Driving in a simulator and lower limb movement variability in elderly persons: can we infer something about pedal errors

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Abstract

Driving through an intersection requires observing and monitoring traffic conditions and the driving environment. It also requires, among other things, accurate right foot movements. It is with podal actions on brake and accelerator pedals that the driver controls the speed of the vehicle. Older adults exhibit greater motor variability than young adults [1, 2]. This increased variability may affect the accuracy of right foot movements while driving. It was hypothesized that, when stopping at an intersection, elderly drivers would show podal movements characterized by hesitation when moving from the accelerator to the brake pedal and by less stable temporal and spatial right foot movements than young drivers. Young (aged 21-42 years, n = 15) and older (aged 61-79 years, n = 25) active drivers participated. A driving simulator was used. Before the experimental session, all subjects drove an 8-km practice run to familiarize themselves with the simulator and the general feel of the pedals and steering. For the experimental run, all participants drove through the same 16-km route of a simulated neighbourhood (27 events consisting of crossings with a stop sign or crossing lights). For each event, the linear amplitude and within-subject variability of the right foot was calculated. The young adult generally released their foot from the accelerator pedal and moved toward the brake pedal without any hesitation. Elderly individuals showed more variable right foot movements (from the accelerator pedal to the brake pedal) characterized by the presence of several submovements (beyond small wobbling movements). Older drivers' right foot movements are more variable than that of young drivers. More research is needed to determine if there is a direct relationship between this lower limb movement variability, and serious pedal errors.

Keywords – Simulator, pedals, intersections, errors

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1. Introduction

Driving through an intersection is one of the most difficult aspects of driving. Hakamies-Blomqvist et al. [3] reported that older drivers have proportionally more accidents occurring in complex traffic situations, such as intersections. For such accidents, both left turn and rear-end collisions are reported. For instance, an analysis of a traffic accident database (2962 car accidents by active or retired police drivers) showed that, for the 65-74 years-old drivers, 70.7% of the accidents occurred at an intersection [4]. This percentage was 66.5% for the 36 to 50 years-old drivers and increased to 76.0% for the 75 and older age group. In another study, Hauer [5] reported that, for drivers 64 years-old and older, 37% of death-related accidents and 60% of injury-related accidents occurred at intersections. For older drivers (> 80 years old), 50% of the death-related accidents occurred at intersections; this represents more than twice what was observed for a 45-64 years-old age-group. A 3-year longitudinal study by Owsley et al. [6] involving more than 300 older drivers showed a similar trend: 70% of all accidents occurred at intersections and more than 37% of the death-related accidents occurred at intersections. To explain these high rates of accidents, Hakamies-Blomqvist et al. [3] suggested that intersections could produce very high momentary mental workload; it is this mental workload that would yield driving errors. In such situations, compensatory and more serial behaviours were observed for older drivers [3]. A more serial behaviour was defined as the use of three simultaneous controls a relatively greater proportion of time than four or more controls. In another paper, we also showed, using the probe reaction time technique that approaching an intersection yields an increased RT to an auditory stimulus [7]. Thus, there is a general agreement that intersections create difficulties for the elderly driver.

When driving, a precise representation of the vehicle-environment relationship is essential. This representation certainly relies upon the integrity of the visual system. When attempting to predict accident frequency of older drivers, however, it has often been reported that visual acuity and common medical examination do not allow distinguishing convicted older drivers with crashes and moving violations from older drivers without moving violation [8]. Results on various visual tests normally account for no more than 20% of the driving performance [9]. This observation simply highlights the complex and multifactorial nature of the driving task. In addition to visual acuity per se, the right foot responses to visual stimuli is certainly an important aspect of the driving task. It is with pedal actions on brake and accelerator pedals that the driver controls the speed (and trajectory) of the vehicle. The ability to repeatedly perform a motor task requiring a muscular contraction with appropriate force and timing is often used to describe successful and skilled performance [10]. Older adults have been shown to exhibit greater motor output variability than young adults during rapid discrete isometric contractions of the lower limb muscles [2], when initiating gait [11] and when performing upper limb goal directed movements [1]. Despite the importance of foot and pedal movements for controlling the vehicle, to our knowledge, there are no published report of foot movements for elderly persons and very few studies with young individuals [12-14]. Much of this literature concerns human errors as a function of pedal positioning and characteristics.

The aim of this experiment was to compare the driving behaviour of elderly persons with that of young adults when facing normal driving simulator situations. It was hypothesized that, when stopping at an intersection, elderly individuals would show more variable pedal movements than young adults. Across intersections, it was expected that elderly drivers would show pedal movements characterized by hesitation when moving from the accelerator to the brake pedal and by less constant temporal and spatial right foot movements than young drivers. We also expected that, compared to decelerating for a stop sign, this effect would be exacerbated when stopping at a crossing light because of the added uncertainty associated with the light change.

2. Method

2.1 Subjects

Twenty-five elderly persons (18 men / 7 women, mean age = 65.4, range of 60-74) and 15 young adults (11 men / 4 women, mean age = 23.5, range of 21-42) participated on a voluntary basis. They gave informed consent according to University protocols. The elderly were recruited through advertisements in local newspapers. A first screening for medical, orthopedic or neurological conditions that could affect normal driving performance was done by telephone. This only served to insure that all elderly subjects selected were independent and ambulatory community dwellers. Upon their first visit, a questionnaire regarding driving habits was given: All elderly were active drivers (on average, 150 km/week with more than 35 years of driving experience). The elderly were evaluated on the Mini Mental Test; the lowest score was 25 (on average, 27.0 vs 28.4 for the young adults). Visual acuity was tested using the Snellen chart. Distance binocular vision was normal or corrected to normal for all subjects. Ocular movements and visual field status showed no deficits for the selected subjects.

2.2 Procedures

A fully interactive driving simulator was used in this study. The simulator consists of an instrumented (brake and accelerator pedals, steering and all manual controls) mid-sized sedan with automatic transmission interfaced with a programmable software [15] allowing to develop driving scenario and to record the driver's performance. Displacement of the accelerator and brake pedals are recorded (Measurement Computing DAS08 12-bit A/D). The visual information is provided through a 19 in a screen located 50 cm from the steering. The center of the screen is located at eye level through the midline of the subject. No external visual information is available as a tunnel made of black cardboard shields all information but that coming from the screen. Before the experimental session, all subjects drove an 8-km practice run to familiarize themselves with the simulator and the general feel of the pedals and steering. All subjects were instructed to drive as normally as possible and to avoid any accident. Two subjects (one elderly and one young) had to withdraw from the experiment, because of simulation sickness. All other subjects reported being comfortable with the simulator after this run. For the experimental run, all participants drove through the same 16-km route of a simulated neighbourhood. They were given 26 events consisting of crossings with a stop sign (18 events) or crossing lights (8 events, the light turned to red for 5 events). For all events, the task required a careful observation of traffic conditions for decelerating and driving through the intersection safely. Subjects were asked to observe speed limitations and to comply with local traffic laws throughout the course of the experiment. Video records of the right foot movements were taken at 30 frames/sec with two digital cameras (JVC-9500U). The cameras were placed just above the floor level, 45 cm from the right foot. The environment was calibrated with a structure of known dimensions. A passive reflective marker was fixed on the external malleolus. Video records were synchronized with the visual information presented by turning on a light emitting diode, not seen by the subjects, when the car they were driving was at 50 m from an event. All video records were captured digitally (Adobe Premiere). Position of the marker for each image of all events was digitalized with software allowing to determine precisely the centroid position of the marker. Data were then transformed with a direct linear transformation approach and linear displacement of the right foot was calculated for each event. Displacement data were filtered using Matlab (Mathworks, Natick, MA) with a second-order low-pass Butterworth filter (7 Hz cutoff frequency and forward/backward passes to eliminate phase shift). Time derivative of the linear displacement was then computed with a finite difference technique. For each subject, mean displacement and their respective within-subject variability were calculated.

2.3 Data Analyses

For each dependent variable, within-subject means were first calculated. Then, all dependant variables were submitted to a two-way Analysis of Variance (Group x Type of intersection) using Statistica 6.0 (Statsoft Inc, Tulsa, OK). The critical value for statistical significance was set at an alpha level of 0.05.

3. Results

Variables describing the global driving performance are provided in Table 1. Only two accidents were recorded for the experimental runs. Both accidents were made by elderly subjects and both were rear-end collisions. We also observed five events for which an elderly driver did not stop at the intersection (5 stops). The local traffic at the time the car crossed the intersection did not yield an accident for these events. Young drivers were not involved in any similar event. Overall, the time needed to complete the experimental run was longer for the elderly than for young adults (on average, 26.1 min vs. 21.4 min; $p < .01$). Table 2 presents a summary of all group means and standard-deviations for all analyses. When looking at the distance of the vehicle from the intersection at the first contact with the brake pedal, elderly drivers were closer to the intersection than young adults (33.9 m vs. 36.95 m, respectively). Their speed, however, was considerably slower than that observed for the young adults (8.15 vs 10.78 m/s, respectively; $p <.001$). This behavior can be considered as more conservative since assuming subjects would progress toward the intersection with a constant speed (often called time-to-intersection) elderly individuals would arrived at the intersection in a longer time than young adults (6.2 s vs 3.6 s, respectively; $p<.05$). The actual time taken to completely decelerate the vehicle (time 0 = first contact with the brake pedal) was 5.2 s for the elderly vs. 4.9 s for the young adults ($p=.537$). When releasing their right foot from the accelerator pedal to initiate the deceleration of the vehicle, the elderly produced a movement that was longer in amplitude than that of the young adults. On average, the linear amplitude of the initial right foot movement was 11.55 cm for the elderly and 10.10 cm for the young adults ($p < .05$). Across all intersections, the within-subject variability of the movement amplitude was also greater for the elderly than for the young adults (1.37 vs. 0.95 cm; $p < .05$). An analysis of the right foot behavior showed that, for the elderly drivers, a number of submovements followed the initial release of the accelerator pedal.

Tab. 1 – Description of global driving performance

Global performance	Group means (SD)	
	Elderly	*Young adults*
Time needed to complete the 16-km experimental run (min.)	26.14 (0.34)	21.43 (0.44)
Major driving errors (Total number of accidents and failure to stop)	7	0

Tab. 2 – Description of dependant variables, group means and standard deviations

	Elderly		*Young adults*	
Vehicle behavior when decelerating at an intersection	Stop signs	Crossing lights	Stop signs	Crossing lights
Distance of the vehicle from the intersection at the first contact with the brake pedal (m)	30.14 (5.28)	37.65 (13.36)	34.88 (7.33)	39.02 (4.39)
Speed of the vehicle at the first contact with the brake pedal (m/s)	8.43 (2.11)	7.88 (2.51)	11.7 (1.49)	9.85 (1.26)
Time-to-intersection at the first contact with the brake pedal (s)	5.73 (2.20)	6.60 (2.74)	3.16 (0.77)	4.03 (0.59)
Time taken to completely decelerate the vehicle (s)	4.40 (1.28)	5.31 (3.13)	3.98 (1.03)	6.50 (1.12)
Right foot behavior and kinematics				
Linear amplitude (cm)	11.40 (1.60)	11.71 (1.80)	10.05 (1.20)	10.15 (1.42)
Within-subject variability of the movement amplitude (cm)	1.35 (0.61)	1.39 (0.87)	0.98 (0.49)	0.89 (0.31)
Number of submovements (with linear speed exceeding 10 cm/s)	2.70 (1.15)	1.18 (1.34)	0.59 (1.29)	0.30 (1.03)
Within-subject variability of number of submovements	1.74 (0.60)	1.25 (0.47)	1.08 (0.61)	0.80 (0.62)

Figure 1 illustrates representative trials for a young adult and an elderly subject. Lateral views of the right malleolus displacement and speed are presented. For the young adult, such submovements were rarely observed; the young adult generally released their foot from the accelerator pedal and moved toward the brake pedal without any hesitation. The corresponding linear speed of this movement, characterized by a bell-shape curve, is presented on the bottom panel. On the other hand, the foot movement of the elderly subject (left panel) is characterized by additional movements. In this example, the corresponding linear speed shows four additional movements before the final activation of the brake pedal. For each subject, the number of such submovements was calculated by identifying the number of times the velocity curve exceeded 10 cm/s before the activation of the brake pedal yielding to a complete stop of the vehicle. The 10 cm/s criteria was selected because it was associated with movements that were clearly beyond small wobbling movements. Figure 2 shows the number of submovements for the red lights and the stop signs for both groups. The ANOVA yield main effects of Group ($F(1,39) = 14.986$, $p<.001$) and type of intersections ($F(1,39) = 13.522$, $p<.001$). On average, elderly individuals produced 1.94 additional submovements whereas young adults showed 0.44 submovements. The within-subject variability associated with this behavior was also more important for the elderly (1.50 vs. 0.94 submovements, respectively; $p < .01$). Contrary to our hypothesis, the number of submovements was more important for stop signs than for red lights and this was observed for both groups (on average, 0.74 and 1.65 for the red lights and stop signs, respectively).

4. Discussion

In this experiment, the elderly adopted a more conservative driving behavior. They drove slower than young adults and they arrived at intersections with a slower speed. The duration of the deceleration (60 m from the intersection) also was longer than that of young adults. Similar observations have been reported for normal as well as simulated driving [3, 16, 17]. The slower speed adopted by the older drivers is often considered as a compensatory and conservative behavior [18]. Elderly may adopt this behavior because of visual impairments resulting in errors in estimating speed and or distances. Indeed, it has been reported that elderly have a decreased ability to detect that a collision is impending [19, 20]. This decreased detection capability may have yielded the increased number of submovements of the right foot we have observed.

It is important to note that for both type of intersection, elderly subjects showed a greater number of submovements than young adults. Contrary to our initial hypothesis, however, we did not observe a greater number of submovements when subjects approached a crossing light. There are several hypotheses for this result. First, this may be the result of a methodological factor since we had only five crossing light compared to 18 stop signs. Also, the green light nearly turned to yellow when subjects were about 105.7 m from the intersection and this may have provided a more stable and fixed stimulus for initiating the braking response. A more complex and varied scenario would be needed to explore this possibility. Sensory degeneration of the lower limbs is one of the most common manifestations of aging [21, 22]. The movements of greater amplitude and the faster brake responses observed in the present experiment could have served to stimulate sensory receptors in order to reach higher thresholds for detecting movement or to provide sufficient sensory information for accurate positioning of the foot on the brake pedal. The absence of proprioception sometimes yields movement of increased amplitude [23]. In our experiment, the sense of position was not measured specifically but elderly subjects showed signs of decreased tactile sensitivity. Alternatively, Christou and Carlton [2] suggested that repetition of the descending command and eventual excitability of the motoneuronal pool could be impaired in old adults. The right foot behavior of the elderly subjects, when compared to that of young adults, was characterized by an increased variability. Increased movement variability is often associated with less efficient and less accurate movements [1, 13]. Increasing the number of submovements and the variability of these movements are likely to increase the likelihood of simple and more serious pedal actuation errors. For example, Rogers and Wierwille [12] reported that scuff, catch (the right foot catches the lower edge of the brake or accelerator pedal), and serious pedal actuation errors (mistakes accelerator for brake or vice versa) do occur.

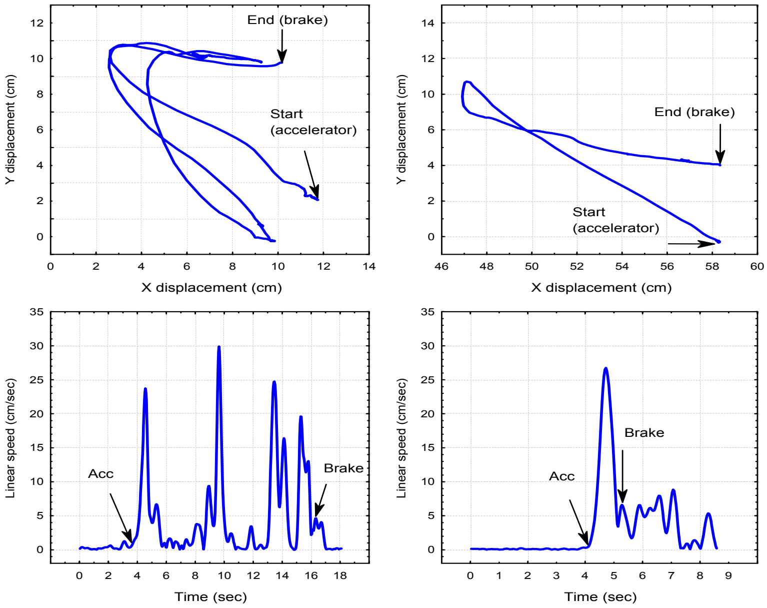

Fig. 1 – Lateral view of the right ankle displacement of a young subject (top right panel) and an elderly subject (top left panel). Lower panels present the corresponding linear velocity.

The release of the accelerator (Acc) and the final activation of the brake pedal (Brake) are indicated with arrows. For the young adult, submovements were rarely observed; the young adult generally released their foot from the accelerator pedal and moved toward the brake pedal without any hesitation. On the other hand, the foot movement of the elderly subject (left panel) is characterized by several submovements. In this example, the corresponding linear speed shows four additional movements before the final activation of the brake pedal. For each subject, the number of such submovements was calculated by identifying the number of times the velocity curve exceeded 10 cm/s before the activation of the brake pedal yielding to a complete stop of the vehicle. The 10 cm/s criteria was selected because it was associated with movements that were clearly beyond small wobbling movements.

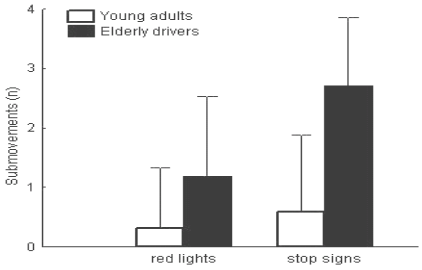

Fig. 2 – Number of submovements for the red lights and the stop signs

Also, Schmidt [13] suggested that the variable and inconsistent processes that generate muscle force are the primary source for serious pedal actuation errors. There are, however, no data on the rate of these errors for elderly individuals. In the present experiment, we did not observe pedal errors as defined by Rogers and Wierwille [12]. Driving conditions, however, were ideal as subject did not report any fatigue or discomfort (the driving performance lasted only about 25 minutes) and were not distracted by any external events (for instance, secondary task involving discussion with passenger). Also, all of our subjects were cognitively fit. Future studies may show that more complex driving situations and more variable pedal movements such as those observed in the present experiment could affect the driving performance by increasing pedal actuations errors. On the other hand, we did observe some serious errors. These errors, since they implied the absence of a braking response were certainly associated with a misperception of the environment. Across all intersections, seven major driving errors were observed for the elderly (just above 1% of all possibilities). It could be argued that these errors were the consequence of a lack of familiarization with the simulator. Lee et al.[24], however, observed a highly significant relationship between an on-road assessment index and a simulated driving index. Could the number of submovements and the variability lead to serious pedal errors is a difficult question to answer. It can be problematic to draw such causal relationships. On the other hand, the use of traditional experimental designs and normal statistics clearly cannot be used for studying worst-case scenarios. The terrible accident that recently occurred in California (Santa Monica) is a typical example of such a case. An older active driver, aged 86, killed ten and injured up to 45 persons before stopping his car. He reported hitting the gas pedal instead of the brake. It is important to mention that no traces of alcohol or psychoactive drugs such as antidepressants and hallucinogens were found in the driver's blood. Similar cases with less dramatic consequences but still involving fatal injuries have been observed elsewhere [25]. Such accidents involving elderly drivers cannot be considered as anecdotic. Schmidt [13], in a literature review of human factors leading to unintended acceleration, has argued that the sources of such errors could be related to motor control processes in pedal operation. The variability we observed for elderly drivers could be one of these sources.

The present experiment did not require subjects to initiate a left turn at any of the intersections. This was imposed by the software and it can be considered as a limitation of the study. Hakamies-Blomqvist et al. [3] reported that older drivers have proportionally more accidents occurring in complex traffic situations, such as intersections. Presumably, this higher rate of accidents is associated with a higher momentary mental workload created by the intersection. If this hypothesis is valid, adding the possibility of a left turn in the present experiment would certainly have yielded a greater number of driving errors as well as some incidence of scuff, catch, and serious pedal actuation errors (mistakes accelerator for brake or vice versa). Future studies are needed to examine this possibility.

5. Conclusion

Older drivers' right foot movements are more variable than that of young drivers. More research is needed to determine if there is a direct relationship between this lower limb movement variability, and serious pedal errors.

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