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Impact of cognitive distraction on driving performance and safety in older adults: A cluster analysis of age, gender, and functional mobility

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ABSTRACT

Any activity that diverts a driver's attention during vehicle operation may compromise driving performance and road safety. This study aimed to analyze the effect of conversational distraction on driving performance, examine the association of age and gender with braking time, and identify driver profiles potentially associated with increased traffic vulnerability. A total of 101 drivers participated: 51 older adults (mean age: 69.5 ± 5.9 years) and 50 younger adults (mean age: 33.4 ± 8.8 years). Driving performance was assessed using a simulator, with braking time and driving speed as primary outcomes. Cognitive function was evaluated using the Mini-Mental State Examination (MMSE), and mobility and balance were assessed using the Timed-Up and Go Test (TUGT), both with and without a cognitive task. Older adults exhibited significantly longer braking times compared to younger adults ($p = 0.046$). However, they also demonstrated lower driving speeds, both with distraction ($p = 0.01$) and without distraction ($p = 0.003$). Conversation did not increase braking time but reduced speed in older adults ($p = 0.01$), suggesting a compensatory driving strategy. Women, regardless of age group, showed significantly longer braking times both with ($p < 0.001$) and without distraction ($p = 0.03$). Cluster analysis identified

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two groups: Cluster 1 ($n = 64$, 63%) and Cluster 2 ($n = 37$, 37%). Cluster 2, characterized by a higher proportion of older adults, lower education levels, slower TUGT performance, longer braking times, and reduced driving speeds, accounted for 24.7% of the variance explained by the multivariate clustering solution. Age and female sex were associated with longer braking times. Although conversation did not increase braking time, it reduced speed among older adults, suggesting a compensatory strategy. Drivers who were older, less educated, and presented reduced functional mobility exhibited a performance profile associated with increased vulnerability in traffic contexts.

1. Introduction

Population aging is contributing to an increasing presence of older drivers around the world on the roads, raising significant concerns about road safety and traffic-related incidents (IBGE, 2023). The proportion of individuals over 65 years old who hold driving licenses is expected to grow substantially in the coming decades (Lin & Cui, 2021), reflecting both the aging population and longer life expectancies. The automobile remains as the primary mode of transportation for older adults (Young & Bunce, 2011), a group particularly vulnerable to road accidents due to a combination of physical frailty and declining cognitive functions (Li et al., 2021).

Driving, a complex task that requires coordination of physical, cognitive, and visual abilities, becomes more challenging with age (Canonica et al., 2023; Silva et al., 2023). As cognitive abilities such as attention, memory, and perception deteriorate, driving behavior may change, potentially compromising safety (Hoff et al., 2013; Llerena et al., 2015; Tsotsos et al., 2021). These cognitive declines are often exacerbated by multifaceted distractions, including in-vehicle conversations**, which have been shown to impair driving performance and increase crash risk across different age groups (Guo et al., 2017; Karthaus et al., 2020). Evidence suggests that older drivers may be particularly vulnerable to the effects of visual and auditory distractions,** highlighting the importance of understanding how these factors influence braking time and overall road safety.

In addition to the physiological effects of aging, gender differences in driving behavior have been identified (Cordellieri et al., 2024). Biological and behavioral distinctions between men and women contribute to divergent patterns of road safety (Aluja et al., 2023). While men tend to take greater risks (De Biase et al., 2024), leading to more severe accidents, women generally exhibit more cautious driving behaviors (Castro-Nuño & Lopez-Valpuesta, 2023). Furthermore, differences in muscle and bone mass, as well as cardiovascular and metabolic conditions, further complicate the understanding of gender's role in road safety. Education and access to vehicle assistance technologies also mediate the ability of older drivers to adapt to modern cars, underscoring the need for tailored approaches to enhance safety across different groups (Casamento-Moran et al., 2022; De Biase et al., 2024).

Although vehicle technology is becoming increasingly automated, the simultaneous execution of multiple tasks while driving—such as managing cognitive distractions—can still impair driving performance (Carizio et al., 2021; Zangi et al., 2022). The capacity to manage distractions while driving is influenced by cognitive functions, particularly working memory, as well as driver experience (Zhang et al., 2020). These factors may contribute to the variation in how different groups handle in-car distractions, especially in more complex driving environments (Pope et al., 2017).

While much of the literature on distracted driving has focused on mobile phone use and navigation systems (Berka et al., 2019a), there remains a gap in understanding the impact of in-car conversations, particularly as a distraction factor among older drivers (Guo et al., 2021; Hossain et al., 2022). Conversations, whether with passengers or on hands-free devices, could potentially alter driving behavior by affecting reaction times, vehicle speed, and decision-making (Llerena et al., 2015; Voinea et al., 2023).

This study aims to fill this gap by investigating the role of conversation as a distraction factor among older drivers (Theofilatos et al., 2018; Zangi et al., 2022). Studying ways to improve the longevity of safe driving is essential, as the cessation of driving can be a traumatic and negative experience, impacting the independence and well-being of older individuals (Savoie et al., 2024). Through identifying key factors that affect driving performance, this research aims to contribute to the development of targeted interventions and strategies that can help mitigate risks associated with older drivers (Lin & Cui, 2021). Ultimately, improving the quality and safety of driving for older adults can enhance their mobility, maintain their autonomy, and reduce the emotional and psychological impacts associated with losing the ability to drive (Li et al., 2021).

The main goal of this study was to identify subgroups of drivers most vulnerable to traffic accidents, using braking time as a key risk indicator. We hypothesize that conversations significantly influence driving behavior, particularly braking time, and that aging and gender modulate these effects. We also hypothesize that older individuals, especially those with cognitive or physical impairments, may show a greater susceptibility to distractions. Through cluster analysis, this study seeks to uncover how aging, gender, and functional status contribute to the likelihood of dangerous driving behaviors and how these factors can inform targeted interventions for improving road safety.

2. Methods

2.1. Study desing

This study is a cross-sectional, quantitative research conducted at the Laboratory of Movement Studies (LEM), Institute of Orthopedics and Traumatology (IOT), Hospital das Clínicas (HC), Faculty of Medicine, University of São Paulo (FMUSP). The study followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines to ensure methodological rigor and transparency in reporting (Malta et al., 2010).

2.2. Participants and settings

A total of 101 community-dwelling drivers of both genders from **São Paulo, Brazil,** participated in this study. Data collection was conducted in **2023** at the LEM-IOT-HC-FMUSP. Participants were recruited through **digital communication platforms and social networks**, where invitations were disseminated to reach potential candidates who met the study's inclusion criteria.

2.3. Sample size calculation

The sample size was determined based on previous studies analyzing braking time and driving performance among older adults. A power analysis was conducted using G*Power software (Kang, 2021), considering a significance level of $\alpha = 0.05$, a power (1-β) of 0.80, and an effect size estimated from similar research on driving distraction and reaction time (Kawai & Nakata, 2022). Based on these parameters, a minimum of 98 participants was required to detect significant differences in braking time between groups. To account for potential dropouts or data inconsistencies, the final sample included 101 drivers, ensuring robust statistical analyses.

2.4. Inclusion and exclusion criteria

Participants were required to have a valid and current driver's license and drive regularly at least two days per week. They also had to report no vestibular, proprioceptive, auditory, neurological, or mental impairments, and could not be using psychoactive drugs (e.g., psychotropics, barbiturates, centrally acting muscle relaxants). Individuals with lower limb injuries, trauma, or surgeries in the past six months were excluded, as were those unable to complete the proposed assessments. Participants were also required to demonstrate full range of motion in the ankle, knee, and hip joints and a clinically normal gait without limping or assistive devices.

2.5. Participants enrollment

A total of 250 individuals responded to the study invitation and were assessed for eligibility, as illustrated in Fig. 1. After initial screening, 80 participants were excluded for not meeting the inclusion criteria and 45 declined to participate or did not complete the assessment. Of the 125 eligible individuals, 24 were further excluded due to incomplete data or technical issues, resulting in a final sample of 101 participants. The sample was divided into two groups: younger adults aged 18–59 years ($n = 50$; mean age 33.4 ± 8.8 years) and older adults aged 60–79 years ($n = 51$; mean age 69.5 ± 5.9 years).

Participants were classified into age groups based on predefined criteria. Older adults were defined as individuals aged 60 to 79 years, in accordance with standard classifications for older populations in developing countries, including Brazil. Younger adults were defined as individuals aged 18 to 59 years, representing the adult population prior to age-related functional decline (IBGE, 2023). Age was initially collected as a continuous variable and subsequently categorized according to these established cutoffs (adults x older adults), rather than by sample distribution.

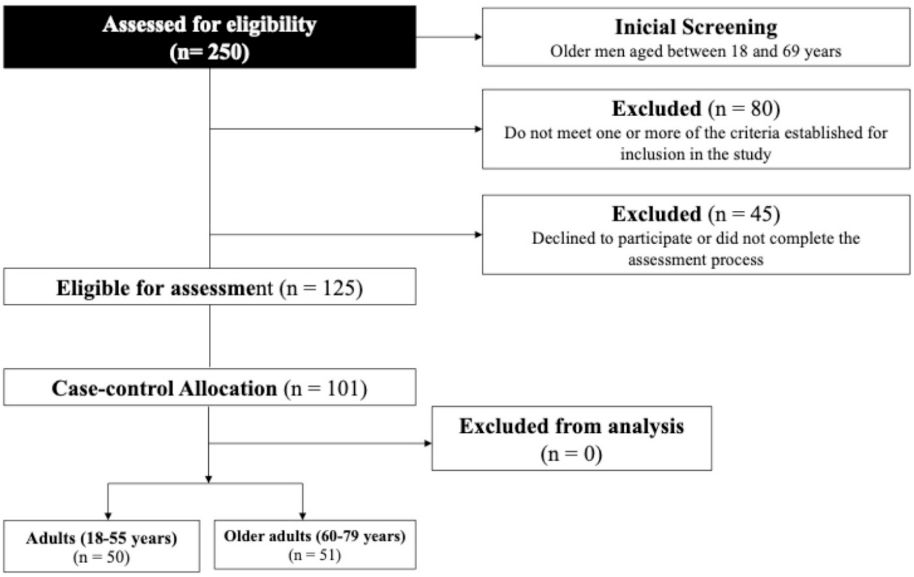

Fig. 1. – Flowchart of study participants enrollment.

2.6. Procedures

Those who expressed interest and met the inclusion criteria were contacted for further screening. Assessments were conducted in a single, pre-scheduled session lasting approximately 45 min. Participants were instructed to wear comfortable clothing and, upon arrival, provided written informed consent before proceeding with the evaluations. During the session, participants performed the braking time task in the driving simulator, as shown in Fig. 2**,** where they were assessed both in a simple condition and with distraction (structured conversation with the evaluator). The task was repeated five times for each condition, and the simulator automatically recorded braking times, total distance driven, and overall driving duration.

2.7. Ethical considerations

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki (Shrestha & Dunn, 2020), and was approved by the Research Ethics Committee of the Faculty of Medicine, University of São Paulo (FMUSP). (protocol CAAE: 42276214.9.0000.0065). All participants provided written informed consent prior to enrollment in the study. Confidentiality and anonymity of the collected data were ensured throughout the research process.

2.8. Instruments

2.8.1. Bio-sociodemographic measurements

Collected data on personal characteristics includes age, education, Body Mass Index (BMI), and weekly physical activity frequency, and driving history (years of driving experience, daily driving hours, and weekly driving frequency).

2.8.2. Cognitive status

The Mini-Mental State Examination **(MMSE)** is a widely used cognitive screening tool with established validity and reliability (Lourenço & Veras, 2006). It consists of 11 items assessing orientation, attention, calculation, recall, language, visuospatial skills, and the ability to follow simple commands. Cutoff scores are 18/19 for illiterate individuals and 24/25 for those with higher literacy. A single overall score was used in the analyses.

2.8.3. Functional mobility

The Timed Up and Go Test (TUG) is a highly valid and reliable measure of functional mobility, widely used to assess mobility and fall risk, particularly in older adults. Studies have demonstrated excellent intra- and inter-rater reliability (ICC = 0.93–0.99) and good correlations with other measures of strength and balance (Podsiadlo & Richardson, 1991).

2.8.4. Cognitive timed up and go test

The Cognitive Timed Up and Go Test (TUG-cog) was used to assess dual-task performance. Participants were instructed to perform the standard TUGT while simultaneously executing a verbal fluency task. In the first trial, they named as many animals as possible, and

Fig. 2. – *Car Simulator test routine.* Fig. 2A - Driver engaged in the braking time task on the FOERST Car Simulator "Trainer" Type F12PT, a simulator with essential driving components in a virtual, single-lane environment without traffic. Fig. 2B - Scores from the braking time task and dual-task condition, comparing braking times with and without distraction during a structured conversation with the evaluator.

in the second trial, they named fruits, continuing until the end of the walking task (Cedervall et al., 2020).

2.8.5. Driving simulator evaluation

Conducted using the FOERST Car Simulator "Trainer" Type F12PT, an automatic driving simulator equipped with a steering wheel, speedometer, brake, accelerator, seat, seatbelt, and headlights. The evaluation was performed in a virtual single-lane driving environment without traffic (Alonso et al., 2016; Casutt et al., 2014).

2.8.6. Braking time task

Participants were seated in the simulator, adjusted the seat and seatbelt, and started the equipment using a key, mimicking real-world vehicle operation. The task measured reaction time (braking time) in response to the sudden appearance of the word "STOP" on the screen. Participants were instructed to press the brake pedal as quickly as possible. Braking time (in seconds) was recorded from the appearance of "STOP" to the moment the foot contacted the brake pedal. The task was repeated five times, and the simulator recorded braking time measurements, total distance driven (3.3 km), and overall driving duration (Alonso et al., 2016).

2.8.7. Dual-task condition (driver distraction)

The procedure was repeated while participants engaged in a structured conversation with the evaluator, following a predefined script covering topics such as family, work, and hobbies. The order of test conditions (with or without distraction) was randomized for each participant to control for potential order effects (Canonica et al., 2023).

3. Statistical analysis

Data analyses were conducted using R software (version 4.0.2, R Foundation for Statistical Computing), utilizing specialized packages for statistical and machine learning analysis. Continuous variables were expressed as means with standard deviations or medians, depending on data distribution, while categorical variables were presented as absolute frequencies and proportions. Normality and homogeneity of variances were assessed using the **Kolmogorov-Smirnov** and **Levene** tests, respectively. **Comparisons between groups** were performed using the **Mann-Whitney *U* test** for non-normally distributed data and the **Wilcoxon test** for paired comparisons. **Associations between categorical variables** were analyzed using the **Chi-square test** or **Fisher's Exact test**, as appropriate.

To identify distinct subgroups among participants, **K-means clustering analysis** was applied, incorporating key variables of sociodemogaphic, clinical health status, and driver history. Prior to clustering, all continuous variables were standardized to **z-scores**. **Euclidean distance** was used as the similarity measure for cluster formation, and the optimal number of clusters was determined based on homogeneity, balance, and cluster validation criteria. This analysis resulted in the classification of participants into two distinct clusters (Figure A, Supplementary File).

4. Results

Table 1 presents the demographic and driving characteristics of the participants. Older adults had a significantly higher median age (69 years) compared to adults (34.5 years, $p < 0.001$). Educational attainment was also significantly different, with adults having a higher median number of years of education (17 vs. 15 years, $p < 0.001$). Driving experience was notably greater among older adults (45 years) compared to adults (10 years, $p < 0.001$). Additionally, adults reported driving for more hours per day (4 vs. 2 h, $p = 0.05$) and with a higher weekly driving frequency (5 vs. 2 days per week, $p = 0.04$). Regarding cognitive and physical function, no significant differences were observed in MMSE scores between groups ($p = 0.98$). Similarly, BMI ($p = 0.23$), PA frequency per week ($p = 0.60$), and TUGT scores ($p = 0.71$) did not differ significantly. However, in the cognitive TUGT, older adults took significantly longer to complete the test compared to adults (10.7 s vs. 7.9 s, $p < 0.001$).

Table 1
Bio-sociodemographic and Driving Characteristics of Participants.

	Adults ($n = 50$)	Older Adults ($n = 51$)	*p*-value
Median Age (years)	34.5	69	< 0.001*
Education (years)	17	15	< 0.001*
Driving experience (years)	10	45	< 0.001*
Driving (hours/day)	4	2	0.05*
Driving frequency/week	5	2	0.04*
MMSE (0–30 points)	29	28	0.98
BMI (kg/m^2)	25.45	26.4	0.23
PA frequency/week	3	2	0.60
TUGT (s)	8.04	8.5	0.71
Cognitive TUGT (s)	7.9	10.7	P < 0.001*

Note: Mann-Whitney U Test, *p < 0.05; **Legend:** MMSE – Mini-Mental State Examination, BMI – Body Mass Index, TUGT – Timed Up and Go Test, PA – Physical Activity.

Table 2 presents categorical variables related to traffic behavior and PA. The distribution of sex was similar between groups ($p = 0.94$). There were no significant differences in traffic violations over the past year, with 42% of adults and 41.2% of older adults reporting at least one violation ($p = 0.54$). Likewise, no significant differences were observed in accident occurrence, although a lower proportion of older adults reported being involved in accidents compared to adults (5.9% vs. 16%, $p = 0.09$). A significant difference was found in PA practice, with a higher percentage of adults engaging in regular PA (64% vs. 41.2%, $p = 0.01$). This result suggests that adults may maintain a more active lifestyle compared to their older counterparts.

Fig. 3 shows the braking time (in seconds) and driving speed for adults and older adults, with and without cognitive distraction. No significant differences were observed in braking time for either group, regardless of distraction (adults: median 0.88 s with distraction vs. 0.87 s without distraction; older adults: median 0.93 s with distraction vs. 0.95 s without distraction). However, significant differences were found in driving speed for older adults, with a reduction in speed under cognitive distraction (median 58.25 km/h with distraction vs. 59.82 km/h without distraction; $P = 0.01$). No significant differences were observed in driving speed in the adults group (median 62.22 km/h with distraction vs. 64.60 km/h without distraction; $P = 0.06$).

Fig. 4 shows the intergroup comparison of braking time and driving speed between adults and older adults, with and without cognitive distractors. Adults exhibited significantly shorter braking times than older adults both with distraction (median 0.87 s vs. 0.93 s; $P = 0.04$) and without distraction (median 0.81 s vs. 0.93 s; $P < 0.001$). In addition, adults demonstrated significantly higher driving speeds compared to older adults under both conditions, with distraction (median 62.22 km/h vs. 58.25 km/h; $P < 0.01$) and without distraction (median 64.60 km/h vs. 60.18 km/h; $P < 0.003$).

Fig. 5 shows the comparison of braking time and driving speed between sexes, with and without cognitive distractors. Women exhibited significantly longer braking times than men both with distraction (median 1.00 s vs. 0.87 s; $P < 0.001$) and without distraction (median 0.93 s vs. 0.85 s; $P < 0.02$). In contrast, no significant differences were observed in driving speed between women and men under either condition, with distraction (median 61.29 km/h vs. 60.59 km/h; $P = 0.63$) and without distraction (median 62.11 km/h vs. 63.00 km/h; $P = 0.79$).

Cluster analysis presented in Fig. 6 revealed two distinct groups: Cluster 1, consisting of 64 participants, and Cluster 2, consisting of 37 participants. The individuals in Cluster 2 exhibited characteristics of older age, lower education levels, more driving experience, longer times to complete the TUG test, and shorter braking times, as well as lower driving speeds. These two dimensions accounted for 24.7% of the variance explained by the multivariate clustering solution derived from the K-means analysis.

Table 3 summarizes the demographic characteristics and driving performance of participants in each cluster. Cluster 1, consisting of adults, exhibited significantly lower age, higher education levels, and less driving experience compared to Cluster 2. Additionally, participants in Cluster 2 demonstrated longer times to complete both the TUGT and the cognitive TUGT, indicating slower physical performance.

Table 4 presents the comparison of categorical factors between the two clusters. A significantly higher proportion of males was found in Cluster 1, while Cluster 2 consisted primarily of females. Furthermore, the adult group was more represented in Cluster 1, while the older group of participants was predominantly found in Cluster 2. However, no significant differences were observed between the clusters in terms of accidents or physical activity practice.

5. Discussion

The main findings of this study reveal that older adults exhibit longer braking times compared to adults, both with and without distractions. Conversation, as a distraction, led to a reduction in driving speed among older adults, suggesting that they may compensate for slower reaction times by driving more cautiously. Additionally, the group at higher risk of accidents, characterized by prolonged braking times, comprised older individuals with lower educational levels and reduced mobility. These factors were found to exacerbate driving challenges, making them more vulnerable to accidents. Furthermore, sex differences played a significant role, as women exhibited longer braking times than men, both with and without distraction, highlighting potential differences in reaction times and driving behavior.

Table 2
Categorical Variables Related to Traffic Behavior and Physical Activity behavior.

	Adults (n = 50)	Older Adults (n = 51)	χ^2 (p-value)
Sex			
Male	25 (50%)	26 (51%)	1.22 (0.94)
Female	25 (50%)	25 (50%)	
Traffic violations in the last year			
No	29 (58%)	30 (58.8%)	1.00 (0.54)
Yes	21 (42%)	21 (41.2%)	
Accidents in the last year			
No	42 (84%)	48 (94.1%)	0.12 (0.09)
Yes	8 (16%)	3 (5.9%)	
Physical activity behavior			
No	18 (36%)	30 (58.8%)	0.02 (0.01) *
Yes	32 (64%)	21 (41.2%)	

Note: Chi-square test or §Fisher's exact test, *$p < 0.05$.

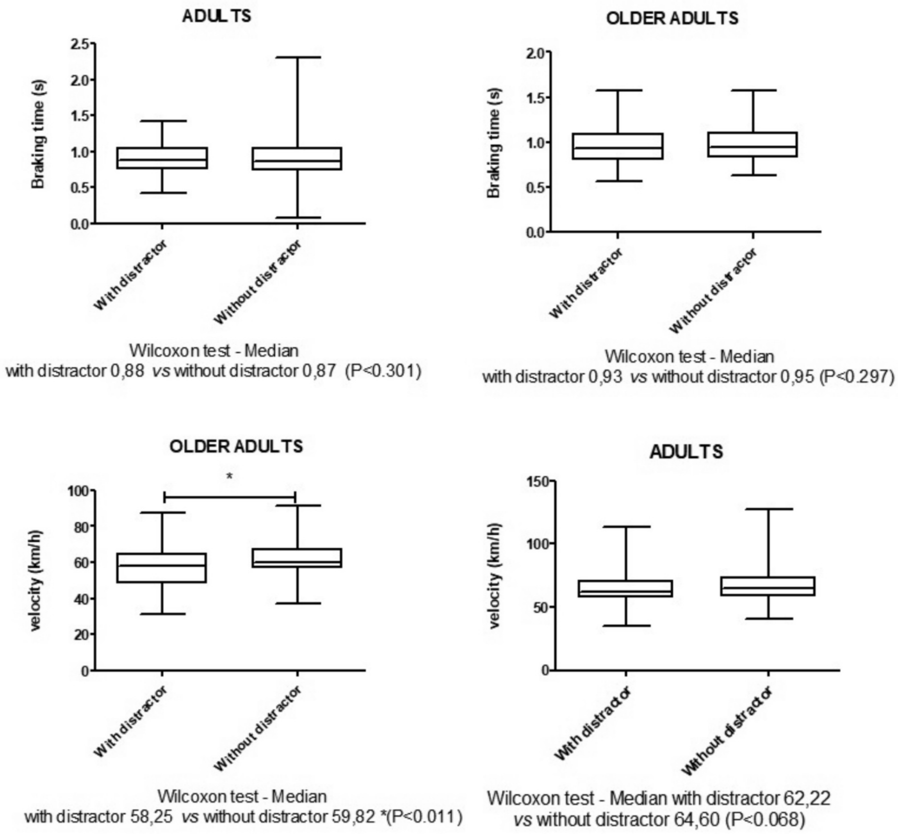

Fig. 3. - The intragroup comparison of braking time and driving speed in a vehicle simulator among adults and older adults, both with and without cognitive distractors. Note: Comparisons within groups were conducted using the Wilcoxon test, while comparisons between groups were performed using the Mann-Whitney *U* test. $p < 0.05$ was considered statistically significant.

Despite no significant difference in driving speed between sexes, women's increased braking times could reflect a greater cognitive load when managing distractions. Overall, while conversation did not significantly increase braking times, it highlighted the compensatory strategy of reducing speed, which, though potentially improving safety margins, does not fully mitigate the risks associated with slower reactions. The combined influence of aging, sex, and individual factors such as education and mobility underscores the need for tailored interventions to address these vulnerabilities in road safety.

Distractions caused by conversations with older adults did not significantly alter braking times but did lead to a decrease in driving speed. Older adults tend to adjust their driving patterns to compensate for age-related declines, such as driving more cautiously, covering shorter distances, and reducing speed to better manage reaction times in unexpected situations (Cantón-Cortés et al., 2010). However, while reducing speed may serve as a compensatory strategy, it can also introduce risks, as slower speeds may increase the likelihood of collisions, especially in situations requiring rapid decision-making or when other drivers misinterpret the older adult's intentions (Canonica et al., 2023).

Although no specific studies on conversations as distractions were found, performance deficiencies have been linked to diverted attention in processing crucial information for driving (Berka et al., 2019; Canonica et al., 2023; Hoff et al., 2013). These studies emphasize conversations and phone calls as common distractions, though with distinct characteristics. A passenger, as a direct participant in the traffic environment, can modulate their interactions based on road conditions, whereas phone conversations lack such modulation, making them potentially more dangerous. Previous studies highlight that neural pathways are activated differently during conversations, leading to less inattentional blindness compared to cell phone use (Hoff et al., 2013), which could explain why in-vehicle conversations, while distracting, might have a lesser impact on driving performance than phone calls.

Older women, exhibited longer braking times. This difference may be attributed to a combination of neurological, physiological, hormonal, and sociocultural factors. Men tend to have shorter reaction times in simple motor tasks, possibly due to higher testosterone levels, which accelerate neuromotor processing (Celec et al., 2015). Greater muscle strength in the lower limbs also facilitates a more efficient brake pedal response, leading to shorter braking times (De Biase et al., 2024; Silverman, 2006). Additionally, men tend to drive more frequently than women, exposing themselves to more risky situations and fostering familiarity with sudden braking (Canonica et al., 2023; De Biase et al., 2024). Selective attention and visual processing also play a role; studies have shown that women generally exhibit slower response times in visual attention tests, which may contribute to longer braking times (Casamento-Moran et al., 2022). However, these differences are not universal and can vary based on individual driving experience.

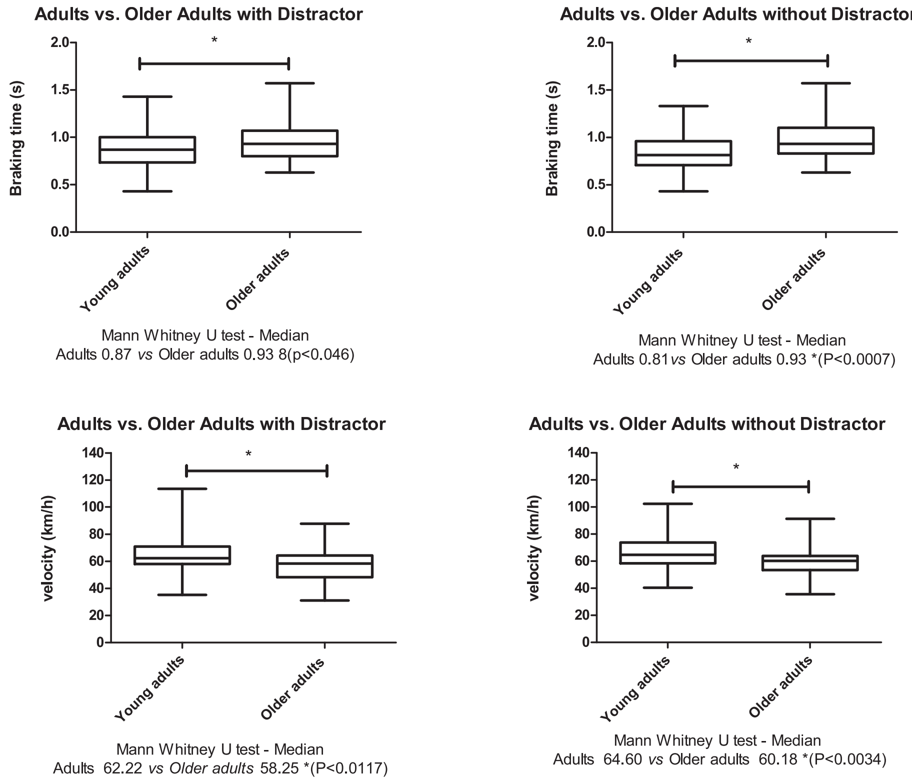

Fig. 4. - Intergroup comparison of braking time and driving speed between adults and older adults in the vehicle driving simulator, with and without cognitive distractors. Significant differences were observed in all groups. Note: Comparisons within groups were conducted using the Wilcoxon test, while comparisons between groups were performed using the Mann-Whitney U test. $p < 0.05$ was considered statistically significant.

Older drivers exhibited longer braking times and lower speeds compared to adults, regardless of distraction presence. The cluster analysis further supported these findings, identifying that older participants with longer driving experience, lower education levels, and reduced functional mobility (as measured by the TUGT) had longer braking times and reduced driving speeds. Numerous studies have demonstrated that driving ability diminishes with age (Anstey et al., 2005; Canonica et al., 2023; De Biase et al., 2024). For instance, a previous research conducted of our group found that older individuals have a 17% longer braking time than middle-aged adults, which also correlates with increased stopping distances (Alonso et al., 2016).

The ability to quickly transition from the accelerator to the brake to prevent collisions requires integrated cognitive, sensory, and motor functions. The decline in these abilities as individuals age contributes to increased braking times and a higher risk of accidents. However, age alone is not a definitive predictor of driving ability, as the aging process is heterogeneous, with significant individual variation (Alonso et al., 2016; De Biase et al., 2024; Silva et al., 2023).

Lower education levels increase the risk of cognitive decline. Education plays a crucial role in creating and developing cognitive reserve, allowing the brain to utilize alternative neural pathways to compensate for age-related cognitive decline (Silva et al., 2023). Higher educational attainment is associated with better cognitive performance, as formal education stimulates problem-solving, memory, and attention, fostering denser and more interconnected neural networks. Education also enhances cognitive flexibility and serves as a protective factor against cognitive decline, keeping the brain engaged and mitigating the effects of aging (Ferreira et al., 2015).

The decline in cognitive and motor abilities with aging is multifactorial, with cognitive decline, slower reaction times, and reduced sensory processing contributing to impaired driving performance (Balzarotti et al., 2022). Furthermore, older adults often adopt compensatory strategies, such as reducing their driving speed, to mitigate their reaction time deficiencies (Souders et al., 2020). While such strategies may reduce the risk of accidents by allowing more time to respond to sudden events, they can also increase the likelihood of certain types of crashes, such as rear-end collisions or accidents at intersections, where speed differences become more critical (Hsiao et al., 2018).

Understanding how these factors interact, particularly in relation to sex differences in driving performance, can help identify high-risk individuals and inform safety interventions aimed at prolonging safe driving among older adults. **The combined influence of age, sex, educational level, and functional mobility further highlights the need for tailored interventions to address these vulnerabilities in road safety.**

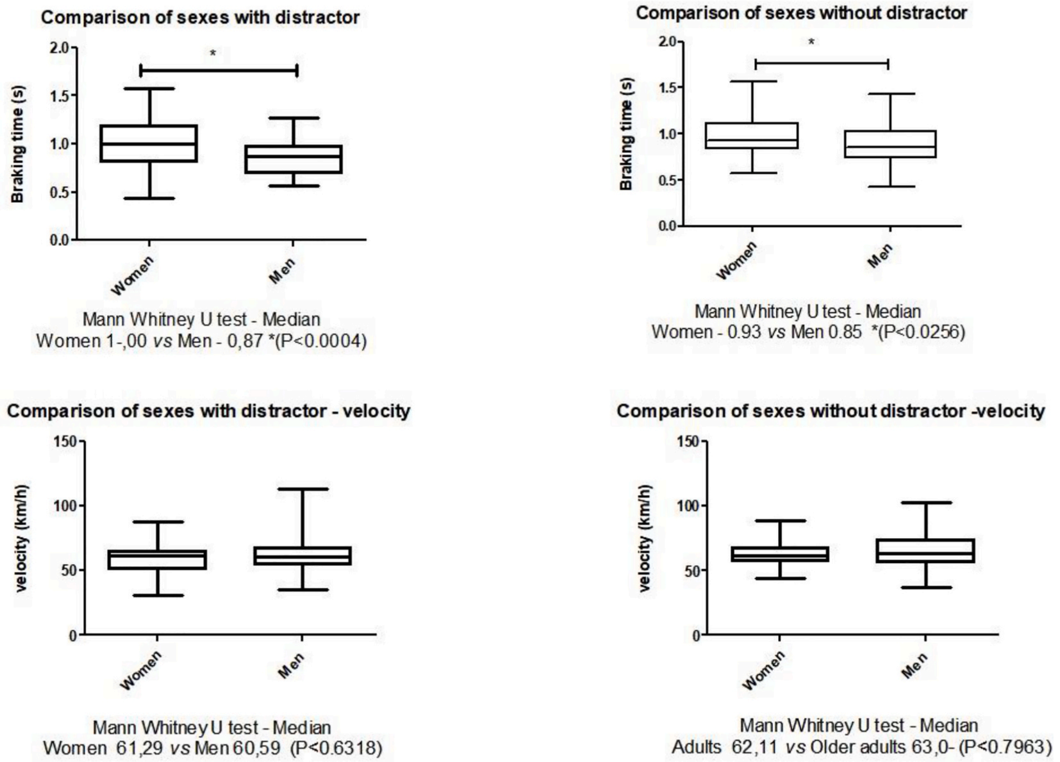

Fig. 5. - Comparison of braking time and driving speed between men and women in the vehicle driving simulator, with and without cognitive distractors. Significant differences were observed in braking time between sexes, with women showing longer braking times in both conditions. Note: Comparisons within groups were conducted using the Mann-Whitney U test. $p < 0.05$ was considered statistically significant.

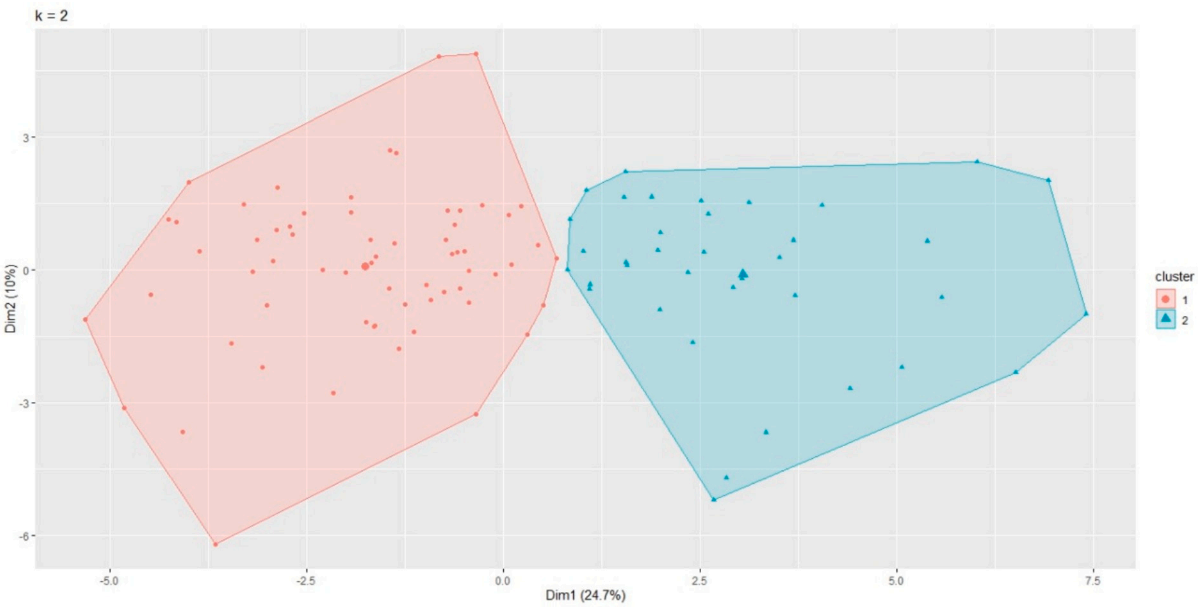

Fig. 6. - Cluster analysis of drivers using the K-Means algorithm, showing the distinct characteristics of two clusters. Cluster 2 consists of older individuals with lower education levels, more driving experience, slower physical performance, and reduced driving speed and braking time. The analysis explains 24.7% of the variability in the dataset.

Table 3
Bio-Sociodemographic Characteristics and Driving Performance by Cluster.

	Cluster 1 M(dp)	Cluster 2 M(dp)	p-value
Age (years)	47.6 (2.1)	60.6 (3.4)	P < 0.001*
Education (years)	16.67 (0.5)	13.6 (0.4)	0.0003*
Driving experience (years)	22.90 (2.1)	32.6 (3.2)	0.0113*
Driving hours/day	2.87 (0.4)	2.0 (0.1)	0.1014
Times per week driving	4.92 (0.3)	4.4 (0.5)	0.1901
MMSE	28.30 (0.2)	28.1(0.2)	0.6158
BMI (kg/m^2)	25.94 (0.6)	26.8 (0.7)	0.3591
TUGT (s)	8.13 (0.3)	10.3 (0.5)	0.0003*
Cognitive TUGT (s)	8.27 (0.3)	10.7 (0.4)	P < 0.001*
Braking time with distractor (s)	0.84 (0,01)	1.07 (0.0)	P < 0.001*
Speed with distractor (km/h)	64.80 (1,9)	55.44 (2.0)	0.0030*
Braking time without distractor (s)	0.80 (0,0)	1.12 (0.0)	P < 0.001*
Speed without distractor (km/h)	64.88 (1,8)	60.40 (2.3)	0.048*

Note: Comparisons were made using the Mann-Whitney U test and Wilcoxon test for non-parametric variables. $p < 0.05$ was considered statistically significant; TUGT: Timed Up and Go Test; MMSE: Mini-Mental State Examination;

Table 4
Intergroup Comparison of Driving Behavior and Categorical Factors.

	Cluster 1 N(%)	Cluster 2 N(%)	χ^2 (p-value)
		Gender	
Male	40 (62.5%)	11 (29.7%)	10.07 (0.002)*
Female	24 (37.5%)	26 (70.3%)	
		Group	
Adults	40 (62.5%)	10 (27.3%)	11.80 (0.001)*
Older adults	24 (37.5%)	27 (72.7%)	
		Accidents in the last year	
No	51 (85.0%)	35 (94.6%)	1.97 (0.20)
Yes	9 (15.0%)	2 (5.4%)	
		Physical activity practice	
No	30 (46.88%)	18 (48.65%)	0.029 (0.86)
Yes	34 (53.13%)	19 51.35%)	

Note: Comparisons were made using the Chi-square test and Fisher's exact test. $p < 0.05$ was considered statistically significant.

5.1. Strengths and limitations, and perspectives for future

This study presents several strengths, including its focus on older drivers and the use of a driving simulator to assess critical driving competencies. The controlled environment of the simulator allowed for precise measurements of braking time and driving speed, enabling a detailed analysis of the impact of distractions on driving performance. Additionally, the use of cluster analysis provided valuable insights into the characteristics of higher-risk drivers, such as those with reduced mobility and lower educational levels.

However, the study's limitations must also be considered. The controlled setting of the driving simulator, while valuable for isolating specific driving behaviors, does not entirely replicate real-world driving conditions. Factors such as traffic, weather, and road unpredictability, which significantly influence driver performance, were not captured in the simulator. Moreover, the single-session nature of the study may not account for variability in performance across different driving contexts or over time. The absence of a family-wise error correction represents a methodological limitation, potentially increasing the risk of type I errors. Additionally, the sample was drawn from a Brazilian population of drivers, and cultural, social, or regional factors may limit the generalizability of our findings to other populations.

Future studies should aim to validate these findings in naturalistic driving environments, employing on-road assessments to better understand how real-world distractions, such as conversations, influence driving behavior. Longitudinal studies could also provide insights into how aging, education, and functional mobility impact driving abilities over time and their relationship with accident risk. Additionally, exploring the effects of different types of distractions, such as phone use or in-car entertainment systems, could further enrich our understanding of distraction-related risks for older drivers.

5.2. Practical implications

The results of this study underline the critical need for road safety policies that address the unique challenges faced by older drivers while ensuring their autonomy and well-being. Policymakers should consider implementing retraining programs specifically tailored to older drivers, along with regular medical evaluations to assess their cognitive and physical abilities. Educational campaigns focusing on safe driving practices can also help raise awareness of the risks associated with distractions and promote safe driving habits.

Additionally, the incorporation of assistive technologies, such as automatic braking systems, lane departure warnings, and distraction alerts, can significantly enhance driving safety for older adults.

Equally important is the need to raise awareness among passengers regarding the role they play in preventing distractions. Passengers should be educated on the potential dangers of engaging older drivers in conversations that may divert their attention from the road. This awareness can help foster safer driving environments, reducing the likelihood of accidents and enhancing road safety for older drivers. Ensuring that both drivers and passengers understand the impact of distractions is vital for creating safer roads for all.

6. Conclusion

Aging and gender significantly impact vehicle driving performance, leading to increased braking times. Conversations act as a distraction, causing fluctuations in driving speed among seniors drivers, who compensate by reducing speed to maintain safety. The group at the highest risk of accidents — due to prolonged braking times — comprises older individuals, those with lower education levels, and those with reduced functional mobility, despite having more driving experience. These findings emphasize the importance of targeted interventions and safety measures for vulnerable drivers to reduce the risk of accidents.

CRediT authorship contribution statement

Sérgio Ayama: Methodology, Investigation, Conceptualization. **Júlia Maria D'Andréa Greve:** Project administration, Methodology, Investigation, Data curation. **Vanderlei Carneiro da Silva:** Methodology, Investigation. **Alexandra Carolina Canonica:** Methodology, Investigation. **Matheus Henrique dos Santos Lino:** Methodology, Investigation. **Alisson de Lima Guiotto:** Visualization, Methodology, Investigation. **Catherine L. Davis:** Writing – review & editing, Writing – original draft. **André Luiz de Seixas Soares:** Methodology. **Francisco Rodrigues:** Validation, Software. **Guilherme Eustáquio Furtado:** Writing – review & editing. **Guilherme Carlos Brech:** Writing – review & editing, Validation, Resources, Methodology, Investigation. **Angelica Castilho Alonso:** Validation, Supervision.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trf.2026.103613.

Data availability

Data will be made available on request.

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