang et al., 2017, Kesler et al., 2005). This is unsurprising given that several age-related changes to the visual system, such as decreased contrast sensitivity and prolonged dark adaptation, degrade vision in dark environments (Lu et al., 2019, Owsley, 2016). Given the established relationship between gaze and gait, it is possible that these lighting-related

gait changes could be mediated by gaze behavior. However, the effect of lighting on gaze behavior has received little attention to date. This is an important area of investigation given (1) the potential of gaze behaviors to impact gait, and (2) the demonstrated impact that lighting has on gait and falls (Emad et al., 2025, Ramulu et al., 2021). However, studying these complex gaze-gait interactions under varying lighting conditions in the physical world poses significant safety risks for older adults as well as methodological challenges in precisely controlling illumination.

To address this, we utilized the Mobility Standardized Test (MOST), which is a newly validated virtual reality platform that offers a robust way to assess the impact of lighting on gaze behavior and mobility performance (Authié et al., 2024). It was originally developed to assess functional mobility in people with low vision at a range of light levels; however, its design makes it well suited for investigating the impact of lighting on vision in mobility in healthy populations as well. Participants must navigate through a series of mazes with different obstacle types at a range of light levels while their eye, head, and body movements are recorded. Thus, the MOST provides a controlled environment to assess how vision is used for mobility that goes beyond the straight-line walking commonly assessed in laboratory settings by incorporating more complex features across varying light levels frequently encountered in daily life.

This study uses the MOST system to analyze how young and older adults coordinate their gaze behavior while navigating various environmental features (turns, ground obstacles, suspended obstacles) at different lighting levels (dim: 1 lux; bright: 400 lux). We focus on (1) where do people look while they navigate the various maze elements? and (2) how do eye, head, and body movements differentially contribute to achieve these gaze positions? We hypothesize that, compared to young adults, older adults would exhibit a reduced look-ahead distance (i.e., looking closer to their feet) and a narrower spatial gaze coverage, evidenced by reduced visual scanning with the eyes and head. We further predict that a reduction in look-ahead distance would be strongly coupled with a decrease in gait speed, allowing older adults to maintain a similar look-ahead time (the temporal planning horizon) as young adults. Finally, we expect these age-related differences to be most pronounced in dim light, reflecting an interaction between age and lighting.

Methods

Participants

Fourteen young (5 female, age mean $\pm$ standard deviation: 22.2 ± 3.6 , height: $1.72 \pm 0.09\text{m}$) and twenty older adults (13 female, age mean $\pm$ standard deviation: 67.2 ± 7.0 , height: $1.67 \pm 0.09\text{m}$) completed all MOST trials. Participants were not eligible if they had any ocular condition, vision not corrected to at least 20/40, or any musculoskeletal, neurological or sensory condition that affected the way they walked. All participants provided informed consent before participating and all research procedures were approved by the University of Pittsburgh Institutional Review Board.

Protocol

Participants wore a HTC Vive Pro Eye headset to track head and eye movements and four Vive trackers (HTC Corp., New Taipei, Taiwan), placed on the front and back of the pelvis and both feet, to track body movements. The trackers and head movement data were collected at 30Hz and the eye-tracking data were collected at 90Hz. Custom software developed in Unity was used to display the virtual environment and record the movement data. Participants completed the entire MOST protocol, which is detailed fully in (Authié et al., 2024), but an overview is given here as well. The MOST requires participants to navigate a series of virtual mazes at increasing light levels. The mazes encompass a 5.2m x 3.6m area and each course length is 22m, consisting of 9 turns, and various obstacles (detailed below). There are 38 unique course configurations, thus preventing participants from memorizing a particular layout.

Participants were first acquainted with the VR environment by performing familiarization trials in bright light (400 lux). During the familiarization trials, participants were introduced to general course paths flanked by blocks with doors, which are designed to prevent movement off the path. Participants were also introduced to the different obstacles, including a plank to step over (10cm high, 50cm wide), a flag to duck under (bottom of flag is adjusted to participant eye height), cones or columns that block the path, and a dead-end segment. Participants practiced maneuvering through these various obstacles individually and together in a practice course configuration before moving onto the testing phase. Following initial obstacle practice, participants performed five training trials in the brightest light level to eliminate learning effects prior to testing (Authié et al., 2024). Subsequently, participants completed a 20-minute dark adaptation period to allow their eyes to adjust to the dimmest light level. Participants completed three mazes at each of six light levels, increasing in luminance from 1 lux to 400 lux. The three mazes were completed binocularly and monocularly (both eyes). Only data from the binocular conditions are presented here. In an initial analysis, we saw that there were minimal behavioral differences across the five brighter lighting conditions, but the dimmest condition was different from the others. Therefore, in this report, we focus on analyzing the data from the dimmest (1 lux) and brightest (400 lux) conditions. All participants were able to complete the entire protocol.

Outcomes

We considered 1. *where* participants looked and 2. *how* they achieved their particular gaze patterns through eye, head, and body movements across the different features of the mazes. Specifically, we examined behavior during turns, plank crossing (ground-level obstacle), and flag crossing (suspended obstacle). We defined each segment as beginning 1.5m before the feature of interest (e.g., the corner of the turn or the base of the plank) and ending when the participant reached the feature of interest. Because of the design of the courses, some features could be in closer proximity to each other than 1.5m. In that case, we trimmed the later segment such that it began only after the previous segment ended.

To analyze where participants looked as they completed the different maze features, we constructed 3D volumetric maps displaying where the top 50% of fixations were concentrated. We binned fixations into 10cm cubic regions and smoothed the resulting volumes using a gaussian filter (MATLAB function:

smooth3, with size of 3). Fixations were first identified by considering the local eye-in-head gaze data. We computed the angular velocity from the gaze vector data, filtered this using a 4th order low pass butterworth filter with 12Hz cut-off frequency, and identified fixations when the velocity remained below 100deg/s for at least 60ms in accordance with (Lajoie et al., 2018). We used a triangle ray intersection method to calculate the 3D intersection of the gaze vector, originating from the gaze origin expressed in world coordinates, with a particular surface in the 3D virtual environment. All computations/processing were completed using MATLAB 2025b (The MathWorks Inc.). To combine gaze locations across all the segments of a given type (e.g., all turns or all planks), we normalized the spatial location of the gaze locations with respect to the feature of interest (e.g., the corner or the middle base of the plank). After qualitatively inspecting these volumetric maps, we quantified the location of peak fixation frequency and the spread of fixations, and included these results in Supplementary Materials.

Look-ahead distance (e.g., how far someone looked in front of themselves on average) and look-ahead time (e.g., how much time it would take for someone's body to reach where they had been looking), were calculated as in real-world walking studies (Matthis et al., 2018). Look-ahead time was calculated as the average across all of a participant's fixations during a given segment type and light level, only including fixations where the participant came within 40cm of the fixation sometime after having made the fixation. We did not apply these additional conditions to the look-ahead distance, as the participant could look at locations that they never crossed or previously crossed; otherwise, we similarly calculated the average look-ahead distance across all of a participant's fixations during a given segment type and light level. We also considered the gaze point at every instance, regardless of eye event, to compute the "moving" look-ahead distance. We present the "moving" look-ahead distance in ensemble average graphs, which are described in more detail below.

To analyze how participants achieved the gaze behaviors described above, we considered the eye-in-head, head-on-body, and body movements that contributed. The eye-in-head data were extracted from the Vive Pro Eye Headset of the combined gaze in the local frame of the headset. The local eye vector was used to calculate the horizontal and vertical eye angles, according to the following equations (Talebi, 2024),

$$\text{Horizontal Angle: } \theta = \tan^{-1} \left(\frac{x}{z} \right)$$

$$\text{Vertical Angle: } \phi = \tan^{-1} \left(\frac{y}{\rho} \right), \text{ given } \rho = \sqrt{x^2 + y^2 + z^2}$$

Where x, z, and y are the mediolateral, anteroposterior, and vertical components of the gaze vector, respectively.

After computing the horizontal and vertical eye angles, an ensemble average of the time series data was calculated by splining the time series for each given segment to 101 points (0 to 100%). This allowed an average time series data to be calculated across all segments of a particular type (e.g., all turns). An average trajectory for each participant was computed and then an ensemble average across all

participants was calculated. In addition to the qualitative trajectory evaluation, we parameterized the peak-to-peak of the horizontal and vertical eye angle data for each participant to quantify the variability of the eye angles. For the vertical direction only, the mean vertical eye angle was calculated to assess the downward or upward gaze angle.

The head-on-body movements were computed by taking the relative quaternion of the headset with respect to the quaternion of the torso (combined from the front and back pelvis trackers). The orientation of the head with respect to the torso was normalized with respect to the neutral posture between the two segments as collected during a static body calibration. Euler angles were extracted from the relative quaternion using a yaw-pitch-roll (YXZ) decomposition. Similar to the eye angle data, ensemble averages of the head yaw and pitch were found and the peak-to-peak of head yaw and pitch were computed as well as mean head pitch.

Gait speed was calculated by finding the total distance traveled in the XZ plane and dividing by the time of interest.

Statistical Analysis

A series of linear mixed models was performed with the various gaze and eye/head/body movement outcomes as the dependent variables with main and interaction effects of lighting and group. A random effect for subject was included when there were multiple observations per participant for a given light level. When interaction effects were significant ($p < 0.05$), we used Student's t-tests to identify significant pairwise comparisons. All statistical analysis was done in JMP (v19, JMP Statistical Discovery LLC).

Results

Across each feature, we first qualitatively describe the general gaze, head, eye, and body movements then present the statistical results of the selected outcomes.

Turns

Right and left turns were evaluated together, mirroring the data from the right turns to align with the behavior during left turns. The gaze behaviors were qualitatively examined using volumetric maps showing gaze locations (Fig. 1) and ensemble average trajectories (Fig. 2). The 3D volumetric maps (Fig. 1) show the regions in the maze where fixations were most highly concentrated as participants were completing a given segment, separated by age group. These maps were generated by considering all participant fixations as they completed the given segment, and not at a single time instance. The 3D volumetric maps for turns show that, overall, both young and older adults looked farther around the corner in bright light (Fig. 1a,d). No clear group differences were seen in the volumetric map of fixations. This was confirmed by the strong similarity between groups for the ensemble average graphs of the look-ahead distance in both light levels (Fig. 2a,g). Differences in eye, head, and body movements between young and older adults were amplified in dim light. In dim light, older adults showed lower vertical eye

angle than young adults (Fig. 2b), but no difference in head pitch (Fig. 2c). Older adults showed little to no difference in the horizontal eye movements (Fig. 2d), but reduced head yaw (Fig. 2e) compared to the young adults in dim light. Older adults also walked slower in dim light compared to the young adults (Fig. 2f). The differences in vertical eye angle, head yaw, and gait speed between older and young adults diminished in bright light.

Planks

As seen in the volumetric fixation heat map (Fig. 1b) and the look-ahead distance series (Fig. 3a), older adults fixated closer to themselves/the plank than young adults in dim light. This decreased look-ahead distance in older adults in dim light was likely achieved by their lower vertical eye angle (Fig. 3b) and increased downward head pitch (Fig. 3c). Again, these differences went away in bright light (Fig. 3h,i). Older adults retained a reduced gait speed compared to the young adults regardless of light level (Fig. 3f,l). Plank crossing was not expected to elicit notable horizontal scanning and indeed there were no notable group or lighting differences in the ensemble average graphs of horizontal eye angle or head yaw (Fig. 3d,e,j,k).

Flags

When approaching the flags, behaviors were similar to those in the turns and planks. By examining the volumetric fixation heat map (Fig. 1c,f), no clear lighting or group differences emerged. The look-ahead distance time series suggested that older adults looked slightly closer to themselves when first approaching the flag in both light conditions (Fig. 4a,g), but this difference went away as they moved closer to the flag. Older adults showed lower vertical eye angle (Fig. 4b), increased downward head pitch (Fig. 4c), and reduced gait speed (Fig. 4f) compared with young adults in dim light. These differences went away or notably reduced in bright light (Fig. 4h,i,l). Similar to planks, we did not expect consistent horizontal scanning during flag crossing and this expectation was confirmed by relatively flat ensemble average graphs of the horizontal eye angle and head yaw for both groups and light conditions (Fig. 4d,e,j,k).

Statistical Results

The results of the statistical tests (F and p values) for each segment can be found in Table 1 with means and standard deviations of each outcome in Table 2. The findings are described below, summarizing across segments as possible.

Look-Ahead Distance: On planks and turns, there were significant lighting and interaction effects on the look-ahead distance. On average, participants looked closer to themselves in dim light (smaller look-ahead distance) and older adults showed a smaller look-ahead distance than young adults only in dim light. The reduced look-ahead distance of the older adults in dim light also led to a significant group effect on turns only. There were no significant effects on look-ahead distance for the flag segments,

although the lighting effect was trending toward significance. This finding supports our hypothesis that older adults look closer to themselves than young adults, particularly in dim light.

Peak-to-Peak Eye and Head Movements: Dim light evoked broader visual scanning behavior with the eyes and head. Across all segments, both groups showed increased horizontal peak-to-peak eye movement in dim light. On turns and planks, both groups also showed increased vertical peak-to-peak eye movement in dim light. There was a significant lighting effect on peak-to-peak head pitch on turns, where both groups showed greater peak-to-peak head pitch in dim light. The only exception to increased visual scanning in dim light was a non-significant lighting trend indicating that participants may display greater peak-to-peak head yaw in bright light during plank crossing only. While there were no group differences in peak-to-peak eye movements, older adults showed smaller head movements than young adults. During turns, older adults showed significantly reduced peak-to-peak head yaw compared to young adults. During flags, older adults significantly reduced peak-to-peak head pitch compared to young adults, with a similar trend that did not reach statistical significance on turns. The reduced head movement in older adults partially supports our hypothesis that older adults would have less broad visual scanning.

Mean Vertical Eye Angle and Head Pitch: Both lighting and age affected mean vertical eye and head angles. There was a significant lighting effect on the mean vertical eye angle and mean head pitch on all segments. For flags, both groups showed higher mean vertical eye angle in bright light. In contrast, for turns and planks, both groups showed lower mean vertical eye angle in bright light. Thus, the eye angle appears to be more strongly drawn in the direction of the feature of interest in bright light (e.g., upward toward the flag or downward toward the plank or corner). Both groups showed more downward head pitch in dim light on all segments. There were significant interaction effects on the mean vertical eye angle on planks and turns. For planks, older adults had a lower mean vertical eye angle than young adults in dim light only. For turns, both groups showed significantly lower mean vertical eye angle in bright light compared to dim light, with this lighting difference being larger in young adults. There were also significant interaction effects on mean head pitch on the flag and plank segments. On the flag segments, older adults showed more downward head pitch in dim light compared to bright light, with no lighting effect in the young adults. Similarly on planks, both older and young adults had more downward head pitch in dim light, but older adults showed a larger lighting effect than young adults. Overall, these results demonstrate that older adults often look downward more than young adults, through both head pitch and vertical eye angle, further supporting our hypothesis that older adults adopt altered eye and head movements that may reduce their visual sampling of the environment.

Look-Ahead Time and Gait Speed: As was hypothesized, older adults walked significantly slower than young adults. There was no group difference in look-ahead time. However, there were significant lighting effects on gait speed and look-ahead time on all segments. Both groups walked slower and had a greater look-ahead time in dim light, potentially indicating a need for a greater planning horizon.

Table 1

Statistical results (F- and p-values) for results of linear mixed models analyzing effects of group, lighting, and their interaction on gaze behaviors and eye, head, and body movements^a.

	Turns			Planks			Flags		
	Group	Light	Group* Light	Group	Light	Group* Light	Group	Light	Group* Light
Look-Ahead Distance	F = 5.14 p = 0.025	F = 29.34 p < 0.001	F = 4.38 p = 0.038	<i>F = 2.86 p = 0.096</i>	F = 18.24 p < 0.001	F = 15.20 p < 0.001		<i>F = 3.41 p = 0.070</i>	
P2P Horizontal Eye		F = 32.14 p < 0.001			F = 12.66 p < 0.001			F = 12.30 p < 0.001	
P2P Vertical Eye		F = 27.69 p < 0.001			F = 14.27 p < 0.001				
P2P Head Yaw	F = 5.23 p = 0.029				<i>F = 3.20 p = 0.077</i>				
P2P Head Pitch	<i>F = 3.18 p = 0.084</i>	F = 20.32 p < 0.001					F = 9.22 p = 0.005		
Mean Vertical Eye		F = 164.31 p < 0.001	F = 9.67 p = 0.002		F = 22.37 p < 0.001	F = 19.08 p < 0.001		F = 35.44 p < 0.001	
Mean Head Pitch		F = 142.55 p < 0.001			F = 56.58 p < 0.001	F = 7.26 p = 0.008		F = 4.00 p = 0.048	F = 9.14 p = 0.003
Gait Speed	F = 12.08 p = 0.002	F = 770.33 p < 0.001		F = 22.36 p < 0.001	F = 179.81 p < 0.001		F = 4.89 p = 0.034	F = 135.94 p < 0.001	
Look-Ahead Time		F = 33.07 p < 0.001			F = 10.26 p = 0.002			F = 13.59 p < 0.001	

a. Italicized cells indicate trends that did not reach significance ($0.05 < p < 0.10$)

Table 2
Means and standard deviations of outcomes for young and older adults across segments and lighting conditions.

Dim Light						
	Turns		Planks		Flags	
	Young	Older	Young	Older	Young	Older
Look-Ahead Distance (m)	1.52 ± 0.19	1.33 ± 0.21	1.54 ± 0.20	1.13 ± 0.27	1.75 ± 0.38	1.72 ± 0.41
P2P Horizontal Eye (°)	30.53 ± 7.45	29.62 ± 8.74	17.78 ± 7.52	20.15 ± 13.80	20.89 ± 8.51	20.66 ± 13.05
P2P Vertical Eye (°)	24.11 ± 9.27	23.41 ± 8.51	26.27 ± 11.82	27.92 ± 10.73	23.84 ± 7.65	21.25 ± 12.00
P2P Head Yaw (°)	40.11 ± 12.01	32.65 ± 6.09	29.71 ± 8.71	27.72 ± 10.56	24.65 ± 10.5	19.89 ± 8.77
P2P Head Pitch (°)	30.81 ± 7.04	26.17 ± 10.31	27.78 ± 8.42	24.23 ± 8.34	40.08 ± 13.64	25.49 ± 16.01
Mean Vertical Eye (°)	-5.36 ± 4.90	-8.04 ± 4.03	-4.07 ± 5.22	-8.47 ± 4.24	-2.72 ± 5.47	-5.58 ± 5.00
Mean Head Pitch (°)	26.97 ± 12.26	27.35 ± 9.61	27.48 ± 13.21	32.27 ± 11.14	11.68 ± 12.64	19.54 ± 11.63
Gait Speed (m/s)	0.61 ± 0.13	0.46 ± 0.09	0.73 ± 0.18	0.48 ± 0.11	0.73 ± 0.30	0.59 ± 0.16
Look-Ahead Time (s)	5.08 ± 2.19	5.91 ± 2.5	3.00 ± 1.66	3.56 ± 2.10	4.21 ± 2.39	3.84 ± 1.95
Bright Light						
	Turns		Planks		Flags	
	Young	Older	Young	Older	Young	Older
Look-Ahead Distance (m)	1.68 ± 0.23	1.67 ± 0.21	1.57 ± 0.26	1.73 ± 0.38	1.94 ± 0.35	1.89 ± 0.38
P2P Horizontal Eye (°)	26.38 ± 3.75	24.77 ± 3.8	12.68 ± 4.07	14.32 ± 4.84	14.31 ± 4.05	15.13 ± 3.99
P2P Vertical Eye (°)	20.95 ± 5.50	18.77 ± 5.07	20.66 ± 6.84	20.39 ± 5.42	21.85 ± 6.60	20.83 ± 7.56
P2P Head Yaw (°)	42.02 ± 16.28	33.81 ± 8.38	34.83 ± 9.81	29.94 ± 10.20	23.56 ± 7.40	22.07 ± 8.84
P2P Head Pitch (°)	26.09 ± 6.38	22.53 ± 6.09	24.18 ± 7.80	22.17 ± 7.02	33.8 ± 8.23	25.46 ± 13.7

Dim Light						
	Turns		Planks		Flags	
Mean Vertical Eye (°)	-10.16 ± 3.31	-10.97 ± 4.34	-9.61 ± 5.31	-8.69 ± 4.65	1.00 ± 7.28	-0.89 ± 6.11
Mean Head Pitch (°)	20.82 ± 12.29	19.38 ± 12.94	22.06 ± 12.68	20.81 ± 14.21	13.66 ± 15.27	9.83 ± 20.03
Gait Speed (m/s)	0.96 ± 0.13	0.86 ± 0.12	1.07 ± 0.20	0.87 ± 0.17	1.17 ± 0.17	1.04 ± 0.23
Look-Ahead Time (s)	2.69 ± 1.25	2.68 ± 0.83	1.72 ± 0.54	2.37 ± 1.06	2.53 ± 0.97	2.32 ± 1.07

Discussion

This study described gaze behaviors as well as the contributing eye, head, and body movements while participants navigated through virtual mazes using the MOST system. Qualitative graphs and quantitative outcomes showed how gaze and visual scanning behaviors are used to navigate through different environmental features and how these behaviors change as a function of lighting and age. Dim lighting evoked notable changes in behavior, including slower speed, gaze directed downward leading to reduced look-ahead distance, and more extensive scanning with the eyes and heads. Older adults were generally more impacted in dim light than young adults, with differences in gaze preferences, head movements, and speed often present in dim light but not bright light. These results contribute to the existing literature on lighting effects on mobility by revealing how gaze behaviors vary while walking in different light levels. This work also provides a template for analyzing gaze behaviors in low vision populations and provides normative data for both young and older age groups.

Both gait and gaze behaviors in visually healthy adults were impacted by lighting level. Consistent with previous literature, both young and older adults showed significantly reduced speed in dim light (Figueiro et al., 2011, Kesler et al., 2005), suggesting a more cautious approach. Both groups tended to look more downward in dim light, with increased downward vertical eye angle as well as increased downward head pitch, a similar strategy as seen in (Timmis and Pardhan, 2012, Timmis et al., 2014). Reduced lighting also led to increased visual scanning such as increased peak-to-peak horizontal eye movement, peak-to-peak vertical eye movement, and peak-to-peak head pitch across the various segments. This could be due to reduced lighting making it more difficult for participants to utilize peripheral vision (Warrant and Johnsen, 2013), thus necessitating broader scanning to be able to identify features of interest in the environment.

Older adults adopted different gaze and gait behaviors than young adults, particularly in dim light. Specifically, older adults reduced gait speed and increased downward gaze through either head pitch or vertical eye angle compared to the young adults in dim light. Given that the young and older groups had similar heights, the increased downward head pitch and vertical eye angle led to reduced look-ahead

distance as discussed in the next paragraph. Regardless of light level, older adults showed reduced head scanning in terms of peak-to-peak head yaw on turns and reduced peak-to-peak head pitch on flags. The reduced head scanning and lack of compensation in eye movements in older adults suggests that they have a narrower effective field of view in dim light. The reduced head scanning is consistent with previous literature reported in older adults in simulated driving (Savage et al., 2020). The reduced head movement could be a compensatory strategy adopted by older adults to lock their head to their trunk in conditions when they feel unstable (e.g., dim light) (Cocks et al., 2021). This behavior may be driven by psychological factors such as anxiety and fear of falling. Dim lighting can act as a postural threat, which triggers a shift toward a more cautious, consciously controlled walking strategy, often referred to as "reinvestment" (Uiga et al., 2015). Anxiety regarding potential missteps may compel older adults to prioritize fixating on the immediate ground to secure each foot placement, at the expense of scanning further ahead for anticipatory path planning (Ellmers et al., 2020, Mak et al., 2026). While these top-down cognitive factors explain the hyper-focus on the immediate path, a complementary bottom-up sensory explanation also exists. Peripheral vision and contrast sensitivity degrade in older adults (Ball et al., 1988, Owsley, 2016), which may reduce their ability to detect low contrast features in their periphery and thus reduce the drive to move the head in the direction of potential stimuli (Ivanov et al., 2016, Vargas-Martín and Peli, 2006, Jo et al., 2024). Similarly, reduced contrast sensitivity in older adults may also reduce the drive to proactively scan in dim light, as the reduced lighting would make it more difficult to identify the objects in the maze with a given contrast with respect to the background environment. Regardless of whether the mechanism is primarily sensory or cognitive, the reduced head scanning could elevate one's risk of colliding with potential obstacles in the travel path.

Both lighting and age affected look-ahead distance and look-ahead time. Look-ahead distance was significantly reduced in dim light, with participants looking about 0.25m closer to themselves in dim light compared to bright light. Additionally, older adults looked on average 0.2m closer to themselves than young adults in dim light. However, when we considered look-ahead time, we found no group differences. Older adults may have elected a similar planning horizon in terms of time as young adults, but the look-ahead distance was reduced given that the older adults elected a slower gait speed. These findings echo those of (Matthis et al., 2018), who found that in a group of young adults walking on outdoor terrains of increasing complexity, the look-ahead distance was reduced on more complex terrains, but because the participants also walked slower on the complex terrains, the look-ahead time remained similar. Matthis et al. suggested that this may indicate a "fundamental limitation of visual memory" such that motor actions are most effectively informed from input within the past 2 seconds. While we similarly show that look-ahead distance was reduced in our more difficult condition (dim vs. bright, analogous to their rough vs. smooth terrain), our results differ in that the look-ahead times continued to differ between lighting conditions. In fact, the look-ahead times increased in dim light compared to bright light. Mean look-ahead times in bright light were on the order of 1.5–2.5 seconds, which were similar to values reported by Matthis et al. However, mean look-ahead times in the dim light ranged from 3–5 seconds. This difference could be related to differences in visual behavior in the real world versus virtual environments, but more likely are specific to lighting effects, which have not been specifically investigated in real-world settings. The increased look-ahead time in dim light ultimately suggests a need for greater planning time in dim

light. If actions are best guided by visual information gathered within the past 2 seconds, adopting look-ahead times twice that in dim light could lead to less precise execution of motor commands and could negatively impact walking stability.

The MOST offers several advantages for evaluating mobility and visual scanning behaviors. First, using a virtual reality environment reduces time spent setting-up/tearing down equivalent physical mazes. Second, the MOST can reduce time spent processing spatial fixations. In real-world environments, manual processing is typically required to identify areas of interest of fixations, which can be time consuming and reduces the feasibility of recruiting large samples. Using the MOST data, we reconstructed the 3D surfaces of each maze and were able to automatically calculate the fixation locations by employing a triangle ray intersection method. Being able to use an automatic algorithm significantly reduces processing time and will allow for efficient analysis of eye tracking data in larger samples. Additionally, the virtual reality environment offers the ability to control the complexity of the walking task and lighting. Moving forward, the MOST could be a valuable platform for studying the effects of lighting on gaze-mobility interactions in both healthy and patient populations.

Limitations

One limitation of using VR for evaluating gaze behavior is a potential lack of ecological validity. Although the MOST includes important features such as turns, obstacles, and varying light levels, the obstacles are static and the participants are adapted to the dim light before proceeding. In reality, individuals frequently encounter dynamic obstacles (e.g., moving people) and rapidly shifting light levels without time to adjust. Future VR assessments could be developed to more specifically probe questions about gaze responses to such dynamic conditions. However, we believe the variety of maze configurations and precisely controlled light levels offered in the MOST make it a useful tool to study the role of vision in mobility and navigation.

In this study, the comparison was between the dimmest (1 lux) and brightest (400 lux) light conditions available in the MOST. This decision was based on our initial analysis that in these visually healthy individuals, behaviors in the dimmest condition were significantly different than all other light levels, even including the next highest light level of 3 lux. Given that individuals with vision loss experience more difficulties in dim lighting (Glen and Crabb, 2015, Owsley et al., 2006), participants with vision loss may continue to show altered behaviors even as lighting increases above the dimmest MOST condition. Future work can investigate if a specific light level is required to elicit similar behaviors between individuals with and without visual conditions.

Future Work

This study showed the potential of using VR for evaluating the impact of lighting on vision and mobility. We are planning to use a similar approach to examine the impact of lighting in populations with different visual impairments (e.g., central vs. peripheral visual field loss). We will identify different patterns of gaze behaviors in these populations and determine if differences in strategies appear beneficial or

maladaptive for completion of courses. Beyond assessment, the MOST protocol holds significant potential as a tool for targeted gaze training. Since maladaptive visual strategies, such as excessive downward gaze and reduced scanning, can elevate collision and fall risks, training individuals to alter where they look can be highly beneficial. Previous research has demonstrated that instructing older adults to adopt an external visual focus (e.g., directing gaze toward the destination or pathway rather than their feet) can restore proactive visual exploration and reduce spatiotemporal gait variability (Mak et al., 2025). Furthermore, targeted gaze training in older adults and visually impaired patients has been shown to successfully correct inappropriate visual sampling and significantly reduce obstacle collisions (Young and Hollands, 2010, Gunn et al., 2019). Future applications of the MOST could incorporate real-time feedback to safely train these proactive gaze strategies under challenging conditions, ultimately bridging the gap between clinical assessment and mobility rehabilitation (Neugebauer et al., 2024).

Declarations

Conflict of Interest:

Colas Authié is an employee of the Streetlab, the developers of the Mobility Standardized Test in Virtual Reality. The other authors have no financial or personal relationships with other people or organizations that could inappropriately influence or bias their work. The funding source had no involvement in the data collection, analysis, or interpretation.

Competing Interests

Colas Authié is an employee of the Streetlab, the developers of the Mobility Standardized Test in Virtual Reality. The other authors have no financial or personal relationships with other people or organizations that could inappropriately influence or bias their work. The funding source had no involvement in the data collection, analysis, or interpretation.

Author Contribution

Author Contributions: Michelle Harter: Conceptualization, Software, Data Curation, Formal Analysis, Visualization, Writing – original draft, Writing – review & editing; Galen Holland: Conceptualization, Methodology, Project Administration, Resources, Writing – Review & Editing; Mark Redfern: Conceptualization, Methodology, Writing – Review & Editing. Colas Authié: Conceptualization, Software, Methodology, Visualization, Formal Analysis, Resources, Writing – Review & Editing, Supervision; Rakié Cham: Conceptualization, Methodology, Visualization, Formal Analysis, Resources, Writing – Review & Editing, Supervision

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Data Availability

Data from this study may be available upon reasonable request to the authors.

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Figures

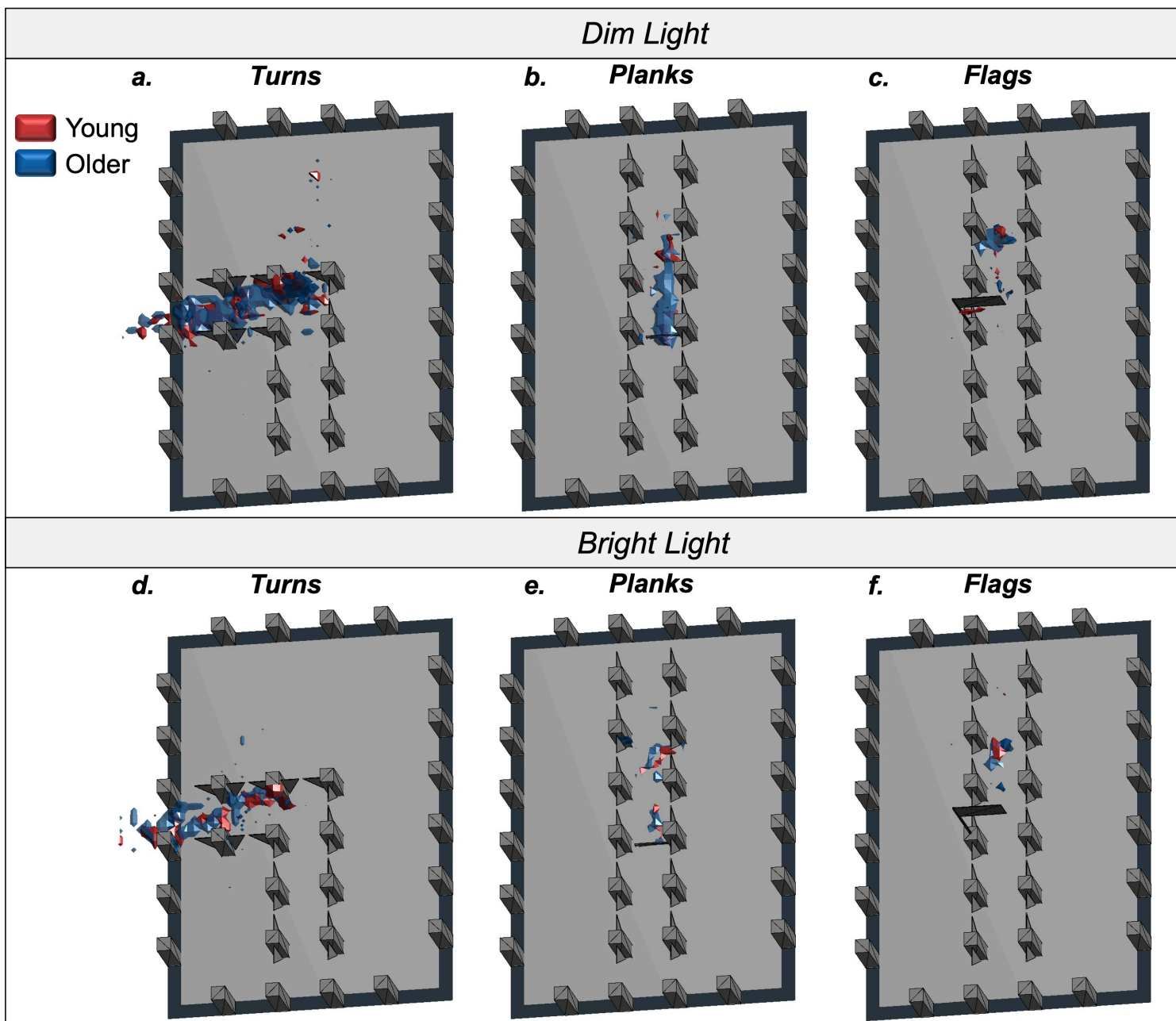


Figure 1

Volumetric heat maps illustrating most common fixation locations for young (red) and older (blue) adults while completing turns, planks, and flags at dim (a-c) and bright (d-f) light levels

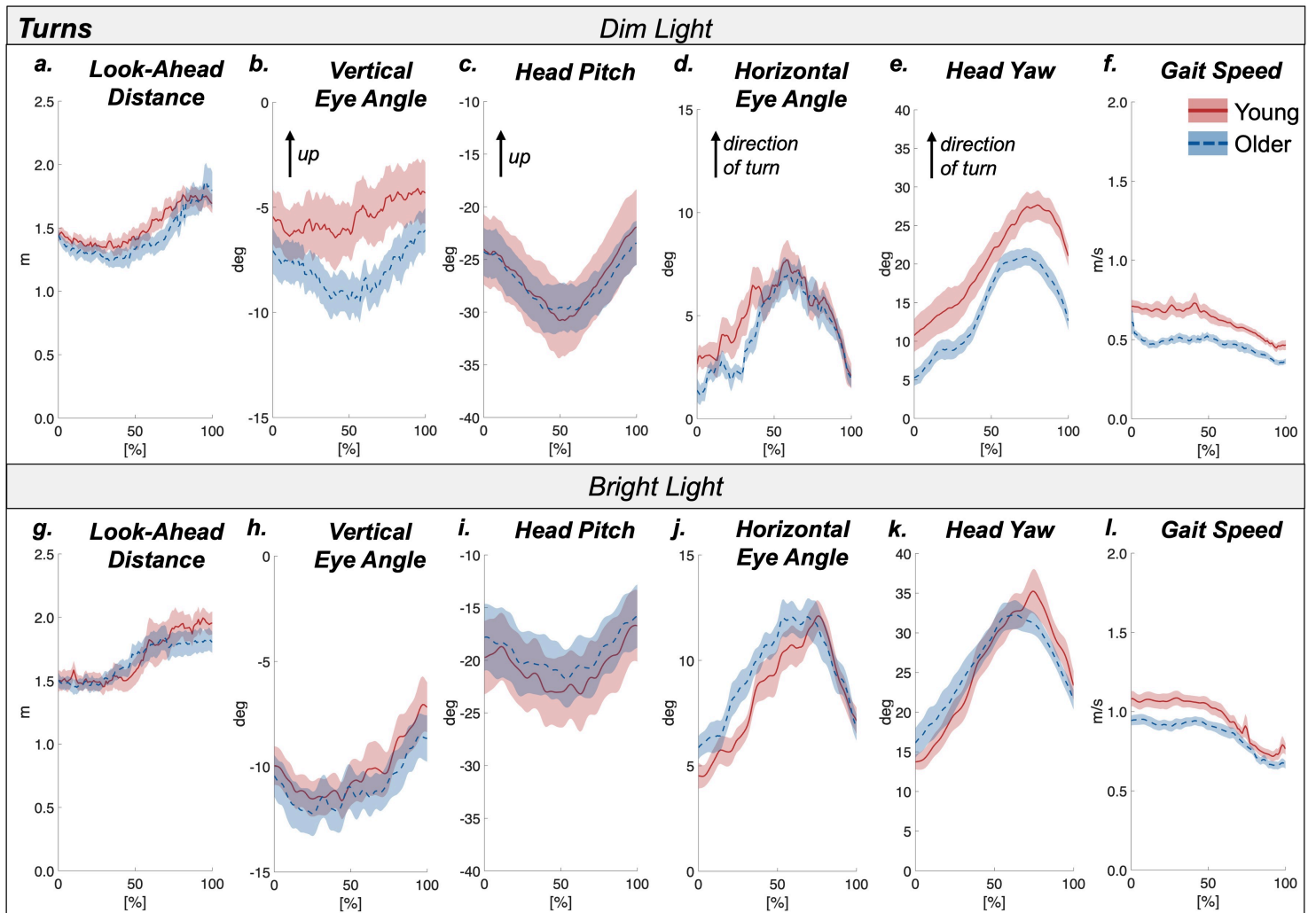


Figure 2

Comparison of behaviors between young (red) and older (blue) adults during turns at dim and bright light levels for (a,g) look-ahead distance, (b,h) vertical eye angle, (c,i) head pitch, (d,j) horizontal eye angle, (e,k) head yaw, and (f,l) gait speed. For the horizontal eye angle and head yaw data, the data from right turns was flipped to align with data from left turns, such that positive values indicate movement in the direction of the turn. Shading indicates ± 1 standard error across participants at each percentage

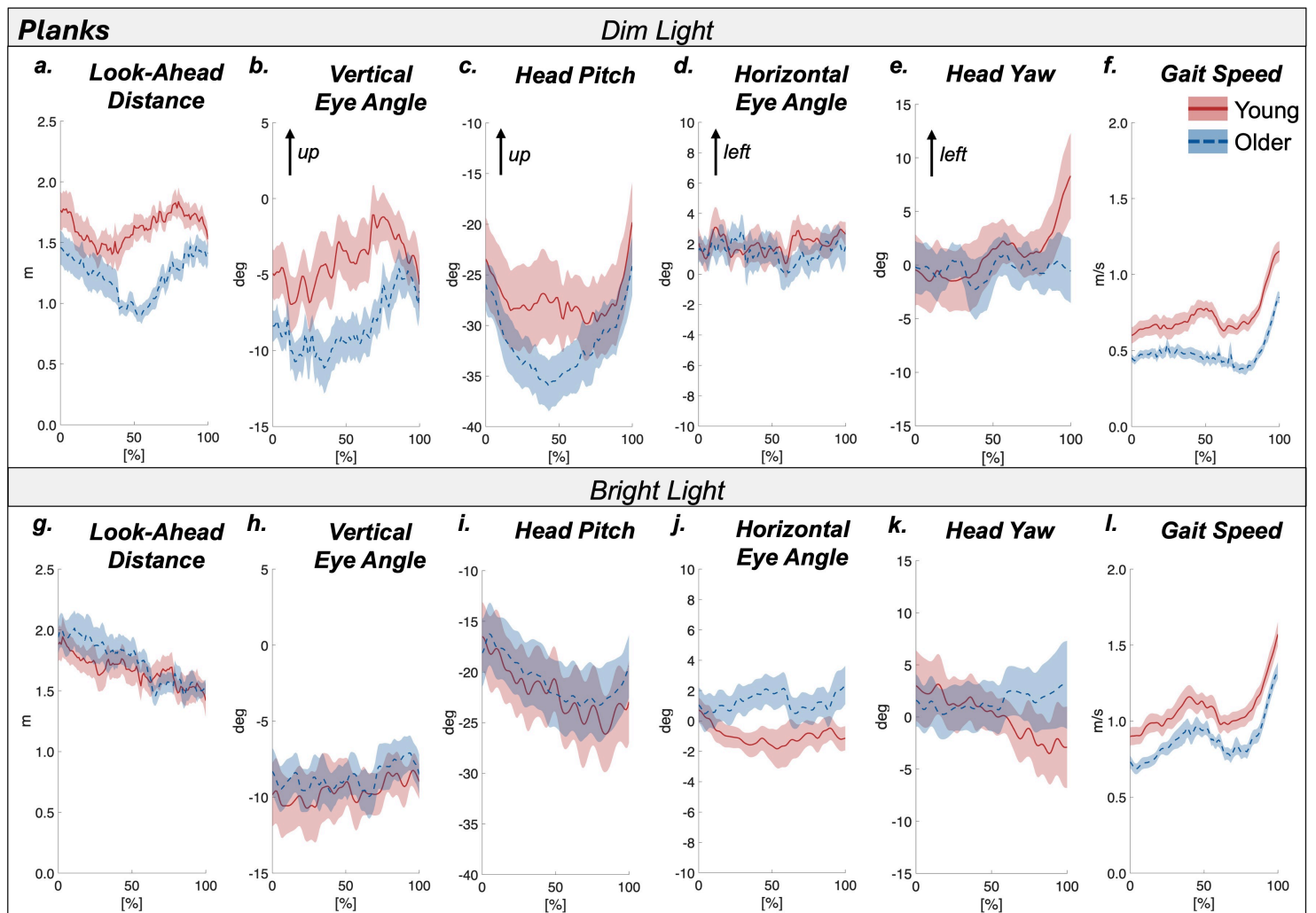


Figure 3

Comparison of behaviors between young (red) and older (blue) adults during plank crossing at dim and bright light levels for (a,g) look-ahead distance, (b,h) vertical eye angle, (c,i) head pitch, (d,j) horizontal eye angle, (e,k) head yaw, and (f,l) gait speed. Shading indicates ± 1 standard error across participants at each percentage

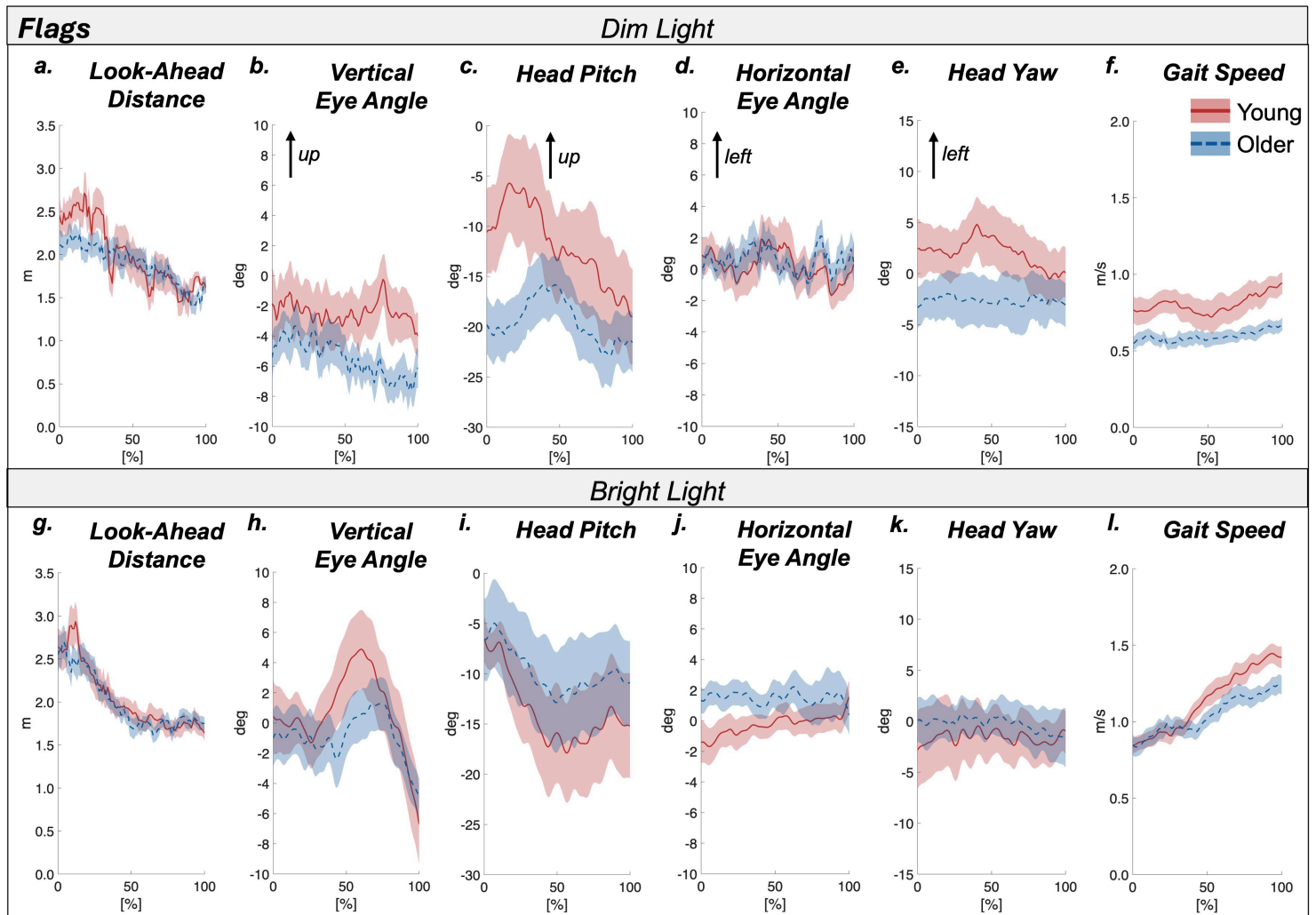


Figure 4

Comparison of behaviors between young (red) and older (blue) adults during flag crossing at dim and bright light levels for (a,g) look-ahead distance, (b,h) vertical eye angle, (c,i) head pitch, (d,j) horizontal eye angle, (e,k) head yaw, and (f,l) gait speed. Shading indicates ± 1 standard error across participants at each percentage

Supplementary Files

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