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Evaluation of older driver head functional range of motion using portable immersive virtual reality

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ABSTRACT

Background: The number of drivers over 65 years of age continues to increase. Although neck rotation range has been identified as a factor associated with self-reported crash history in older drivers, it was not consistently reported as indicators of older driver performance or crashes across previous studies. It is likely that drivers use neck and trunk rotation when driving, and therefore the functional range of motion (ROM) (i.e. overall rotation used during a task) of older drivers should be further examined.
Objective: Evaluate older driver performance in an immersive virtual reality, simulated, dynamic driving blind spot target detection task.
Methods: A cross-sectional laboratory study recruited twenty-six licensed drivers (14 young between 18 and 35 years, and 12 older between 65 to 75 years) from the local community. Participants were asked to detect targets by performing blind spot check movements while neck and trunk rotation was tracked. Functional ROM, target detection success, and time to detection were analyzed.
Results: In addition to neck rotation, older and younger drivers on average rotated their trunks 9.96°and 18.04°, respectively. The younger drivers generally demonstrated 15.6° greater functional ROM ($p < .001$), were nearly twice as successful in target detection due to target location ($p = .008$), and had 0.46 s less target detection time ($p = .016$) than the older drivers.
Conclusion: Assessing older driver functional ROM may provide more comprehensive assessment of driving ability than neck ROM. Target detection success and time to detection may also be part of the aging process as these measures differed between driver groups.

1. Introduction

The number of drivers over 65 years old is increasing, which is indicated by a rise in the percentage of older individuals possessing a driver's license, and also an increase in car access and number of trips traveled by car for older drivers (Sivak and Schoettle, 2012; Stav et al., 2008). Driving is a complex task, and the safe operation of a motor vehicle requires good vision, motor function, and cognition (Desapriya et al., 2014). Changes in physical and cognitive abilities are part of a normal aging process. These changes include visual attention, visual impairment, physical fragility and function, reaction time and processing speed, which are associated risk factors for older drivers and adverse driving incidents (Anstey et al., 2005; Dukic and Broberg, 2012; Eby et al., 1998). One particular physical change, the neck axial rotation range of motion (ROM), has been identified as a risk factor for older drivers (Isler et al., 1997; Marottoli et al., 1998).

Neck ROM or neck rotation has been studied in various driving and road safety related research. In addition to investigating the relationship between neck rotation and driving performance or risk in driving, some studies aimed to provide a reliable test battery or explored predictors of safe driving characteristics in older adults. However, the association between neck rotation and driving varied across studies (Ball et al., 2006; Edwards et al., 2010; Isler et al., 1997; Marottoli et al., 1998; Molnar et al., 2007; Stav et al., 2008; Wood et al., 2008). It was identified that the reduction in neck rotation ROM doubled the risk of crashing (Marottoli et al., 1998). A statistically significant difference in total neck rotation was found between safe and unsafe older drivers, yet neck rotation was not a good statistical predictor among the measured variables of driver on-road performance rated by an occupational therapist experienced in driving assessment (Wood et al., 2008). It was also reported that neck rotation did not demonstrate a positive association with motor vehicle crashes or poor driving performance (Ball et al., 2006; Molnar et al., 2007; Stav et al., 2008). In a 10-year

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longitudinal study, Edwards et al. (2010) showed that head–neck rotation was not statistically associated with driving cessation. These findings provided valuable information by associating individually measured physical characteristics to driver traffic incidents or decision to continue driving, yet their findings or recommendations were not always consistent. It is possible that during an actual driving situation, such as backing up or lane changing, drivers utilize motions other than neck rotation for tasks that require more dynamic movements.

In addition to considering neck rotation and its relation to driver safety, both neck and trunk rotation and flexibility were taken into account in other studies. Trunk rotation was also measured in the test battery assessment of Marottoli et al. (1998), however only neck rotation was found to be statistically related to crashes. Instead of separating spinal flexibility into neck rotation and trunk rotation, Reimer et al. (2008) examined the involvement of overall spinal flexibility in rear-window checking and backing up situations between younger and older drivers, and the younger drivers demonstrated greater spinal flexibility. As countermeasures to driving accidents in older drivers, training programs or physical therapy interventions have been implemented and the results were generally positive (Ashman et al., 1994; Marottoli et al., 2007; Ostrow et al., 1992). These interventions were either instructor-led courses or self-administered exercises at home for which the older drivers performed neck and trunk rotation drills that lasted a few class periods or over the course of three months. During on-road performance assessment after these interventions, the older drivers demonstrated an improvement in driving performance (Ashman et al., 1994; Marottoli et al., 2007; Ostrow et al., 1992). Neck and trunk ROM have also improved over the course of training (Caragata et al., 2009). These findings implied the importance of the neck and trunk rotation in older adult drivers.

Due to the impracticality of evaluating older driver performance on-the road, some studies have used driving simulators to study driver safety. Park et al. (2011) compared driving behavior between older and younger drivers in a driving simulator, and their results indicated that unsafe driving and car crashes were more prevalent in older than in younger drivers. Although simulators provided complex driving situations were used in studying driver performance, driver physical capabilities were not always measured (Lee et al., 2003; Park et al., 2011; Romoser et al., 2005). Examining the rotational movement of drivers in a driving context with other dynamic objects, such as moving cars, may provide a more comprehensive understanding of older driver performance including neck and trunk rotations since spinal rotation and flexibility are important in driving safety (Reimer et al., 2008).

Immersive virtual reality (VR) created by computer graphics and 3D displays presents a new research paradigm and offers potential solutions to the challenges posed by traditional research technology. Recent innovations have made this technology portable, inexpensive, and widely available, eliminating the need for a fully immersive driving simulator and motion tracking instruments. Programmable systems make studies or prototyping in VR more cost-effective since changes could be done in software. It is inherently safe for simulating hazardous tasks or for training because the virtual environment constitutes graphics and the users are not exposed to physical dangers. Utilizing the flexibility of VR, researchers have used it as an educational tool (Dalgarno and Lee, 2010; Lee and Wong, 2008), training (Dugdale et al., 2004; Lange et al., 2000), and rehabilitation (Holden, 2001). Virtual reality also has been used for assessment, such as to measure human motion, evaluate physical risk factors in ergonomics, evoke senses of exertion and biomechanical measurements, and capture human movement (Chen et al., 2015; Pontonnier et al., 2013; Sarig-Bahat et al., 2009). Given the flexibility and low cost of VR, we propose using VR for studying older driver performance. Immersive VR can provide greater graphical and visual fidelity, and users may be able to perform driving tasks more similar to how they typically do. Moreover, VR permits participants to perform the experiment with lower risk than actual driving on streets, and the outcome measures can be directly collected by the VR system.

The objective of this study was to explore driver performance during a blind spot checking task in a VR environment with moving virtual cars to represent a dynamic driving situation. Specifically, the extent of rotational movement of the drivers was examined. For the purpose of this study, driver functional ROM during the experimental task was defined as the overall rotation movement performed by the driver to execute the experimental task. Conventional neck rotation ROM was also measured, but it was obtained independently of the experimental task at the start of a session. Additionally, the performance differences between younger and older drivers were compared. It was hypothesized that the functional ROM during the task is different from the neck rotation ROM. It was also hypothesized that the older drivers would exhibit different biomechanical characteristics and performance from the younger drivers.

2. Methods

2.1. Participants

Fourteen younger (mean age 24.5, SD 5.2 years; eight females) and 12 older (mean age 70.3, SD 3.2 years; seven females) drivers were recruited from the local community. The volunteers were self-identified drivers who responded to a flyer posted in the local community, or they were participants of previous studies who agreed to be contacted for future studies. Volunteers were screened via telephone contact for eligibility. Exclusion criteria for both driver groups were inability to see three-dimensional (3D) stereo images, neuro-motor impairments or injuries that prevented the individual to reach for an object overhead or rotating the neck, a condition that limits the individual's ability to exercise the neck and shoulder, experience of epileptic seizure or blackout, high tendency for motion sickness or nausea when experiencing visual motion conflicts, and have or had an occupation that required more than 50% of work time driving. Inclusion criteria of age for the younger group was between the age of 18 to 35 and for the older group was between 65 to 75, self-report of normal or corrected-to-normal vision, and possessed a valid driver's license at the time of the study. All participants self-reported that they were actively driving at the time of the study, and none reported being and have been a vehicle operator as an occupation (e.g. not a taxicab driver). Written informed consent was obtained from all participants and the study was approved by the New England Independent Review Board.

2.2. Instrumentation

The VR system, which included a steering wheel and pedal set (G27 Racing Wheel, Logitech, Newark, CA, USA) for driver input and a head-mount display with inertial sensors (Development Kit 1 Oculus Rift, Oculus VR, LLC, Menlo Park, CA, USA) primarily for visual feedback and also provided head-neck orientation tracking, is depicted in Fig. 1. The head-mounted display had 110° field of view in diagonal and a combined resolution of 1280×800, and a sampling frequency of 60 Hz. An active marker infrared motion tracking system (Optotrak Certus, Northern Digital Inc., Ontario, Canada) recorded body kinematics of the participant. The active marker motion tracking system had a resolution of 0.01 mm, a 3D accuracy of 0.1 mm, and the sampling frequency was synchronized to the head-mounted display at 60 Hz. The VR scenario was written in C++ and based on Ogre, an open source 3D graphics rendering engine. The visuals were retrieved from an open source 3D model repository (Trimble 3D Warehouse, Google, Mountain View, CA, USA) and modified in SketchUp (Trimble Navigation, Ltd., Sunnyvale, CA, USA).

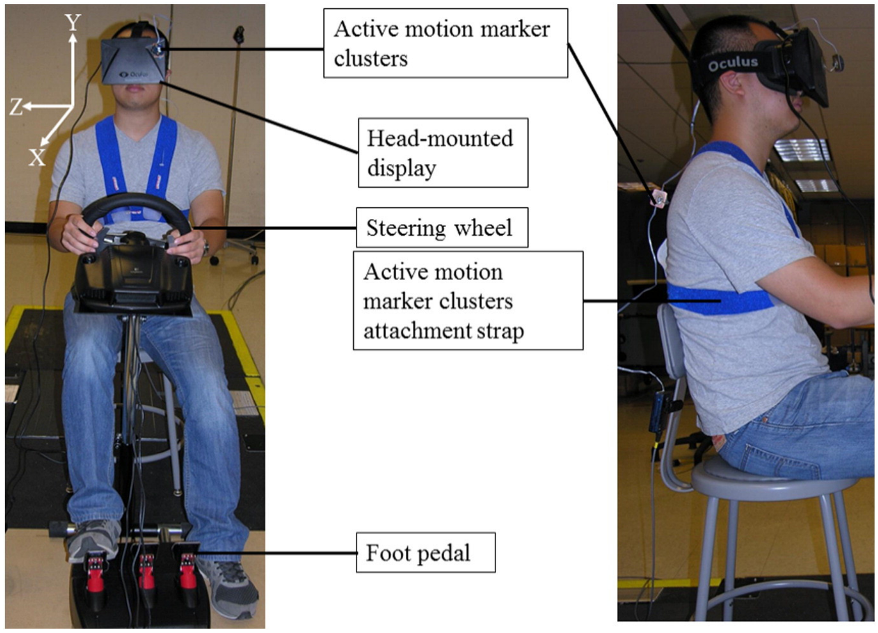

Fig. 1. A participant wore a head-mounted display and positioned the hands on a steering wheel, while the foot rested against one foot pedal. Active motion marker clusters were placed on the head-mounted display and on the trunk of the participant. The left image corresponds to the coordinate system indicated in the figure.

2.3. Experimental procedure

Participants were seated in a stationary chair with a backrest but without armrests and wore a head-mounted display (Fig. 1). They assumed a "ready position" that was a neutral upright posture with the participants looking forward and the head and trunk aligned. The calibration and the coordinate system were based on a study by Xu et al. (2015). The global coordinate system at the ready position had the x-axis normal to the coronal plane pointed forward, the y-axis normal to the transverse plane pointed upward, and the z-axis normal to the sagittal plane pointed to the right side of the participant. A total of two active motion marker clusters were placed onto the participant: one of which was affixed to the surface of the head-mounted display and another cluster was attached to the upper trunk by a strap. Anatomical landmarks were digitized when the participants situated in an upright posture at the start of every session. Sternal notch, xiphoid process, C7, T8 were digitized with respect to the clusters on the upper trunk, while the left and right tragion, vertex, and the four corners of the head-mounted display were digitized with respect to the cluster mounted on the head-mounted display. The trunk local coordinate system followed the International Society of Biomechanics standards (Wu et al., 2005). For the head, the z-axis was from the left to the right tragion, and the x-axis was normal to the plane that included the z-axis and the x-axis vertex pointed forward. The head-mounted display local coordinate system x-axis was normal to the front surface of the display pointed forward, and the z-axis was from the lower left to the lower right corner.

The baseline neck ROM was measured by the head-mounted display at the start of the session, which included axial rotation, flexion and extension, and lateral bending. These ROM measurements were obtained following the same verbal instructions as Youdas et al. (1992). Participants then performed the experimental task that consisted of 40 repetitions of a head–neck rotation movement, which was similar to a blind spot checking movement in a driving situation. At least five practice blind spot checking task trials were given. Each participant attended one session that lasted no more than 60 min.

2.4. Experimental task

The experimental task was to perform blind spot check movements that are typically carried out prior to making a lane change maneuver while driving, and then to step on the foot pedal if a stationary white ambulance target appeared. The target was visually distinct from other cars in the VR scenario. There were a total of 40 trials and only 20 trials had a target, which were randomized throughout the task. The first 20 trials involved checking the blind spot on the right side and the remaining 20 trials involved checking the blind spot on the left side, or vice versa. The order of the sides was randomized, and it was counterbalanced where half of the participants started with the right side and the other half of the participants started with the left side. Each side had either a near or a far target, resulted in four possible target locations: left near, left far, right near, and right far (Fig. 2). The near targets were located at a position that required approximately 60° of overall axial rotation to become visible, and the far targets were placed at a position that required approximately 90° of overall axial rotation to become visible.

The standard instruction to the participant was, "For this task, please check your blind spot as if you are about to change lane. If you don't see a white truck, tap the blinker handle on the steering wheel to signal. If you happen to identify a white truck when you are checking the blind spot, step on the foot pedal. Do you have any questions?" Before the start of each trial, the experimenter verbally indicated the side (i.e., left or right) to be checked, and then announced "go" to instruct the participant to start checking the blind spot. Participants returned to the "ready position" before the start of each trial, and the head-mounted display was zeroed at the "ready position" as soon as a trial was initialized.

2.5. Variables and data analysis

Independent variables were target side, target location, task situation, and driver group. Target side (left and right), target location (near and far), and task situation were within-subject variables. Task situation referred to the state where the drivers did not have to perform the blind spot checking task at baseline, and other situation was that the drivers checked the blind spot. The only between-subject variable was driver group (younger and older).

Dependent variables included kinematics and performance measures. Axial ROM was a kinematics measurement made at baseline and during the task. The baseline neck axial ROM was the active cervical spine rotation about the global y-axis (i.e. axial rotation) at baseline

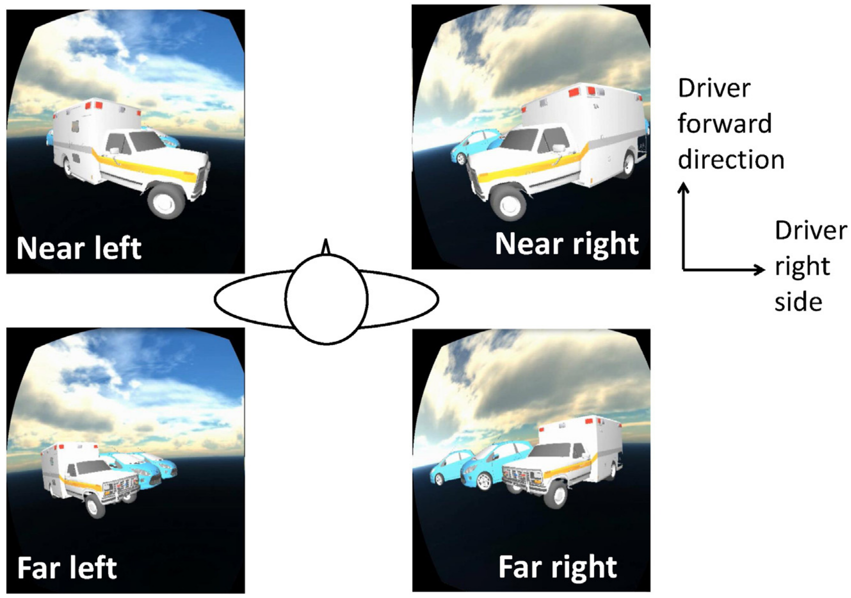

Fig. 2. Four different locations where the target (e.g., white ambulance) appeared relative to the driver. The sizes of the target were also relative to the location from the driver.

measured in a seated upright neutral posture. The baseline neck axial ROM angle was measured from the driver's head ready position when facing along the x-axis, to the farthest extent that the drivers could turn the neck until feeling tightness and without causing pain. The functional axial ROM was operationally defined as the ROM involved during the experimental task, which was the overall rotation movement performed by the driver when checking the blind spot. The functional axial ROM angle was measured from the driver's head ready position when facing along the x-axis, to the head orientation at the instance when the driver stepped on the brake or signal the blinker. The trunk axial rotation was also measured during the experimental task, and it was measured from the driver's trunk ready position facing along the x-axis to the trunk orientation at the instance when the drivers stepped on the brake or signal the blinker.

Performance measures were target detection and detection time. Detection was a dichotomous variable (0 or 1) when a driver respectively missed or successfully identified the target in a trial. Detection time was the time elapsed for detection, and detection was marked at the instance when the drivers stepped on the brake.

Baseline axial ROM was first analyzed using an independent *t*-test to compare between the driver groups. The axial ROM was analyzed using a two-way (driver group × situation) repeated measures ANOVA. Trunk axial rotation was analyzed using an independent *t*-test by comparing between the driver groups. Detection was analyzed against age group and target location using logistic regression of generalized linear modeling. Detection time was analyzed using a two-way (driver group × target location) repeated measures ANOVA. Only the trials with a target were used for the analysis of detection and detection time. Type I error was set at $\alpha = .05$. All statistical analyses were performed with R for Windows, version 3.1.2 (Comprehensive R Archive Network, R Foundation for Statistical Computing, Vienna, Austria).

3. Results

There was no statistical difference in ROM and detection time between the left and right side neck, and therefore the data for both sides were pooled. The mean baseline axial ROM measured before the task was 63.48° (SD 10.96) and 78.10° (SD 8.58) for the older and younger drivers, respectively. The baseline axial ROM was statistically significantly different between the driver groups ($t(24) = 3.81$, $p < .001$).

During the task, the mean functional ROM of older and younger drivers were 71.93° (SD 12.48) and 101.61° (SD 13.68), respectively. An effect of situation on axial ROM (Fig. 3) occurred when the functional ROM during the blind spot checking movement was 15.6° greater than the baseline neck axial ROM ($F(1,24) = 41.68$, $p < .001$). While including task situation as a covariate, or, statistically controlling for task situation, the ROM of the younger drivers was 16.3° greater than the older drivers ($F(1,24) = 51.61$, $p < .001$). There was also a significant interaction between task situation and driver group ($F(1,24) = 9.99$, $p = .004$), suggesting that the difference in ROM between the situations for the younger drivers was 15.3° greater than the older drivers.

Trunk axial rotation during the blind spot movement of the younger drivers 8.2° greater than the older drivers, and this difference between the groups was statistically significant ($t(24) = 2.25$, $p = .03$) (Fig. 4).

The younger drivers detected all trials out of a total of 280 trials that had a target, which yielded a 100% detection rate. The older drivers overall detected 128 trials out of a total of 236 trials with a target, which yielded a 54% detection rate. Logistic regression further revealed that there was no effect of age group (χ^2 (1,N = 26) = .02, $p > .05$) on detection rate. Instead, the target location significantly affected the detection rate (χ^2 (1,N = 26) = 6.97, $p = .008$). Detection frequency and detection rate by driver group and target location is show in Table 1.

Detection time was statistically significantly different between the driver groups, with the younger drivers on average detected the target

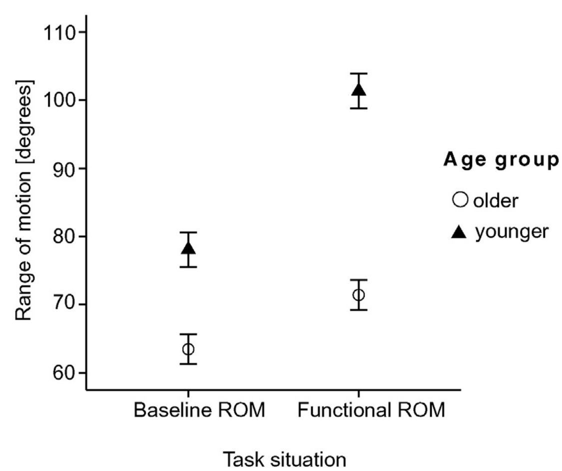

Fig. 3. Axial range of motion measured at two situations by driver groups (±1S.E.).

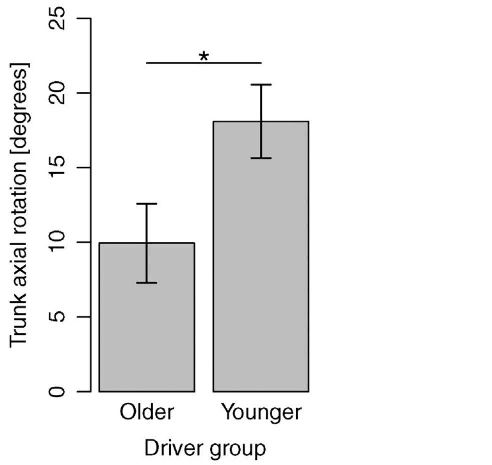

Fig. 4. Trunk axial rotation during the blind spot checking task of the two driver groups (±1S.E.).

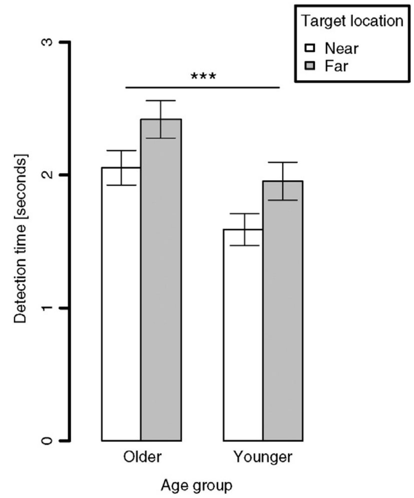

Fig. 5. Detection time difference between the two age groups by target location (±1S.E.). ***$p < .001$.

0.46 s faster than the older drivers ($F(1,24.85) = 6.70$, $p = .016$). Target location also significantly affected detection time ($F(1,16.20) = 56.41$, $p < .001$), where the detection time for the farther targets were 0.36 s greater than for the nearer targets (Fig. 5).

4. Discussion

This study used inexpensive VR technology for examining driver neck and trunk rotation. During the task a target would not have been visible unless an axial rotation movement was sufficient. Detection rate and the time to detect the target were also examined. Generally, the younger drivers exhibited greater functional ROM, detected more targets, and were faster at detecting the targets than the older drivers. The functional ROM in this study was defined as the overall rotation movement performed by the driver to execute a blind spot checking movement.

The first hypothesis was that the functional ROM during blind spot checking was different from the baseline neck axial ROM, and this was supported by the data. Across both driver groups, the mean functional ROM was 15.6° greater than the baseline neck axial ROM. This suggested that the functional ROM, or the overall rotational movement exhibited by drivers when blind spot checking, was greater than their typical neck ROM. Through observation during the experiment, it was confirmed that older and younger drivers engaged both neck and trunk rotational movements while they checked blind spots. Moreover, biomechanical measurement and observation indicated that the functional ROM during this task was a combination of neck and trunk rotational movement. Given the instructions provided for this task, where the drivers were told to perform as they normally would, the functional ROM may have closer resemblance to the ROM involved in an actual driving event.

In a study by Reimer et al. (2008), younger (18 to 25 years of age) and older (65 years of age or above) drivers' spinal rotation angle during a car backing up task was evaluated, and they reported that on average

Table 1
Target detection frequency out of the trials with a target by driver groups and by target locations. The data are displayed in number of detected target trials/total number of trials with a target.

Driver group	Older	Younger
Target location		
Left near	57/58	69/69
Left far	5/60	69/69
Right near	58/60	70/70
Right far	8/58	70/70
Overall detection frequency	128/236	278/278
Overall detection rate	54%	100%

the younger drivers rotated 113° to 115° and the older drivers rotated 99° to 100° during the task. In our study the mean functional ROM of the younger and older drivers was 101.63° (SD 101.1) and 71.82° (SD 10.3), respectively. Although Reimer et al. (2008) reported greater rotation angle, their backing up task was different from our blind spot checking task, and they also permitted the drivers to brace the back of the passenger seat when backing up the car. The results from Reimer et al. (2008) indicated that greater rotational movement when backing up a car, yet the current study suggested that during blind spot checking the drivers may not involve as much rotation.

To make certain that the baseline neck axial ROM of the participants from the present study was not different from others, the baseline neck axial ROM was compared with previous studies. The neck ROM of the younger drivers from the present study is similar to those described by Chiu and Lo (2002) that was 78.0° (SD 6.4) and 77.2° (SD 7.6) for right and left rotations, and Swinkels and Swinkels-Meewisse (2014) 79° (SD 6.6) and 78° (SD 8.0) for right and left rotation in both men and women, whose study participants were free of musculoskeletal conditions and their mean age was between 20 to 30 years. The mean neck ROM of the older drivers from the present study was approximately on average 7° to 10° greater than what was reported by Youdas et al. (1992), which were 53.6° (SD 7.4) and 56.6° (SD 6.7) for right and left neck rotation in healthy men 60 to 69 years in age. The baseline neck axial ROM of current study population is somewhat comparable to other studies and therefore this result might not be atypical in blind spot checking. However, it cannot be concluded whether the drivers rotated their neck to their fullest extent during the experimental task. It may be possible that through the trunk rotation movement the drivers did not have to expend as much of neck rotation movement in order to detect the target.

Although this study revealed functional ROM to be different from neck ROM, neck axial ROM alone in the past has been a common measurement for driver ability evaluation. For instance, Marottoli et al. (1998) has found neck rotation angle to be a strong factor associated with adverse driving events but not trunk rotation angle. However not all studies reached similar conclusions; neck ROM was not considered to be one of the best predictors of poor driver performance or crashes in older drivers, or driving cessation in older adults (Edwards et al., 2010; Molnar et al., 2007; Stav et al., 2008). The current Gross Impairment Screening Battery (GRIMPS) General Physical and Mental Abilities (Staplin et al., 2003) includes the upper torso rotation as part of the head/neck rotation assessment in the test battery, which assessed the drivers' ability to look over their shoulder, yet it is scored as pass or fail. The results from the present study agree with the GRIMPS assessment in considering neck and trunk rotation, and the present study provides greater information in drivers' biomechanical measurements. Possibly, including a simple technology to create a simulation of an on-road environment at driver license issuing locations to evaluate driver functional ROM. In order to further screen for high risk drivers, a follow-up functional ROM study using VR should be conducted. Such a study could recruit drivers who had different incidents of at-fault crash histories, and then evaluate their functional ROM in the VR environment.

Results from the current study still shared similarities with previous studies, where the younger drivers demonstrated greater spinal flexibility than older drivers in general. The mean baseline neck axial ROM of the younger and older drivers was 78.1° (SD 8.6) and 63.48° (SD 11.0), respectively. Also, the degree of trunk axial rotation was different between the driver groups, with the mean trunk rotation angle being 18.1° (SD 11.15) and 9.94° (SD 6.13) for the younger and older drivers, respectively.

In addition to ROM, target detection success and detection time were examined for the trials that had a target. The younger drivers successfully detected all the trials with a target. However, the older drivers only had a 54% detection rate, meaning that the older drivers only successfully identified a target slightly more than half of the time. After statistically controlling for the location of the target, it was found that the older drivers did not detect the far right and far left targets, which were farther away from the forward view. The effect of target location on detection was more pronounced in the older driver group, which could be related to the change in physical capabilities during the normal aging process.

In general, the near targets had shorter detection time than the far targets. Spatially it took longer for both driver groups to complete the functional ROM rotation and to observe the far targets. The positive relationship in target acquisition time to target distance has been demonstrated by Radwin et al. (1990), where users rotated their heads from an initial point to a target location on a computer screening with a head-controlled input device. In the present study, the younger drivers were 0.46 s faster to detect the targets than the older drivers, which suggested that younger drivers may be able to react quicker to identify objects during this task. Similarly, in reaction time tasks the older participants responded slower to visual stimuli than younger participants (Hultsch et al., 2002). The older drivers' ROM, target detection success, and target detection time differed from younger drivers in this study, which may suggest that there are several factors that should be considered when evaluating the driving capacity of older drivers.

Conducting this experiment in VR provided a safe study environment, convenience, and straightforward data collection, yet it was different from actual physically driving. It is possible that drivers react and respond differently to on-road events in an actual driving scenario, such as using mirrors to assist in speculating the environment before performing lane change maneuvers. It was also possible that other strategies could have assisted in target detection during a blind spot checking task, such as utilizing the peripheral visual field in the lateral direction. Checking the blind spot is a multi-factor action and many components are involved, but the functional ROM was the primary focus of this study and therefore the contribution of visual field of view was not measured. In addition, the field of view in a VR environment was different from the physical environment, and the participants might not be able to use their natural peripheral vision to aid in the detection of the target in the blind spot checking task. Specifically, the VR environment of this study had 110° of field of view in *diagonal*. This suggested that the horizontal visual field of the VR environment was likely to be less than the normal human horizontal visual field in the lateral direction, which is approximately 100° (Spector, 1990). Moreover, blind spots could vary among different vehicle manufacturers, and therefore the targets were not placed at locations that mapped into any specific vehicle models. The targets were placed at general locations outside of the front visual field of view and would require drivers to axially rotate before the targets became visible. It should be noted that the seat in this study was different from a car seat, lacked a seatbelt and a head cushion, which could have further restricted driver motion. However, in order to place active motion marker cluster on the back of the participants it was not feasible to use chair with a larger chair back as it would occlude the marker. Lastly, it was not studied what would be an appropriate cut-off value for functional ROM or detection time to conclude which drivers at more at risk, which could be a possible future direction. Despite these limitations we conclude that VR testing of functional ROM is a more representative method for evaluating driver ability than conventional neck ROM measures.

In conclusion, the functional ROM of younger and older drivers in performing blind spot checking movements in a VR environment was greater than their active axial neck ROM. The functional ROM observed in this study consisted of neck and trunk rotation motion, which suggested that drivers rotated both neck and trunk when they checked blind spot. Trunk rotation in driving may not be neglected and its role should be further studied. Target detection and detection time were also different between the driver groups, which suggested that these measures may also be important factors of the aging process.

Conflict of interest

The authors have no conflicts of interest.

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References

Anstey, K.J., Wood, J., Lord, S., Walker, J.G., 2005. Cognitive, sensory and physical factors enabling driving safety in older adults. Clin. Psychol. Rev. 25, 45–65.
Ashman, R.D., Bishu, R.R., Foster, B.G., McCoy, P.T., 1994. Countermeasures to improve the driving performance of older drivers. Educ. Gerontol. Int. Q. 20, 567–577.
Ball, K.K., Roenker, D.L., Wadley, V.G., Edwards, J.D., Roth, D.L., McGwin, G., Raleigh, R., Joyce, J.J., Cissell, G.M., Dube, T., 2006. Can high-risk older drivers be identified through performance-based measures in a department of motor vehicles setting? J. Am. Geriatr. Soc. 54, 77–84.
Caragata, G.E., Tuokko, H., Damini, A., 2009. Fit to drive: a pilot study to improve the physical fitness of older drivers. Act. Adapt. Aging 33, 240–255.
Chen, K.B., Ponto, K., Tredinnick, R.D., Radwin, R.G., 2015. Virtual exertions evoking the sense of exerting forces in virtual reality using gestures and muscle activity. Hum. Factors J. Hum. Factors Ergon. Soc. 57, 658–673.
Chiu, T.T.W., Lo, S.K., 2002. Evaluation of cervical range of motion and isometric neck muscle strength: reliability and validity. Clin. Rehabil. 16, 851–858.
Dalgarno, B., Lee, M.J.W., 2010. What are the learning affordances of 3-D virtual environments? Br. J. Educ. Technol. 41, 10–32.
Desapriya, E., Harjee, R., Brubacher, J., Chan, H., Hewapathirane, D.S., Subzwari, S., Pike, I., 2014. Vision screening of older drivers for preventing road traffic injuries and fatalities. Cochrane Database Syst. Rev. (2). http://dx.doi.org/10.1002/14651858.CD006252.pub4.
Dugdale, J., Pavard, B., Pallamin, N., el Jed, M., Maugan, L., 2004. Emergency fire incident training in a virtual world. Proceedings of the International Workshop on Information Systems for Crisis Response and Management (ISCRAM 2004).
Dukic, T., Broberg, T., 2012. Older drivers' visual search behaviour at intersections. Transp. Res. F Traffic Psychol. Behav. 15, 462–470.
Eby, D.W., Trombley, D.A., Molnar, L.J., Shope, J.T., 1998. The assessment of older drivers' capabilities: a review of the literature. Ann Arbor 1001, 48109.
Edwards, J.D., Bart, E., O'Connor, M.L., Cissell, G., 2010. Ten years down the road: predictors of driving cessation. Gerontologist 50, 393–399.
Holden, M.K., 2001. Neurorehabilitation using "learning by imitation" in virtual environments. Usability Eval. interface Des. Cogn. Eng. Intell. agents virtual reality. Lawrence Erlbaum, London, pp. 624–628.
Hultsch, D.F., MacDonald, S.W.S., Dixon, R.A., 2002. Variability in reaction time performance of younger and older adults. J. Gerontol. Ser. B Psychol. Sci. Soc. Sci. 57 (2), P101–P115. http://dx.doi.org/10.1093/geronb/57.2.P101.
Isler, R.B., Parsonson, B.S., Hansson, G.J., 1997. Age related effects of restricted head movements on the useful field of view of drivers. Accid. Anal. Prev. 29, 793–801.
Lange, T., Indelicato, D.J., Rosen, J.M., 2000. Virtual reality in surgical training. Surg. Oncol. Clin. N. Am. 9, 61–79 (vii).
Lee, E.A.-L., Wong, K.W., 2008. A review of using virtual reality for learning. Transactions on Edutainment I. Springer, pp. 231–241.
Lee, H.C., Lee, A.H., Cameron, D., Li-Tsang, C., 2003. Using a driving simulator to identify older drivers at inflated risk of motor vehicle crashes. J. Saf. Res. 34, 453–459.

Marottoli, R.A., Richardson, E.D., Stowe, M.H., Miller, E.G., Brass, L.M., Cooney Jr., L.M., Tinetti, M.E., 1998. Development of a test battery to identify older drivers at risk for self-reported adverse driving events. J. Am. Geriatr. Soc. 46, 562–568.

Marottoli, R.A., Allore, H., Araujo, K.L.B., Iannone, L.P., Acampora, D., Gottschalk, M., Charpentier, P., Kasl, S., Peduzzi, P., 2007. A randomized trial of a physical conditioning program to enhance the driving performance of older persons. J. Gen. Intern. Med. 22, 590–597.

Molnar, F.J., Marshall, S.C., Man-Son-Hing, M., Wilson, K.G., Byszewski, A.M., Stiell, I., 2007. Acceptability and concurrent validity of measures to predict older driver involvement in motor vehicle crashes: an emergency department pilot case–control study. Accid. Anal. Prev. 39, 1056–1063.

Ostrow, A.C., Shaffron, P., McPherson, K., 1992. The effects of a joint range-of-motion physical fitness training program on the automobile driving skills of older adults. J. Saf. Res. 23, 207–219.

Park, S.-W., Choi, E.S., Lim, M.H., Kim, E.J., Hwang, S. I, Choi, K.-I., Yoo, H.-C., Lee, K.J., Jung, H.-E., 2011. Association between unsafe driving performance and cognitive–perceptual dysfunction in older drivers. PM R 3, 198–203.

Pontonnier, C., Samani, A., Badawi, M., Madeleine, P., Dumont, G., 2013. Assessing the Ability of a VR-Based Assembly Task Simulation to Evaluate Physical Risk Factors.

Radwin, R.G., Vanderheiden, G.C., Lin, M.-L., 1990. A method for evaluating head-controlled computer input devices using Fitts' law. Hum. Factors J. Hum. Factors Ergon. Soc. 32, 423–438.

Reimer, B., D'Ambrosio, L.A., Coughlin, J.F., Puleo, R.M., Cichon, J.E., Griffith, J.D., 2008. Effects of age on spinal rotation during a driving task. Transp. Res. Rec. J. Transp. Res. Board 2078, 57–61.

Romoser, M.R.E., Fisher, D.L., Mourant, R., Wachtel, J., Sizov, K., 2005. The use of a driving simulator to assess senior driver performance: Increasing situational awareness through post-drive one-on-one advisement. Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design, pp. 456–463.

Sarig-Bahat, H., Weiss, P.L., Laufer, Y., 2009. Cervical motion assessment using virtual reality. Spine (Phila Pa 1976) 34, 1018–1024.

Sivak, M., Schoettle, B., 2012. Recent changes in the age composition of drivers in 15 countries. Traffic Inj. Prev. 13, 126–132.

Spector, R.H., 1990. Visual fields. In: Walker, H., Hall, W., Hurst, J. (Eds.), Clinical Methods: The History, Physical, and Laboratory Examinations. Butterworth, Boston.

Staplin, L., Lococo, K.H., Gish, K.W., Decina, L.E., 2003. Model driver screening and evaluation program final technical report. Project Summary and Model Program Recommendations volume 1.

Stav, W.B., Justiss, M.D., McCarthy, D.P., Mann, W.C., Lanford, D.N., 2008. Predictability of clinical assessments for driving performance. J. Saf. Res. 39, 1–7.

Swinkels, R.A.H.M., Swinkels-Meewisse, I.E., 2014. Normal values for cervical range of motion. Spine (Phila Pa 1976) 39, 362–367.

Wood, J.M., Anstey, K.J., Kerr, G.K., Lacherez, P.F., Lord, S., 2008. A multidomain approach for predicting older driver safety under in-traffic road conditions. J. Am. Geriatr. Soc. 56, 986–993.

Wu, G., Van Der Helm, F.C.T., Veeger, H.E.J.D., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992.

Xu, X., Chen, K.B., Lin, J.-H., Radwin, R.G., 2015. The accuracy of the oculus rift virtual reality head-mounted display during cervical spine mobility measurement. J. Biomech. 48, 721–724.

Youdas, J.W., Garrett, T.R., Suman, V.J., Bogard, C.L., Hallman, H.O., Carey, J.R., 1992. Normal range of motion of the cervical spine: an initial goniometric study. Phys. Ther. 72, 770–780.