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The effects of physical motion cues on driving performance in older and younger adults

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A R T I C L E I N F O

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A B S T R A C T

Driving is a multisensory task relying on inputs from our sensory systems, including vestibular and somatosensory (i.e. physical motion cues). However, the effects of different physical motion parameters (translations and rotations) on driving performance during simulated realistic conditions is not well understood. Further, there are known age-related changes to vestibular function and multisensory integration, which may affect driving differently in older versus younger adults.

This study used a high-fidelity driving simulator to investigate whether different physical motion cues (from no motion, to yaw rotation, to 6-degrees of freedom motion) affect driving performance, and whether these effects differ between older and younger adults.

Forty-five younger adults (18–35 years, 26 females, 19 males) and 40 older adults (65 + years, 19 females, 21 males) completed driving scenarios under one of three motion conditions: no motion (fixed-base), yaw rotation (turntable), or full motion (turntable and hexapod). Scenarios included straight roads, turns, and hills, chosen to introduce specific types of physical motions. Driving performance measures included mean speed, speed variability, steering reversals, and variability in acceleration (longitudinal and lateral).

Motion-related effects were most pronounced between no motion and full motion conditions. However, for scenario elements involving pitch (e.g., hills), the largest effects were between yaw rotation and full motion conditions. Older adults exhibited more motion-related effects than younger adults, though not consistently across all elements or measures.

These findings enhance understanding of how physical motion influences driving behavior, with potential implications for vehicle design and simulator research.

1. Introduction

Driving is a complex, multisensory task that is informed by visual, vestibular, somatosensory (proprioceptive and tactile), and auditory cues (Correia Grácio et al., 2011; Campos et al., 2018; Ramkhalawansingh et al., 2016, 2017, 2018; Markkula et al., 2019;

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Campos et al., 2012; Pinto et al., 2008). The two sensory signals that provide particularly important information for self-motion perception used to guide driving behaviours are visual and vestibular inputs. Visual self-motion perception is informed by optic flow (Frenz & Lappe, 2005; Gibson, 1950; Larish & Flach, 1990; Warren et al., 1988) and landmark-based cues in the environment (Barhorst-Cates et al., 2020, 2021; Lambrey & Berthoz, 2007; Servotte et al., 2020). Inertial self-motion perception is informed by the vestibular system, which detects head accelerations and is comprised of the semicircular canals and the otoliths (Carriot et al., 2015; Cullen, 2019; Kingma, 2005; Macneilage et al., 2010; Purves et al., 2004), as well as the somatosensory system (Goldstein and Cacciamani, 2021). During basic perceptual self-motion tasks, ego-movement parameter estimation (e.g., estimates of one's own velocity, heading, distance travelled) is typically most precise when multiple senses provide congruent information compared to any single sense alone, with each sensory input weighted as a function of their relative reliability (Angelaki et al., 2011; Butler et al., 2010, 2014; Campos et al., 2012, 2014; Campos & Bülthoff, 2012; Fetsch et al., 2013; Ramkhalawansingh et al., 2018). However, much less is understood as to whether similar multisensory principles apply in the context of complex self-motion tasks such as driving (Ramkhalawansingh et al., 2017) and how they change over the adult lifespan. The objectives of the present study were to use a high-fidelity, motion-based driving simulator to systematically compare driving performance across different physical motion types (i.e., different types of vestibular/inertial stimulation; no motion, rotational and rotational + translational), and to examine whether any effects of motion types on driving performance are differentially observed in older versus younger adults.

1.1. *Aging and multisensory self-motion perception*

Age-related changes to sensory abilities are common and may have implications for self-motion perception and associated behaviours such as driving. Age-related changes to vision include reduced visual acuity and contrast sensitivity, smaller field of view, and slower visual processing speed (Jackson et al., 1999; Madden, 2007; Owsley, 2011). Compared to younger adults, older adults also have higher thresholds for detecting egocentric visual motion during linear and curvilinear movements (Warren et al., 1989; Gabriel et al., 2022), do not adjust their direction of locomotion in response to changing directional optic flow signals (Berard et al., 2009), and require greater magnitude differences to discriminate between optic flow speeds (Snowden & Kavanagh, 2006). Age-related changes to the vestibular system include a 25 % reduction in vestibular hair cells in the otoliths and a 40 % reduction in the semicircular canals in adults over the age of 60 years (Anson & Jeka, 2016; Rosenhall & Rubin, 1975; Taylor et al., 2015). Compared to younger adults, older adults also demonstrate higher vestibular perceptual thresholds for detecting physical accelerations (Bermúdez-Rey et al., 2016; Beylergil et al., 2019), demonstrate poorer spatial orientation during passive movements in the dark (Schweigart et al., 2002), and are less able to use vestibular information alone to recreate their path travelled during passive movements (Allen et al., 2004). Further, while older adults demonstrate higher direction-discrimination vestibular thresholds for sway, heave, roll tilt, pitch, and linear movements compared to younger adults, their thresholds for yaw rotation are largely comparable (Roditi and Crane, 2012; Bermúdez-Rey et al., 2016; Beylergil et al., 2019; Chang et al., 2014; Karmali et al., 2017; Kobel et al., 2021). These age-related reductions in vestibular sensitivity may result in older adults requiring more physical motion to detect and interpret self-motion, which could have implications for driving behaviour.

In addition to age-related declines in unisensory functioning, there is evidence that older adults also demonstrate heightened multisensory integration (Mozolic et al., 2012; de Dieuleveult et al., 2017). For example, compared to younger adults, older adults often demonstrate a proportionally greater increase in precision when congruent visual and vestibular cues are presented concurrently relative to individually (i.e., "heightened integration"). In a visual-vestibular heading discrimination task, Ramkhalawansingh et al. (2018) demonstrated that while both older and younger adults exhibited greater bimodal, relative to unimodal, benefits in precision, these benefits were proportionally larger in older adults. This heightened integration in older adults may be, in part, related to the Principle of Inverse Effectiveness (Meredith & Stein, 1986), whereby the benefits of integrating multiple sensory inputs with low reliability (e.g., due to age-related sensory declines) is greater than the benefits of integrating multiple highly reliable sensory inputs (which are individually already informative). However, the specific mechanisms underlying this multisensory enhancement in older adults and how this is related to complex, everyday percepts and behaviours such as driving remain unclear.

1.2. *Multisensory driving in older and younger adults*

Using a basic driving scenario, our team previously investigated how driving performance (e.g., speed, lane keeping) of older and younger adults differed depending on whether multisensory cues to driving were available (Ramkhalawansingh et al., 2017). Specifically, conditions included visual-only (unisensory) and visual combined with 6-degrees of freedom (6-DoF) physical motion (multisensory) conditions. Although older adults had significantly greater speed variability in the visual-only condition compared to younger adults, the magnitude of these age-related differences was significantly reduced when 6-DoF motion cues were added. In other words, speed variability was decreased to a greater degree with the addition of motion in older adults relative to younger adults. However, this was not the case for lane keeping (rotational and translational motion), where the addition of motion cues led to *more variable* lane keeping in older adults compared to when only visual cues were available. This may be due, in part, to limitations in the range of rotational motion cues provided by the hexapod motion platform in that study. While 6-DoF motion platforms provided translational motion along the x, y, and z axes as well as rotational motion across the pitch, roll, and yaw axes, the total motion envelope of most hexapod motion platforms remains restricted. For instance, accurately simulating yaw motion is particularly relevant for many driving tasks such as slow-speed turns. If there are limitations in the magnitude with which the yaw motion introduced by the motion platform can accurately match the visual self-motion cues, this could lead to undesirable sensory conflicts between the visual and vestibular senses. Since older adults may demonstrate heightened multisensory integration, they may be more sensitive to sensory conflicts when the physical motion range is limited (i.e., they could persist in integrating across largely conflicting cues), which could result in greater driving performance decrements than in younger adults (Ramkhalawansingh et al., 2018). However, the effects of particular motion types or ranges of motion on different parameters of driving performance have not been empirically studied in the context of aging.

The characteristics of other sensory inputs (e.g., visual inputs) and the nature of the driving tasks (e.g., straight vs. curved driving) can also influence the extent to which sensory conflicts are detectable and the relative reliability of the individual sensory inputs. For example, Ramkhalawansingh et al. (2017) used a relatively simple virtual environment with improverished visuals involving mainly optic flow and few idenitifiable landmarks. Further, the driving task itself was very simple (i.e., no traffic signals, no sharp turns, no stopping events, and no intersections). Therefore, the complexity of the visuals and the nature of the driving tasks may also affect the extent to which the visual and vestibular systems are stimulated. Further, with constant velocity motion, the vestibular signals are minimized, whereas under conditions involving frequent changes in velocity (acceleration/declerations) across different axes of motion, the effects of vestibular inputs on driving performance may be more apparent. One strategy to examine how these changes in velocity across motion axes affect driving performance is to strategicially select driving scenario elements that intentionally introduce these movements, such as curved segments and turns (yaw), as well as hills (pitch). To summarize, it could be that with more realistic visuals, more complex terrains/physical motion components, and/or higher driving task demands, the relative importance of motion cues and/or age-related effects on driving performance outcomes may differ.

1.3. The effect of different axes of motion on driving performance

Driving simulators offer the ability to introduce different types of motions varying in magnitude in a carefully controlled and systematic manner. While most driving simulators provide no motion cues (fixed-base), many simulators provide just rotational motion, just for-aft translational motion, or some combination of different types of rotation and translation, including 6-DoF motion and beyond. However, even "full" motion simulators have a limited motion envelope. Therefore, understanding how the introduction of each of these types of motion affects driving performance is important for: a) the foundational knowledge of understanding how different types of inertial inputs (e.g., vestibular cues) contribute to self-motion perception and associated behaviours, and b) applied knowledge regarding vehicle and simulator design.

Past stimulator studies have shown that, compared to fixed-base simulators, full motion simulation results in slower driving and lower lateral accelerations (Correia Grácio et al., 2011; Siegler et al., 2001), fewer steering reversals, and are more likely to increase the likelihood of completing a slalom course without crashing (Berthoz et al., 2013; Colombet et al., 2008; Feenstra et al., 2010; Pinto et al., 2008; Wolters et al., 2018). Others have demonstrated that, compared to no motion, full motion simulation results in fewer heading errors and lane departures (Greenberg et al., 2003; Savona et al., 2014), and better disturbance rejection performance (responding to simulated wind gusts via changes in the steering wheel rotation) (Lakerveld et al., 2016; Wolters et al., 2018). Theoretical studies that examined contributions of individual motion axes have found that driver models are better able to adhere to a prescribed driving path with yaw motion compared to no motion (Markkula et al., 2019). Still others investigated combinations across several motion axes. For example, Savona and colleagues (2014) investigated how different combinations of lateral motion (lateral tilt + longitudinal and lateral translational motion), yaw motion, and roll motion differentially affected simulator driving performance. They found that only lateral motion (high pass filtered translation with roll tilt coordination) had a significant effect on driving performance, leading to fewer steering reversals during a slalom maneuver as lateral motion gain increased. Yaw motion had a significant effect in this case, while the addition of high pass filtered roll to the roll from tilt coordination had no effect at all on driving performance (Savona et al., 2014). Lakerveld and colleagues (2016) investigated the combination of yaw and sway motion and found that sway motion led to improved disturbance rejection performance, while yaw motion led to reduced steering control activity with worse lane keeping. Finally, Hogema and colleages (2012) found that when driving through turns, the addition of extended yaw motion led to comparatively smaller steering wheel amplitudes, slower lateral accelerations, slower speeds and slower longitudinal accelerations (Hogema et al., 2012). Few studies have investigated the role of 360-degree yaw on driving performance, using a centrifuge motion channel, and even fewer have done so using more realistic and varied visual and inertial scenario elements that can stimulate the various axes of motion. Importantly, studies that have considered the effects of different axes of motion on the driving performance of older adults are, to the best of our knowledge, largely missing, which is relevant given the extent to which a) vestibular function changes with older age, b) multisensory, visual-vestibular processing changes with older age, c) the importance of understanding how age-related sensory changes may influence driving performance outcomes.

1.4. Current study

The objectives of the present study were to use a high-fidelity, motion-based driving simulator to 1) systematically introduce and compare driving performance across different motion types, including no motion ("fixed-base") vs. yaw motion only ("turntable") vs. full 6-DoF motion ("full motion") and 2) examine whether any effects of motion types on driving performance are differentially observed in older versus younger adults. Scenario elements were strategically chosen to introduce inertial cues across various motion axes including, for example, straight segments (linear translations), turns (yaw rotations), and hills (pitch rotations).

2. Methods

2.1. Participants

Forty older adults (65 + years: 19 females, 21 males) and 45 younger adults (18–35 years: 26 females, 19 males) were recruited from the community. Eleven older adults (3 in the fixed-base, 3 in the turntable condition, and 5 in the full motion condition) and seven younger adults (3 in the fixed-base, 2 in the turntable condition, and 2 in the full motion condition) withdrew prior to completing the experiment due to simulator sickness and were not included in the analysis. Thus, the final sample was comprised of $n = 22$ participants in the fixed-base condition (13 younger, 9 older adults), $n = 22$ participants in the turntable condition (12 younger, 10 older adults), and $n = 22$ participants in the full motion condition (13 younger, 9 older adults). The sample size was a priori calculated to provide sufficient test power for detecting large effects ($\eta^2 = 0.14$) for analyses involving the 2-level factor age (1-beta = 0.87) and the 3-level factor motion (1-beta = 0.79), respectively. Demographic information as well as age and sex distributions are provided in Table 1. All participants were pre-screened to ensure that they held a valid driver's license and had no serious medical conditions (e.g., history of seizures, vestibular disorders, heart conditions), no physical conditions that may affect their driving ability (e.g., hip or leg injury), did not use medications that may impair driving performance, had no self-reported uncorrected visual or hearing impairments, and were not highly susceptible to traditional motion sickness (e.g., while travelling with car, boat etc.). All older participants passed the Montreal Cognitive Assessment screening cut-off for mild cognitive impairment (>26/30; Nasreddine et al., 2005). Participants were randomly assigned to one of three different motion conditions: fixed-base, turntable, or full motion. Participants were compensated $15/hour for their time. This study abided by the principles set forth by the Declaration of Helsinki and was approved by the Research Ethics Boards of the University Health Network (REB 18–5432) and the University of Toronto (Protocol #: 00037464).

2.2. Apparatus

The driving task took place in DriverLab (Haycock et al., 2016), a high-fidelity driving simulator located at KITE's Challenging Environment Assessment Laboratory (CEAL), Toronto Rehabilitation Institute – University Health Network (Fig. 1). DriverLab is equipped with a full-sized passenger car (Audi A3) containing all its original internal components (e.g., steering wheel, gas/brake pedals, seats, and dashboard). The vehicle is surrounded by a curved projection display with 12 1920x1200@120 Hz projectors, creating a seamless 360-degrees horizontal field-of-view immersive experience. DriverLab also has vehicle-integrated surround sound (Pioneer VSX-45 Receiver, 5.1 sound; JL Audio powered sub and Focal speakers). Motion cuing is provided via a turntable with +/-360-degrees of yaw rotation upon which the vehicle is mounted inside the dome, and the entire dome is mounted on a Bosch-Rexroth Hymotion 11,000 6- DoF hexapod motion platform. A classic washout motion cueing algorithm was utilized, with all rotational channels (including yaw) set to a gain of 0.4, heave at 0.3, and surge and sway at 0.4, with second order high-pass filters in all axes. The filter break frequencies were set at 2 rad/s for the translational degrees-of-freedom, while roll and pitch were set at 0.05 rad/s and 0.7 rad/s in yaw. The low-pass tilt-coordination filters for surge and sway were third order, combining a 2 rad/s second order and 50 rad/s first order filter, with rate limits of 6-degrees. The motion cueing was developed in the MathWorks' Simulink environment, compiled and run in real-time using Quanser's QUARC operating system (Bukal, 2020), with a vehicle dynamics model built in Mechanical Simulation's CarSim.

Table 1
Demographics and baseline sensory, motor, cognitive functioning scores.

	Younger Adults		Older Adults		
	Mean	*SD*	Mean	*SD*	**p* − value
Age (years)					
All Participants	26.13($n = 38$)	4.79	73.96($n = 28$)	5.77	< 0.001
Fixed-base: Females	27.37($n = 8$)	6.16	71.00($n = 4$)	3.82	< 0.001
Fixed-base: Males	26.20($n = 5$)	2.58	72.30($n = 5$)	5.24	< 0.001
Turntable: Females	30.20($n = 5$)	7.15	72.66($n = 3$)	3.74	< 0.001
Turntable: Males	24.00($n = 7$)	3.06	74.85($n = 7$)	4.25	< 0.001
Full Motion: Females	24.67($n = 9$)	3.64	71.25($n = 4$)	7.84	< 0.001
Full Motion: Males	25.50($n = 4$)	3.87	80.00($n = 5$)	8.12	< 0.001
Static Visual Acuity					
Better Eye Static Acuity Score (Snellen)	21.14	7.23	35.14	12.78	< 0.001
Dynamic Visual Acuity					
Dynamic Visual Acuity vertical	23.98	7.49	43.57	18.74	< 0.001
Dynamic Visual Acuity horizontal	30.14	9.77	46.57	19.43	< 0.001
Balance					
COP path length (cm) eyes open tandem	45.83	32.11	57.98	29.95	*ns*
COP path length (cm) eyes closed tandem	100.90	77.46	124.65	64.16	*ns*
Cognition					
MoCA/30			26.82	2.24	

* *p*-value from independent samples t-tests comparing older to younger adults.

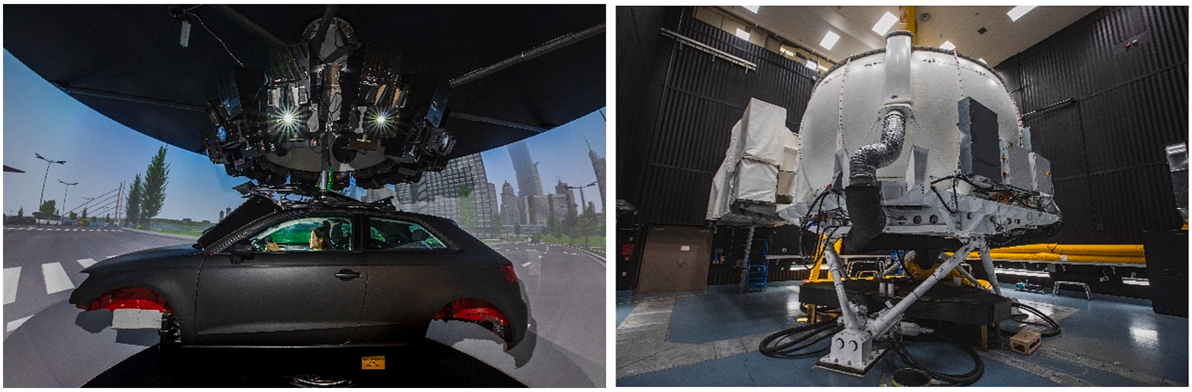

Fig. 1. Interior and exterior view of DriverLab (left) and DriverLab mounted on the hexapod motion platform (right).

2.3. Driving scenarios

The driving scenarios were developed and presented using Oktal SCANeR Studio version 1.8 and MATLAB R2018b (The MathWorks Inc., 2018). The visual driving scene consisted of clear daytime driving conditions on a two-lane road with 2 m sidewalks flush with the height of the road to prevent off-road excursions causing physical disturbances in the full motion condition. Each scenario contained elements of urban, suburban, and rural areas created by populating the periphery with buildings, houses, foliage, and parks. Traffic signs included speed limit signs and yield signs. Each scenario was approximately 12 km long and took between 12 and 15 min to complete. There was an equal number of left and right curves, with different radii randomly counterbalanced between straight segments, presenting participants with lower to higher ranges of centripetal accelerations. The scenarios also included two hills with peaks at 7.5 m and a 5 m trough which were used to introduce physical pitch movements during the full motion condition. These values (combinations of radii, height, velocity) were selected to represent typical accelerations that people experience when driving and to generate supra-threshold vestibular input for younger adults and older adults (Bermúdez-Rey et al., 2016; Karmali et al., 2017). The scenarios included four intersections with yield signs requiring a turn. No other moving objects (e.g., vehicles, pedestrians, animals) or obstacles were included in the scenarios. Fig. 2 illustrates a visualization of the sample scenario elements. Dependent variables (See section 2.4.7) were calculated separately for straight segments, turns, and hills as a way of evaluating how the unique motion parameters involved in each of these scenario elements that differed primarily on linear/translational motion, rotational motion (yaw), and rotational motion (pitch) respectively, influenced driving performance.

An 8–10 min long practice drive including all curves (no intersections or hills) was used to familiarize participants with the driving simulator. Within each of the three experimental conditions (fixed-base, turntable, full motion) participants also completed three separate drives. All participant groups drove with no motion on Drive 1 (used as a comparative control drive across groups, with no driving performance differences between groups observed) and then drove in their respective physical motion conditions in Drives 2 and 3. All drives were comprised of the same scenario elements (e.g., curves, turns, hills), but these elements were presented in different orders across the three scenarios to minimize practice effects.

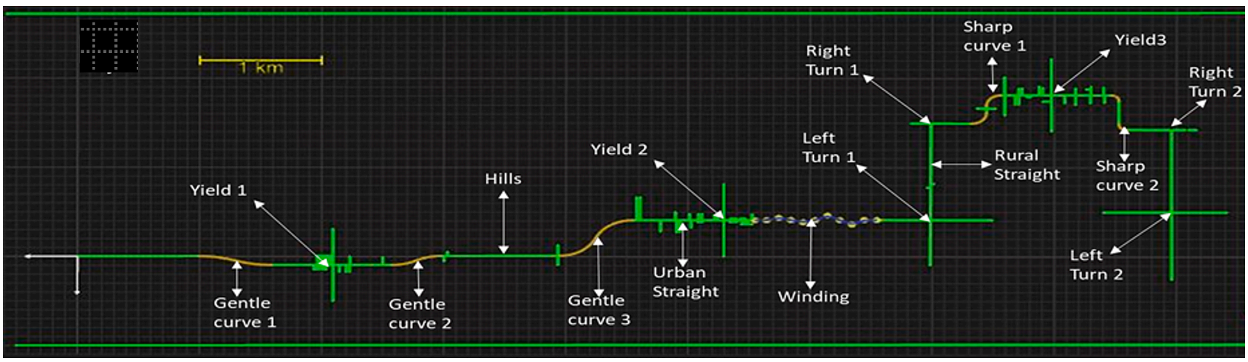

Fig. 2. Example top-down view of the road networks for one drive with scenario elements labeled. All drives contained the same scenario elements, but presented in different orders.

2.4. Baseline assessments

2.4.1. Static visual acuity

To measure corrected visual acuity, each eye was tested standing two meters away from an Early Treatment Diabetic Retinopathy Study (ETDRS) eye chart while wearing corrective lenses as required. Higher logMAR scores indicate worse visual acuity.

2.4.2. Dynamic Visual Acuity (DVA)

Participants completed a dynamic visual acuity test, which indirectly assesses the Vestibular Ocular Reflex (VOR), a measure of vestibular functioning (Herdman et al., 1998; Vital et al., 2010). Participants were asked to sit on a chair, 2 m away from the ETDRS visual acuity eye chart wearing corrective lenses as required. The experimenter then placed their hands on the participant's head and oscillated their head in the horizontal axis and then in the vertical axis at approximately 2 Hz. Participants were asked to read the characters on the chart with both eyes while their head was in motion, stopping when they were no longer able to read the characters. Their score was based on the difference between their best-eye static visual acuity test score and their horizontal or vertical dynamic visual acuity scores, with larger differences indicating poorer vestibular functioning and smaller differences indicating better vestibular functioning.

2.4.3. Balance/vestibular function

As a measure of general vestibular/somatosensory function reflective of self-movement perception/behaviours, participants were asked to take their shoes off and stand on a force plate, (AMTI MSA-6 MiniAmp strain gauge amplifier) focus straight ahead, and stand still for 30 s with their feet in a tandem stance (with preferred foot in front), once with eyes open and once with eyes closed. Center of pressure (COP) path length, defined as the summation of the ground reaction forces applied between the feet and the force surface (Winter, 2009), was measured (cm). Longer COP path lengths are associated with greater postural sway.

2.4.4. Montreal Cognitive Assessment (MoCA)

Older adults were asked to complete the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), which screens for mild cognitive impairment across different cognitive domains: attention and concentration, executive functions, memory, language, visuo-constructional skills, conceptual thinking, calculations, and orientation. The MoCA was scored out of 30, with a score of 26 and above being considered normal. No participants in this study scored below 26.

2.4.5. Fast Motion Sickness Scale (FMS)

Participants were asked to provide ratings of simulator sickness (i.e., nausea, general discomfort) three times per drive as well as before and after every drive using the FMS (Keshavarz & Hecht, 2011) in order to track their level of simulator sickness. The FMS is a verbal rating scale ranging from 0 (no nausea) to 20 (severe nausea). The drive was terminated if participants requested to stop or if an FMS score of 15 or higher was reported. Participants were also asked to report their FMS rating upon completing the experiment and were only released from the lab once any symptoms had completely resolved.

2.4.6. Simulator Sickness Questionnaire (SSQ)

At the end of the entire driving task (whether or not they finished the whole experiment), participants were also asked to rate their level of simulator sickness using the SSQ (Kennedy et al., 1993), a 16-item questionnaire that was used to classify simulator sickness symptoms across three clusters of symptoms (nausea, oculomotor, and disorientation), as well as a total score following a weighting procedure. Participants were required to score each item on a scale ranging from 0 (*none*) to 3 (*severe*). Note that the full results of the simulator sickness data (FMS and SSQ), including the participants who withdrew, are not further discussed here as this would go beyond the scope of the present paper; however, for the participants in the current study there were no differences in simulator sickness scores across conditions. The full simulator sickness results are reported separately (Nowosielski et al., 2022; Nowosielski et al., in preparation).

2.4.7. Driving performance measures

Driving performance was measured using the following parameters. *a) mean speed* (m/s) and *Standard Deviation of speed* (SD speed, m/s) were calculated for each scenario element (e.g., straight, hills, turns); *b) Steering Reversals (total number)* included the number of times the rotation of the steering exceeded at least 1 degree in one direction followed by a rotation of at least 1 degree in the opposite direction (Society of Automotive Engineers, 2013) for straight segments; *c) Standard Deviation of Longitudinal Accelerations* (SDLongAcc; m/s^2) are the variances of all forward/backward accelerations and decelerations for hills and turns; *d) Standard Deviation of Lateral Accelerations* (SDLatAcc; m/s^2) is the variance of all lateral (left/right) accelerations for turns. Within each experimental condition (fixed base, turntable, full motion) participants completed three drives, with all participants driving with no motion on Drive 1 (used a comparative control drive) and driving in their respective physical motion conditions in Drives 2 and 3. Performance measures were averaged across Drives 2 and 3, which were used for the final analyses.

2.5. Procedure

Once written informed consent was obtained, static and dynamic visual acuity, posturography, and the demographics and health history questionnaire were administered to all participants. Older adults also completed the MoCA. Participants were then randomly assigned to either the fixed-base, turntable, or full motion condition. Participants were seated inside the driving simulator where they were instructed to maintain a target speed of 65 km/h, unless otherwise specified by the speed limit signs, to adhere to the center of their lane, and to drive the simulator as they would their own vehicle. The end of each drive was demarcated by a road barrier and a pair of stop signs.

2.6. Statistical analyses

The study design included the two between-subjects factors Age (younger vs. older) and Motion Condition (fixed-base, turntable, full motion). Linear Mixed Models (LMMs) were conducted separately for each scenario element, specifically straight segments, turns, and hills. When main effects and/or interaction effects were observed, Tukey post-hoc tests were only reported for the effects that were driven by the factor Motion Condition. Analyses were conducted using R statistical software (R Core Team, 2021) and all LMMs were conducted using the lmer function from the lme package, summaries were generated using the ANOVA function from the stats package and post-hoc Tukey tests were analysed using the emmeans function and package. LMMs have been found to be robust against violations of distributional assumptions (Schielzeth et al., 2020), therefore, no additional action was taken against assumption violations. The full set of statistical analysis outputs are described in the Results section below and summarized in Supplementary Table 1.

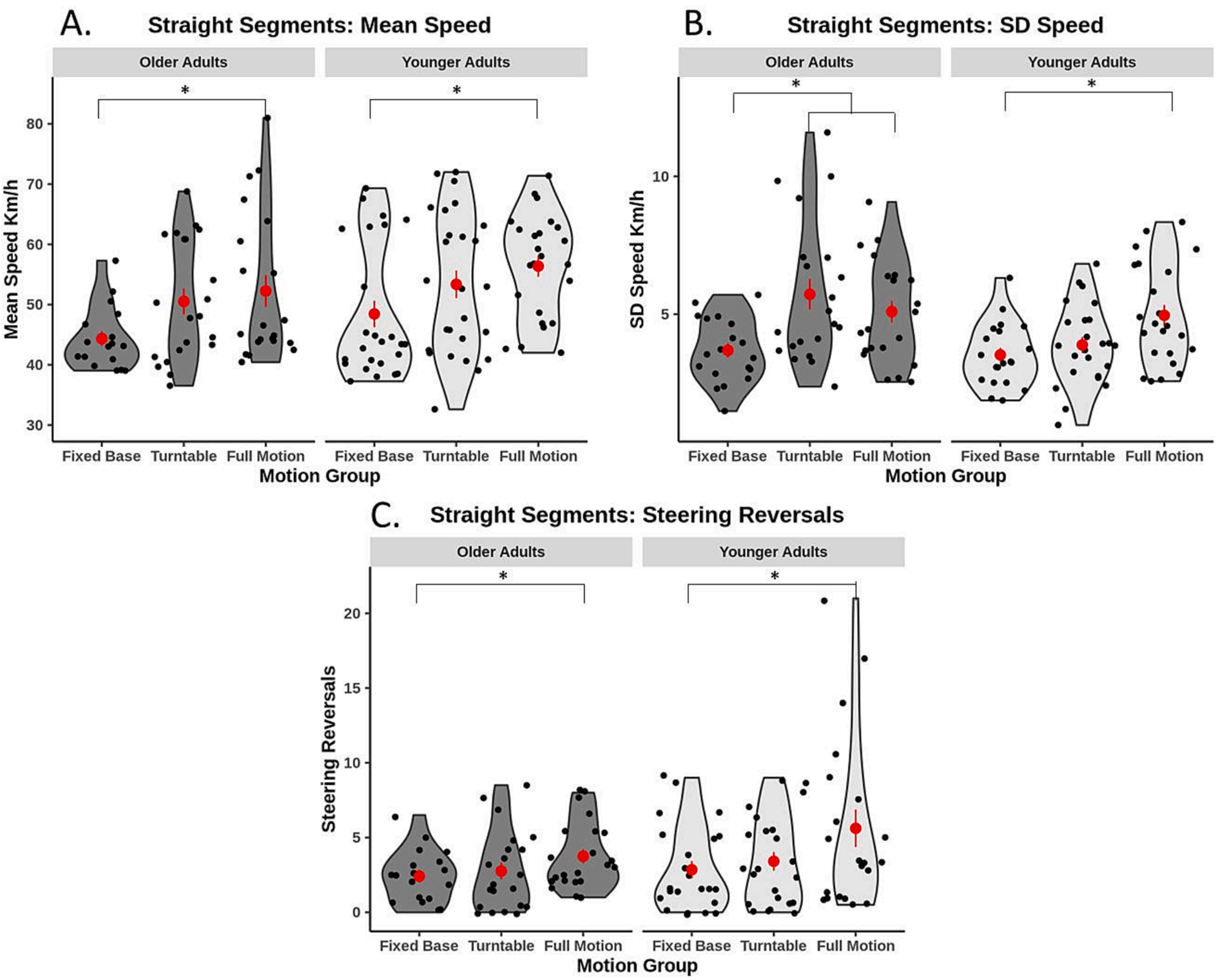

Fig. 3. Straight Segments: a) Mean speed, b) SD speed and c) steering reversals observed for older and younger adults across the three motion conditions. Width of each violin plot indicates the frequency of values on the y-axis, black dots reflect individual data points, red dots reflect means, red lines reflect error bars at ± 1SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Linear mixed models for each scenario element

The results of the LMMs are grouped by scenario elements (e.g., straight, turns, hills). This was done because we predicted that there would be unique effects of Motion Condition (e.g., full motion vs. no motion) on specific dependent measures (e.g., speed) that would differ as a function of the scenario elements. For example, we predicted that, because full motion is the only condition that provides pitch motion, bigger differences between full motion and fixed-base/turntable motion would occur for hills. The same differences may not necessarily be observed for curves, where mostly vestibular inputs related to yaw would be stimulated and thus differences between the full motion and turntable condition would be minimized (since both have equal yaw stimulation).

3.1.1. Straight segments

The following analyses were conducted on two straight, 1 km long sections with speed limits of 50 km/h (urban) and 65 km/h (rural), respectively. Across driving measures, results showed main effects of Motion Condition and Age and/or a Motion x Age interaction for mean speed, SD Speed and Steering Reversals.

With regards to *mean speed*, a main effect of Motion Condition was found, $F(2, 73.85) = 5.29$, $p = 0.007$, $\eta p^2 = 0.13$ (Fig. 3A). Post hoc tests indicated that, for both age groups, the mean speed in the fixed-base condition was slower than in the full motion condition ($p = 0.007$) and marginally slower than in the turntable condition ($M = 52.12$, $SE = 1.64$, $p = 0.056$). No other significant effects were observed (Fig. 3A).

With regards to *SD speed,* on straight segments, there was a main effect of Age, $F(1,64.80) = 5.55$, $p = 0.021$, $\eta p^2 = 0.08$, with

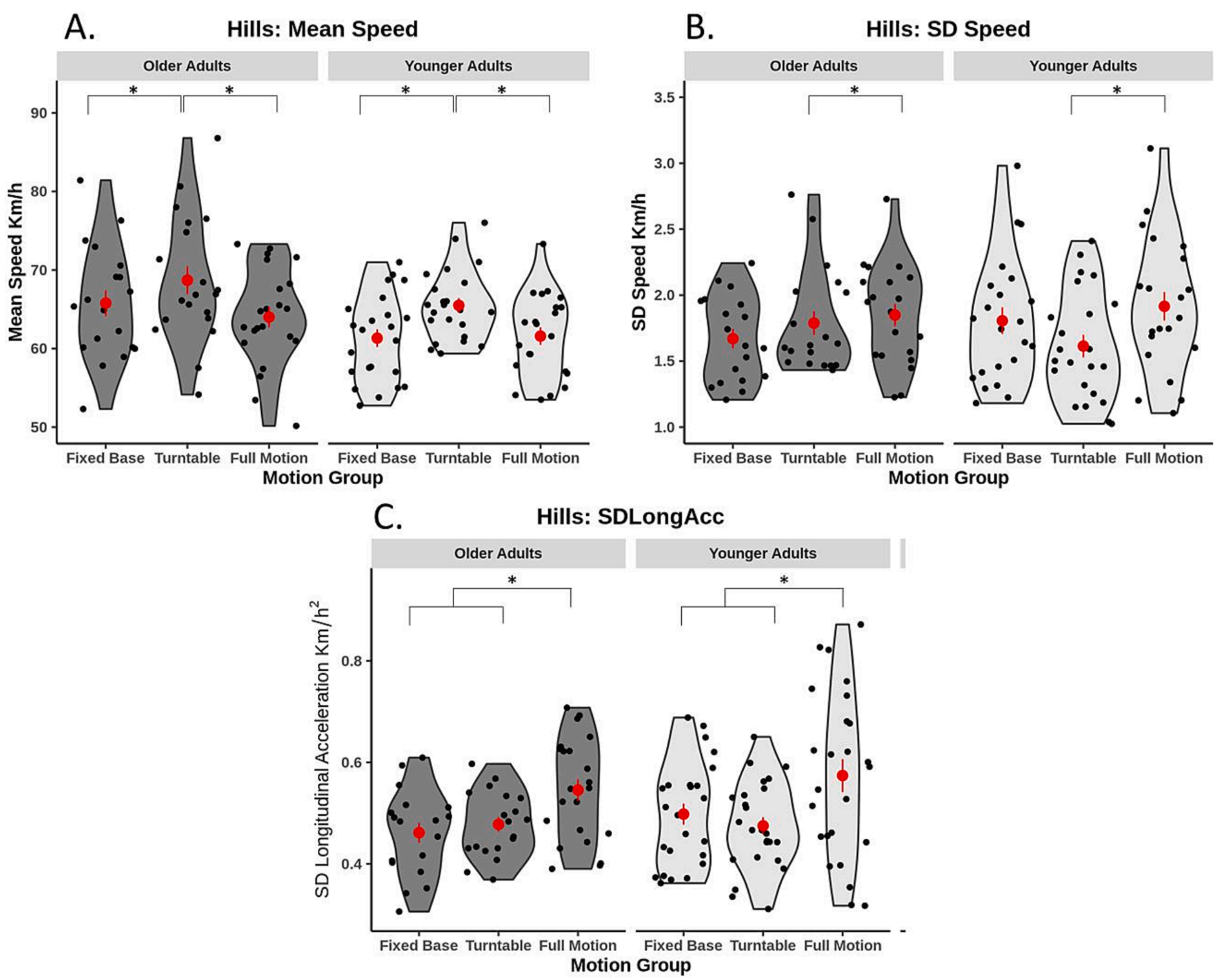

Fig. 4. Hills: a) Mean speed, b) SD speed and c) SDLongAcc observed for older and younger adults across the three motion conditions. Width of each violin plot indicates the frequency of values on the y-axis, black dots reflect individual data points, red dots reflect means, red lines reflect error bars at ± 1SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

younger adults having lower SD speeds than older adults (Fig. 3B). There was also a main effect of Motion Condition, $F(2,64.79) = 7.83$, $p = 0.001$, $\eta p^2 = 0.19$, which was qualified by a significant Age x Motion Condition interaction $F(2,64.71) = 3.35$, $p = 0.041$, $\eta p^2 = 0.09$. That is, in older adults, SD speed was significantly lower in the fixed-base condition compared to the turntable ($p = 0.001$) and full motion conditions ($p = 0.035$). However, for younger adults, SD speed was significantly lower in the fixed-base condition compared to the full motion condition ($p = 0.025$), but not compared to the turntable condition ($p > 0.05$). Older adults also had higher SD speed than younger adults in the turntable condition ($p < 0.001$) but not the fixed-base and full motion condition.

With regards to *steering reversals* on straight segments, there was a significant main effect of Motion Condition, $F(2,68.71) = 3.47$, $p = 0.036$, $\eta p^2 = 0.9$ (Fig. 3C). Specifically, Steering Reversals in the full motion condition were significantly higher than in the fixed-base ($M = 2.69$, $SE = 0.64$, $p = 0.045$) but not the turntable ($p > 0.05$) condition. No other significant effects were observed.

3.1.2. Hills

The following analysis was conducted on a set of two hills with vertical peaks of 7.5 m separated by a trough of 5 m. With respect to *mean speed* on hills, there was a main effect of Age $F(1,67.84) = 4.54$, $p = 0.036$, $\eta_p^2 = 0.06$, with older adults driving significantly faster than younger adults (Fig. 4A). There was also a main effect of Motion Condition $F(2,67.84) = 4.82$, $p = 0.011$, $\eta_p^2 = 0.12$, demonstrating that mean speed was significantly faster in the turntable condition compared to both the fixed-base and full motion conditions, even though there was no heave or pitch motion in this condition. There was no interaction effect.

With respect to *SD speed* on hills, there was a main effect of Motion Condition $F(1,73.91) = 3.24$, $p = 0.045$, $\eta_p^2 = 0.08$, such that SD speed was significantly higher in the full motion condition than the turntable condition, but not the fixed-base condition (Fig. 4B). No other significant main or interaction effects were observed.

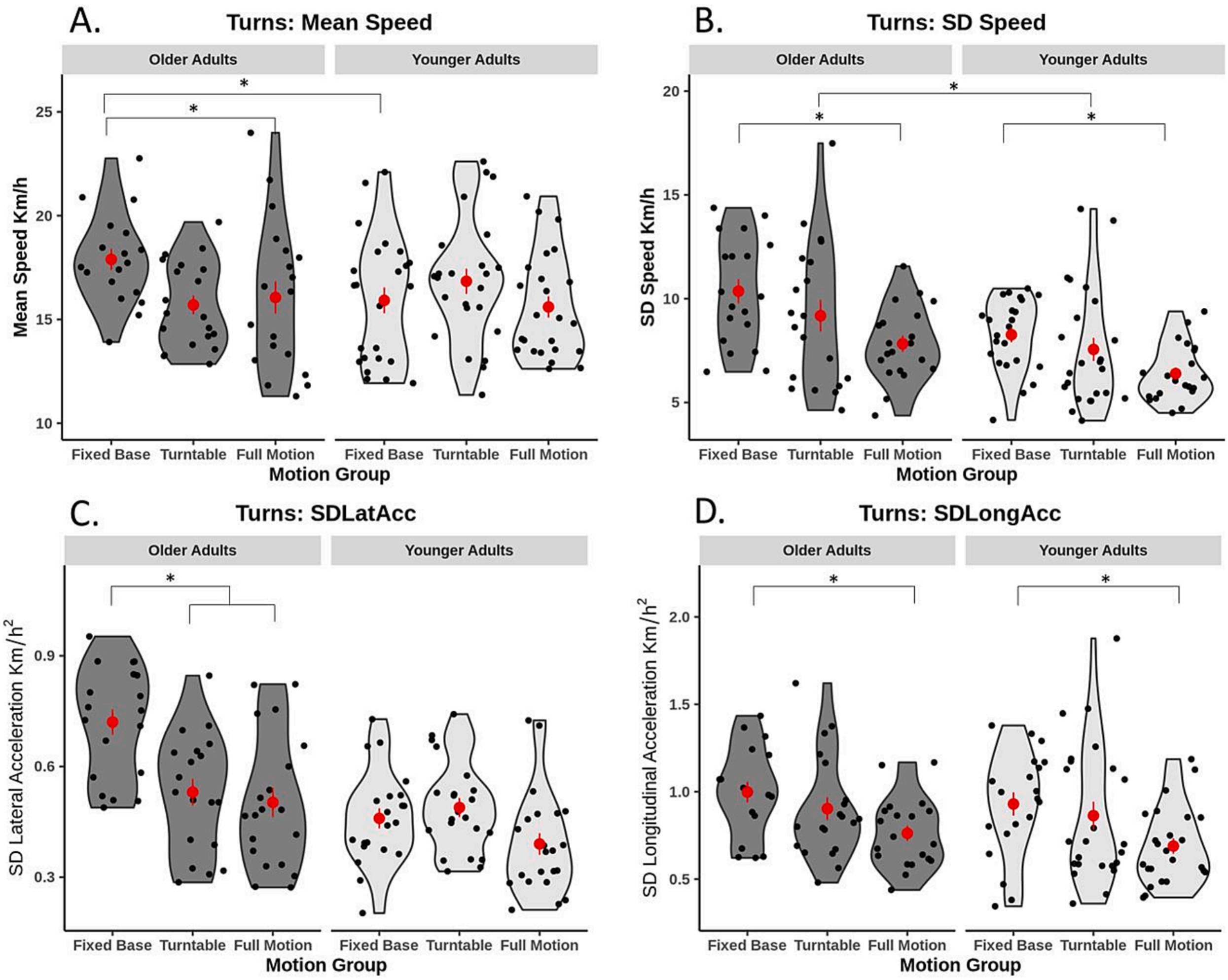

Fig. 5. Turns: a) Mean speed, b) SD speed, c) SDLatAcc, and d) SDLongAcc observed for older and younger adults across the three motion conditions. Width of each violin plot indicates the frequency of values on the y-axis, black dots reflect individual data points, red dots reflect means, red lines reflect error bars at ± 1SE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

With respect to *SDLongAcc* on hills, there was a main effect of Motion Condition $F(2, 70.76) = 7.21$, $p = 0.001$, $\eta_p^2 = 0.17$, demonstrating that SDLongAcc was significantly higher in the full motion condition compared to both the turntable and fixed- conditions (Fig. 4C). No other significant main or interaction effects were observed.

3.1.3. Turns

The following analysis was conducted on a series of two left and two right turns that occurred at three-way and four-way intersections, with a radius of 5 m. With respect to *mean speed* on turns, there was a significant Age x Motion Condition interaction $F(2,70.98) = 3.75$, $p = 0.028$, $\eta_p 2 = 0.10$ (Fig. 5A). Specifically, older adults had faster mean speeds in the fixed-base condition than younger adults. Further, older adults' mean speed in the fixed-base condition was faster than it was in the full motion condition ($p = 0.048$) but not the turntable condition ($p > 0.05$). No motion-related effects were observed for younger adults.

With respect to *SD speed* on turns, there was a significant main effect of Age $F(1,69.36) = 14.05$, $p < 0.001$, $\eta_p^2 = 0.17$, with older adults having a higher SD speed than younger adults (Fig. 5B). There was also a significant main effect of Motion Condition $F(2,69.42) = 6.04$, $p = 0.002$, $\eta_p^2 = 0.15$, with greater SD speed in the fixed-base condition than in the full motion condition ($p = 0.002$), but not the turntable condition ($p > 0.05$). There was no interaction effect.

With respect to *SDLatAcc* on turns, there was a significant main effect of Age $F(2,70.82) = 18.67$, $p < 0.001$, $\eta_p^2 = 0.21$, a significant main effect of Motion Condition $F(2,70.80) = 6.54 p = 0.002$, $\eta_p^2 = 0.16$, and a significant Age x Motion Condition interaction $F(2,70.80) = 4.34$, $p = 0.016$, $\eta_p^2 = 0.11$ (Fig. 5C). Specifically, older adults had significantly higher SDLatAcc in the fixed-base condition compared to the turntable condition ($p = 0.002$) and the full motion condition ($p < 0.001$), whereas no motion-related effects were observed for younger adults. Furthermore, older adults had higher SDLatAcc compared to younger adults in the fixed-base ($p = 0.001$) and full motion ($p = 0.039$) conditions, but not the turntable condition.

With respect to *SDLongAcc* on turns, there was a main effect of Motion Condition $F(2,70.63) = 3.30$, $p = 0.042$, $\eta_p^2 = 0.09$, with lower SDLongAcc in the full motion condition than in the fixed-base condition ($p = 0.038$) but not the turntable condition ($p > 0.05$) (Fig. 5D). No other significant effects were observed.

4. Discussion

In the present study, we examined how different types of motion cues (no motion, yaw rotation, full motion) affect driving performance across different scenario elements considering different age groups. Overall, motion-related effects on driving performance outcomes were most pronounced between the fixed-base condition (no translation or rotation) and the full motion condition (translation and rotation around all three axes) across most scenario elements. However, during scenario elements for which pitch was particularly relevant (i.e. hills), the most pronounced motion-related effects were between the turntable condition and the full motion condition (which included physical pitch rotation). Older adults demonstrated the same pattern of motion-related effects on driving performance outcomes as younger adults when driving through straight segments and hills, but older adults exhibited additional motion-related effects not experienced by younger adults on mean speed and SDLongAcc when driving through turns. While many observed patterns were predicted, there were also several inconsistencies and effects that were not necessarily anticipated. In the following sections, we will discuss the patterns of specific motion-related effects on driving performance and their interaction with age.

4.1. Motion-related effects on driving performance for each scenario element

For *straight segments*, the largest and most consistent motion-related effects were between the fixed-base condition and the full motion conditions. While this pattern of results was largely consistent across both age groups, for SD speed, older adults also demonstrated significant differences between the turntable condition and both the fixed and full motion conditions. These findings were predicted given that the most relevant axis of motion for straight segments is for/aft accelerations, which differ most notably between the fixed and full motion conditions. Very few of the published studies examined driving performance in the context of straight, or mostly straight, driving, however, of those that did, the results are generally consistent. For example, when looking at the effect of motion on speed, Colombet and colleagues (2008), also found the addition of motion led to higher mean speeds. Further, when exmaining the effect of motion on lane variability during straight driving, Ramkhalawansingh et al (2018), found that older adults, but not younger adults, exhibited greater lane variability with more motion, a metric that is typically positively correlated with steering reversals (the metric included in the current study).

For *hill segments*, the largest and most consistent motion-related effects were observed between the full motion condition and the turntable condition (for all three driving performance measures; mean speed, SD speed, and SDLongAcc) and also between full motion and fixed-base conditions for SDLongAcc. These findings were predicted given that the most unique axis of motion for hills compared to other segments is the pitch motion that is introduced and for which the full motion condition is the only condition in which physical pitch motions were experienced. As such, it was predicted that motion-related differences on hills would be greatest between full motion and fixed/turntable conditions, which was generally confirmed. Hills remain an understudied scenario element with no previously cited studies investigating the effect of motion on driving performance on hills.

During *turns*, all axes of motion were activated, including lateral and longitudinal translations, and rotations around all three axes of pitch, yaw, and roll. For these reasons, it would be predicted that the largest motion-related effects would be observed for the fixed condition (no translation or rotation) compared to the full motion condition (translation + three degrees of rotation). Indeed, for older adults, we observed the greatest motion-related differences to driving performance in the fixed vs. full motion condition across all four driving performance measures (mean speed, SD speed, SDLatAcc, SDLongAcc) and for younger adults for two driving performance measures (SD speed and SDLongAcc). Older adults also demonstrated significant differences between the fixed and turntable condition for SDLatAcc, whereas younger adults did not. Lakerveld et al., (2016) found that the addition of yaw motion led to reduced steering control activity in a slalom maneuver, while Hogema and colleages (2012) found that the addition of yaw motion lead to lower SDLongAcc and SDLatAcc, which is consistent with our findings. However, in the current study, only older adults demonstrated the effect of full motion (relative to fixed) on SDLatAcc.

4.2. Effects of age and interactions with motion conditions on driving performance

While there were several significant main effects of age for some dependent measures (e.g., older adults drove faster on hills and had more variable speed during turns than younger adults), these main age-related effects were not observed across all measures and scenario elements. There were, however, several interaction effects between age and motion condition, suggestive of differential effects of motion on younger and older adults. Most notably, this was observed for mean speed during turns (only older adults reduced their speed with full motion compared to fixed-base), SDLatAcc during turns (only older adults reduced their variance in the turntable and full motion conditions compared to fixed-base), and standard deviation of speed during straight segments (only older adults reduced their variance in speed with full motion compared to turntable). There were no conditions under which younger adults demonstrated motion-related effects on driving performance outcomes when older adults did not. This suggests that when interactions with age were observed, the pattern indicates that older adults' driving performance differed to a greater extent across motion conditions than younger adults' and that these motion-related effects were generally in favour of better driving performance (e.g. reduced speed and reduced variance). Overall, the findings from this study may have implications for simulator-based driving assessments and simulator design. While the current study can only describe driving performance without drawing conclusions about safety, the findings do demonstrate that physical motion characteristics can influence driving behaviours. As such, any simulator-based assessment of driving behaviours may be biased if relevant cues to motion are not provided. These effects may be most pronounced in older adults, who demonstrated larger and more consistent effects of motion types on driving performance measures. For example, older adults drove more slowly on average and accelerated more smoothly during turns when they experienced full motion cues compared to the fixed-base condition. Therefore, driving assessment outcomes that are observed in a fixed-base driving simulator may underestimate the safety of older adult drivers compared to a full motion simulator. These motion-related considerations are also relevant for the development of driving simulation technologies that are designed for driver assessment; specifically, multiple axes of motion could be beneficial to integrate into the design of these assessments, depending on the characteristics of the testing scenarios (e.g., number of turns, hills).

4.3. Limitations

A between-subjects design was chosen for this study to prevent any carryover effects that would likely occur if every participant were asked to complete every motion condition. However, variability due to individual differences (e.g., driving experience, simulator experience) may have reduced sensitivity to motion-related effects across conditions/groups. That said, as a part of the experimental design, we confirmed that the baseline driving performance within the initial fixed-base drive that was completed by all participants, across all motion condition group assignments, did not differ across groups. This provides some reassurance that the groups were generally equitable in baseline driving performance from the start, and therefore, the effects observed may be a conservative estimate of what might be expected for a within-subjects design that better controlled for individual variability across motion conditions.

We also experienced a roughly 21 % attrition rate due to simulator sickness, at approximately equal rates across motion conditions and age groups, which may have reduced the power to observe more subtle effects of motion or age. Further, while this study represented more complex and realistic driving scenarios compared to many previous studies, the demands of the driving task may still have been lower than what might be experienced during other real-world or simulated driving situations such as those including pedestrian and vehicular traffic and/or multitasking requirements (Nowosielski, 2022). It would be of interest to investigate whether increasing the sensory, motor, or cognitive demands by, for example, including unexpected events or more sophisticated maneuvers affects how motion influences driving performance across age groups.

5. Conclusions

Driving is a task that requires integration from information across the sensory systems, including the inertial information perceived through the vestibular system. In this study, it was observed that for situations where translational information is relevant and important (straight driving and turns) motion-related effects were most pronounced between the condition for which no motion was available (fixed-base) and the conditions for which the full range of motion, including translational motion, was available to inform driving behaviours (full motion). However, during scenario elements for which pitch was particularly relevant (i.e. hills), the most pronounced motion-related effects were observed between the turntable condition (only yaw rotation) and the full motion condition (which uniquely included pitch rotation). Interestingly, there were several observed interactions between motion condition and age, in all cases demonstrating motion-related effects on the driving performance of older adults, but not younger adults. Overall, these findings may have implications for understanding how physical motion cues and age-related changes affect driving performance, particularly in the context of vehicle and driving simulator design and application.

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CRediT authorship contribution statement

Robert J. Nowosielski: Writing – original draft, Project administration, Methodology, Formal analysis, Data curation. **Behrang Keshavarz:** Writing – review & editing, Conceptualization. **Bruce C. Haycock:** Writing – review & editing, Conceptualization. **Jennifer L. Campos:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization (RN, BK, BH, JLC), data curation (RN), Formal analysis (RN, JLC), Funding acquisition (JLC), Supervision (JLC), Writing – original draft (RN), Writing – review and editing (RN, BK, BH, JLC).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2025.01.019.

Data availability

The authors do not have permission to share data.

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