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Age-related differences in takeover performance: A comparative analysis of older and younger drivers in prolonged partially automated driving

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ABSTRACT

Objective: Vehicle automation technologies have the potential to address the mobility needs of older adults. However, age-related cognitive declines may pose new challenges for older drivers when they are required to take back or "takeover" control of their automated vehicle. This study aims to explore the impact of age on takeover performance under partially automated driving conditions and the interaction effect between age and voluntary non-driving-related tasks (NDRTs) on takeover performance.

Method: A total of 42 older drivers (M=65.5 years, SD = 4.4) and 40 younger drivers (M=37.2 years, SD = 4.5) participated in this mixed-design driving simulation experiment (between subjects: age [older drivers vs. younger drivers] and NDRT engagement [road monitoring vs. voluntary NDRTs]; within subjects: hazardous event occurrence time [7.5th min vs. 38.5th min]).

Results: Older drivers exhibited poorer visual exploration performance (i.e., longer fixation point duration and smaller saccade amplitude), lower use of advanced driving assistance systems (ADAS; e.g., lower percentage of time adaptive cruise control activated [ACCA]) and poorer takeover performance (e.g., longer takeover time, larger maximum resulting acceleration, and larger standard deviation of lane position) compared to younger drivers. Furthermore, older drivers were less likely to experience driving drowsiness (e.g., lower percentage of time the eyes are fully closed and Karolinska Sleepiness Scale levels); however, this advantage did not compensate for the differences in takeover performance with younger drivers. Older drivers had lower NDRT engagement (i.e., lower percentage of fixation time on NDRTs), and NDRTs did not significantly affect their drowsiness but impaired takeover performance (e.g., higher collision rate, longer takeover time, and larger maximum resulting acceleration).

Conclusions: These findings indicate the necessity of addressing the impaired takeover performance due to cognitive decline in older drivers and discourage them from engaging in inappropriate NDRTs, thereby reducing their crash risk during automated driving.

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Partially automated driving; older driver; non-driving related tasks; takeover performance; eye-tracking

Introduction

With the increasing human life expectancy, the proportion of older adults in the population is steadily rising. For example, in 2016 adults aged 65 and older in the United Kingdom constituted 18% of the total population; however, this is projected to increase to 25% of the total population by 2046 (S. Li, Blythe, Guo, and Namdeo 2019). Similarly, in 2020 the population of adults aged 65 and older in China was reported to be 190.64 million, accounting for 14% of the total population, and it is projected to reach 24% by 2050 (J. Li et al. 2023). Accompanying this trend is a rise in older driver licensing rates (Koppel and Berecki-Gisolf 2015).

Aging and automated driving

Existing research does not provide a precise definition for "older" age (Folli and Bennett 2023). There is consensus that though there are many individual differences in the aging process, even relatively healthy older adults are likely to experience some level of functional decline in sensory, physical, and cognitive areas from the age of 60 that can affect their fitness to drive.

Previous studies (Depestele et al. 2020) have specifically investigated the impact of age-related cognitive declines in older drivers on driving performance during manual driving. The aging process is associated with changes in brain structure and connectivity, including a decrease in gray matter

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volume and white matter tract integrity (Harada et al. 2013; Depestele et al. 2020). Consequently, this leads to a decline in cognitive functions and motor control abilities required for safe road behavior. For instance, the decline in cognitive functions can lead to inferior attention management, reduced hazard perception (Folli and Bennett 2023), decreased working memory, slower information processing speed, and extended reaction time (Svetina 2016), etc. Furthermore, older drivers can have diminished muscle strength, impaired limb flexibility, and impaired movement precision (Huang et al. 2020; Li et al. 2021). These declines in motor capacities lead to poor vehicle control. Therefore, age-related cognitive and motor ability declines can result in reduced fitness to drive.

To compensate for the potential driving safety hazards associated with age-related functional impairments, many older adults modify and regulate their driving behaviors to reduce or avoid situations that pose difficulties or potential dangers (Molnar et al. 2014). For instance, they may choose to refrain from driving in adverse weather conditions, refrain from driving at night (S. Li et al. 2018), or even cease driving. However, self-regulated driving behaviors can be associated with a reduction in the mobility of older drivers and have the potential to increase their sense of social isolation (Gasne et al. 2022).

Fortunately, the development of advanced driving assistance systems (ADAS) may extend the safe driving period for older adults (S. Li, Blythe, Guo, and Namdeo 2019) and thus enhance their quality of life and overall well-being (Gasne et al. 2022). Partially automated driving systems aid drivers in both lateral and longitudinal controls of the vehicle and allow drivers to be physically disengaged from driving. However, drivers still need to monitor driving and are required to conduct timely takeover operations upon receiving takeover requests (TORs). Such automation-initiated control transitions typically occur when the system reaches capacity limits. These limits can arise from various factors, including congested roads, uncontrolled traffic flow, missing road markings, the degradation of sensor performance due to adverse weather conditions, and unpredictable behaviors of other road users (e.g., pedestrians, bicycles), that may be beyond the operational design domain of the automated driving system. The new challenge faced by older drivers is whether they can promptly, smoothly, and safely take over control of the vehicle in these unexpected—sometimes critical—situations. However, there is a lack of research specially focusing on the takeover performance of older drivers (Gasne et al. 2022).

Takeover performance and voluntary non-driving-related tasks

According to the limited relevant literature (S. Li et al. 2018; S. Li, Blythe, Guo, Namdeo, Edwards et al. 2019; Wu et al. 2019, 2020; Gasne et al. 2022), takeover maneuvers may pose challenges for older drivers in terms of time or quality of takeover. Compared to the younger drivers, older drivers had longer takeover time or reaction time (S. Li et al. 2018; S. Li, Blythe, Guo, Namdeo, Edwards et al. 2019; Wu et al. 2019, 2020), inferior takeover qualities (e.g., greater steering wheel variation: Wu et al. 2019; shorter time to collision: S. Li et al. 2018; and lower driving speeds during takeover). In an attempt to explain these differences between younger and older drivers, existing research has explored numerous factors that influence older drivers' takeover performance (e.g., weather conditions, TOR modality, etc.), with participation in non-driving-related tasks (NDRTs) being of particular interest.

However, NDRT engagement in previous research is typically mandatory (Gasne et al. 2022), which does not align with real-world situations. Drivers would decide whether or to what extent to participate based on their own assessment of the accident risk (Clark and Feng 2017). Older drivers have lower acceptance of automated vehicles (Haghzare et al. 2021), which may result in lower acceptance and less frequent use of the ADAS. When older drivers are aware of their declining driving abilities, they may adopt necessary self-regulation measures (Molnar et al. 2014; Huang et al. 2020), such as decreasing their NDRT engagement to avoid diverting attention away from the driving task. Although existing research (Wu et al. 2019, 2020; Gasne et al. 2022) has commonly concluded that NDRTs negatively impact takeover performance in older drivers, such experimental designs of mandatory engagement may exaggerate the adverse effects of NDRTs on older drivers. Therefore, experimental designs that involve voluntary participation in NDRTs will help provide a more accurate understanding of how older drivers cope with the challenges of vehicle control transitioning due to their declining functional abilities. To the best of our knowledge, there is scarce research on effects of voluntary NDRTs on older drivers' driving performance.

Clark and Feng (2017) explored the effect of voluntary NDRTs on drivers' takeover performance and found that older drivers were more inclined to initiate conversations with the experimenter, whereas younger drivers were more eager to use electronic devices. They also found that the takeover time did not differ significantly between younger and older drivers, but older drivers applied lower driving speed and smaller standard deviation of lane position. This was because older drivers adopted a more cautious driving style, employing greater braking pedal input to reduce vehicle speed, thereby enhancing the lateral stability of the vehicle. However, the duration of the automated driving experiment in Clark and Feng (2017) was only 1.5 to 2 min, and there has been limited consideration of age differences in the effect of voluntary NDRTs on takeover performance following extended periods of automated driving.

Takeover performance during prolonged automated driving

After prolonged exposure to a monotonous driving environment (e.g., roads with few geometric changes or low traffic flow, automated driving), drivers can experience drowsiness due to mental underload and lack of sensory stimulation. Aging brings changes to sleep–wakefulness patterns (Mander et al. 2017). Older adults may require less sleep than younger adults to feel adequately rested (Song et al. 2017; Scarpelli et al. 2021). Additionally, older drivers, with their extensive driving experience and skills, are more adept at recognizing signs of drowsiness and taking proactive measures to maintain alertness. Hence, in the context of prolonged automated driving, the advantage of older drivers in maintaining alertness could potentially compensate for the disadvantage of their age-related cognitive declines, thus contributing to better driving performance during takeover situations.

In addition, mandatory NDRTs have been shown to reduce drowsiness (e.g., higher Karolinska Sleepiness Scale [KSS] scores and long eyeblink duration) of younger drivers, thereby enhancing their takeover abilities (e.g., shorter steering time; Pan, He et al. 2023). However, limited research has specifically investigated the impact of NDRTs on the takeover performance of older drivers during prolonged automated driving, particularly considering older drivers' voluntary NDRT engagement or self-regulation behaviors.

Aims of the study

Based on the literature review and research gap identified above, the aims and relevant hypotheses of this study are as follows:

Aim 1: To investigate the impact of age on drivers' takeover performance under short and prolonged exposure to partially automated driving

Hypothesis 1: Older drivers have poorer takeover performance compared to younger drivers under short-duration of automated driving condition.

Hypothesis 2: Older drivers have better takeover performance compared to younger drivers under prolonged-duration of partially automated driving condition.

Aim 2: To explore differences in the effect of voluntary NDRTs on the takeover performance between younger and older drivers

Hypothesis 3: NDRTs enhance the takeover performance of younger drivers during prolonged exposure to automated driving.

Hypothesis 4: NDRTs negatively affect the takeover performance of older drivers during both short and prolonged exposure to partially automated driving.

Methods

Participants

A total of 82 participants were recruited to participate in this experiment. The mean age of the older driver group ($n=42$, 10 females) was 65.5 years (SD = 4.4, range = 61–69 years). They had held a driving license for an average of 36.9 years (SD = 8.1). The mean age of the younger driver group ($n=40$, 12 females) was 37.2 years (SD = 4.5, range = 30–47 years). They had held a driving license for an average of 15.9 years (SD = 4.7). All participants were asked to complete the Mini-Mental State Examination (MMSE); further details on the MMSE are provided in the online supplement. The experiment was conducted on a fixed-based driving simulator (Figure A1, see online supplement).

Driving scenario

The traffic scenario of the experiment was based on a simulated highway (Figure A2, see online supplement), specifically selected from a 70-km section of the Bin-De Expressway in Shandong, China. The simulated highway was a 6-lane dual carriageway with speed limits set at 90, 110, and 120 km/h for different lanes. The traffic volume for each lane ranged from 540 to 900 vehicles/hour. Please refer to the online supplement for a detailed description of the partially automated driving system.

Experimental design

Drivers in both age groups were distributed into 2 subgroups of similar sizes (Figure A3, see online supplement) with age and gender balanced. Two subgroups of drivers were not required to engage in any NDRTs during the driving process and instead maintained constant focus on road monitoring. The other subgroups of drivers were allowed to voluntarily participate in a movie-watching NDRT. Please refer to the online supplement for a detailed description of the voluntary NDRTs and participant training.

Once the formal experiment commenced, participants were asked to start the vehicle and accelerate to 100 km/h, drive it manually for 2 min, and then activate the automation system (Figure A2). After 7.5 min spent in automated driving (P.1), the first hazardous event (H.1) was triggered and the driver needed to perform the first takeover maneuver (Figure A4, see online supplement). The automation system can be reactivated 1 min after the first takeover operation. There was a 30-min automated driving interval (P.2) between the end of the first takeover and the triggering of the second takeover (H.2), designed to induce driver drowsiness.

Research variables

NDRT engagement

The displays were divided into 2 areas of interest: NDRT-related area, which refers to the in-vehicle entertainment system and driving-related area, which included the road ahead and rearview mirrors. The percentage of fixation time on NDRTs (PoFToN, %) and rate of correctness of NDRT-related questions were utilized to assess drivers' NDRT engagement.

Eye movement metrics

Average duration of fixation point (ms) and average amplitude of saccade (°) were selected in this research to help understand drivers' visual exploration behaviors. The percentage of time the eyes were fully closed (PERCLOS) was selected to measure drivers' drowsiness.

Subjective drowsiness

The KSS was used to assess drivers' subjective drowsiness. The assessment was conducted using a 9-point Likert scale, ranging from 1 = *extremely vigilant* to 9 = *extremely sleepy and [requiring] great effort to stay awake*.

Use of ADAS

We included 3 metrics to measure drivers' use of ADAS: percentage of time ACC was activated (ACCA, %), frequency of lane departure assist (LDA) activated (LDAA, times/2 min), and frequency with which drivers overruled the LDA (DOLDA, times/2 min). LDAA refers to how often the lane departure assist system intervened to override the driver's actions and maintain the vehicle within its lane. DOLDA refers to how often the drivers intervened or overrode the LDA system to surpass or cancel the lateral control of the LDA system.

Takeover performance

Takeover time (s), standard deviation of lane position (SDLP, m), maximal resulting acceleration (MRA, m/s^2), and collision (binary variable: 0 = no, 1 = yes) were selected to measure takeover performance.

Statistical analysis

The normality of the distribution of research variables was assessed using the Shapiro-Wilk test. Due to the relatively small sample size, not all research variables followed a normal distribution. Therefore, we employed the Kruskal-Wallis test to examine differences in research variables between the 2 age groups of drivers during road monitoring and NDRT engagement. Dunn's test was used for post hoc comparisons. Additionally, within-group Wilcoxon matched-pairs tests were conducted to assess the impact of takeover operation orders (first vs. second) on takeover performance. The effect size was measured using Cohen's d coefficient.

Results

NDRT engagement

As shown in Figure A5 (see online supplement), following the activation of automation, the PoFToN for both age groups of drivers increased and reached a stable level (P.1). After the occurrence of the first hazardous event (H1), there was a decline in PoFToN followed by a subsequent increase. Younger drivers reached a stable level of PoFToN earlier than older drivers. Indeed, older drivers exhibited a trend of "increase–decrease–stabilization–increase–stabilization" in PoFToN (P.2). After the second hazardous event (H2), the PoFToN in both driver groups decreased once again.

The results of the Mann-Whitney U tests indicated that the PoFToN of younger drivers was higher than that of older drivers (z = −4.667, d = 2.129, $P < .001$) during the automated driving phases (P.1 + P.2). Younger drivers had a higher rate of correct answers to the NDRT-related questions compared to older drivers (younger: 76.7% vs. older: 34.7%, z = −4.372, d = 1.869, $P < .001$).

Eye movement metrics

As shown in Figure A6 (see online supplement), the results of Kruskal-Wallis tests indicated that there were significant differences in average duration of fixation point, $\chi^2_{(df=3)}$ = 37.594, d = 1.811, $P < .001$, average amplitude of saccade, $\chi^2_{(df=3)}$ = 29.857, d = 1.476, $P < .001$, and PERCLOS, $\chi^2_{(df=3)}$ = 47.653, d = 2.340, $P < .001$, among older and younger drivers during road monitoring and NDRT engagement.

Older drivers had longer fixation point durations than younger drivers when performing both road monitoring ($P < .05$) and NDRTs ($P < .001$). Compared to road monitoring, engaging in NDRTs led to longer fixation point durations for older drivers ($P < .01$), whereas the impact on younger drivers was not significant.

When performing the road monitoring tasks, there was no significant difference in saccade amplitudes between young and older drivers. However, engaging in NDRTs contributed to an increase in saccade amplitudes for both age groups. Specifically, younger drivers exhibited larger saccade amplitudes when involved in NDRTs ($P < .05$).

Younger drivers exhibited significantly higher PERCLOS ($P < .01$) during the road monitoring task; however, engaging in NDRTs reduced their PERCLOS ($P < .001$). Younger drivers had lower PERCLOS than older drivers when engaging in NDRTs.

Use of ADAS

As shown in Table 1, the results of Kruskal-Wallis tests indicated that there were significant differences in ACCA, $\chi^2_{(df=3)}$ = 15.258, d = 0.898, $P < .01$, LDAA, $\chi^2_{(df=3)}$ = 26.849, d = 1.355, $P < .001$, and DOLDA, $\chi^2_{(df=3)}$ = 21.789, d = 1.156, $P < .001$, among older and younger drivers during road monitoring and NDRT engagement.

NDRTs only resulted in numerical increases in ACCA compared to road monitoring, but no statistically significant differences were found among older drivers (older drivers–road monitoring [O-R]: 64.5% vs. older drivers–voluntary [O-V]: 70.7%, P = .124) or younger drivers (younger drivers–road monitoring [Y-R]: 75.2% vs. younger drivers–voluntary [Y-V]: 81.9%, P = .137). Older drivers had lower ACCA than younger drivers only when performing road monitoring ($P < .05$) and NDRTs ($P < .05$).

Table 1. Summary of ADAS use among drivers.

	O-R, mean (SD)	Y-R, mean (SD)	O-V, mean (SD)	Y-V, mean (SD)
ACCA (%)	64.5 (10.5)	75.2 (8.9)	70.7 (12.2)	81.9 (14.2)
LDAA (times/2 min)	0.9 (0.6)	1.3 (0.9)	3.3 (1.11)	2.3 (1.6)
DOLDA (times/2 min)	2.3 (1.0)	0.9 (0.5)	1.0 (0.7)	1.1 (0.5)

Older drivers only had more LDAA than younger drivers when performing NDRTs ($P = .066$). Compared to road monitoring, engaging in NDRTs led to more LDAA for both older drivers ($P < .01$) and younger drivers ($P < .05$).

Compared to road monitoring, engaging in NDRTs led to less DOLDA for older drivers ($P < .001$), whereas the impact on younger drivers was not significant ($P = .223$). Older drivers had more DOLDA than younger drivers only when performing road monitoring ($P < .001$); however, there was no significant effect of age on DOLDA when performing the NDRT ($P = .579$).

Subjective drowsiness

The result of the Kruskal-Wallis test indicated that before the first takeover operation, there was no significant effect of age or NDRT on KSS level (O-R: 3.2 vs. Y-R: 3.0 vs. O-V: 3.1 vs. Y-V: 2.9), $\chi^2_{(df=3)}$ = 2.214, $d = 0.104$, $P = .455$. After performing 30 min of road monitoring, younger drivers had significantly higher KSS levels compared to older drivers (O-R: 5.4 < Y-R: 6.6, $P < .01$).

Before the second takeover operation, the average KSS levels for younger and older drivers who performed NDRTs were $M = 4.0$ and $M = 4.6$, respectively. Engaging in NDRTs resulted in lower KSS levels for younger drivers (Y-N: 4.0 < Y-R: 6.6, $P < .001$), but it did not have a significant impact on older drivers (O-N: 4.6 vs. O-R: 5.4, $P = .165$).

Takeover performance

Takeover time

The results of the Kruskal-Wallis tests indicated significant differences in takeover time between older and younger drivers during road monitoring and NDRTs for both the first, $\chi^2_{(df=3)}$ = 37.659, $d = 1.814$, $P < .001$, and second, $\chi^2_{(df=3)}$ = 35.364, $d = 1.710$, $P < .001$, takeover operations.

As shown in Figure A7 (see online supplement), in the first takeover operation, the effect of age on takeover time for drivers performing road monitoring was not significant ($P = .155$). However, NDRTs prolonged the takeover time for both age groups, with older drivers experiencing longer takeover times than the younger drivers (O-V: 2.68 s > Y-V: 2.15 s, $P < .01$).

The results of within-group Wilcoxon matched pairs tests revealed that only young drivers engaged in road monitoring exhibited a significant change in takeover time between the 2 takeover operations. Their second takeover time was significantly longer compared to the first one (first: 1.85 s < second: 2.90 s, $P < .001$). In the second takeover operation, NDRTs increased takeover time for older drivers (O-V: 2.65 s > O-R: 2.10 s, $P < .001$) but shortened it for younger drivers (Y-V: 2.14 s < Y-R: 2.90 s, $P < .001$).

Maximal resulting acceleration

The results of the Kruskal-Wallis tests indicated significant differences in maximal resulting acceleration between older and younger drivers during road monitoring and NDRTs for both the first, $\chi^2_{(df=3)}$ = 28.129, $d = 1.406$, $P < .001$, and second, $\chi^2_{(df=3)}$ = 19.567, $d = 1.069$, $P < .001$, takeover operations.

As shown in Figure A8 (see online supplement), in the first takeover operation, older drivers adopted higher maximal resulting acceleration during both road monitoring (O-R: 7.35 m/s^2 > Y-R: 5.20 m/s^2) and NDRTs (O-V: 7.93 m/s^2 > Y-V: 6.13 m/s^2). However, the participation in NDRTs only resulted in numerical increases in the maximum resulting acceleration for both older ($P = .189$) and younger ($P = .111$) drivers, with no statistically significant differences observed.

The results of within-group Wilcoxon matched pairs tests revealed that only young drivers engaged in road monitoring exhibited a significant increment in maximal resulting acceleration in the second takeover operations (first: 5.20 m/s^2 < second 7.33 m/s^2, $P < .01$), whereas there were no significant variations observed for other drivers.

In the second takeover operation, road monitoring led to higher maximal resulting acceleration for younger drivers compared to older drivers. NDRTs increased the maximal resulting acceleration for older drivers (O-V: 8.23 m/s^2 > O-R: 6.88 m/s^2, $P < .01$) but decreased it for younger drivers (Y-V: 6.15 m/s^2 < Y-R: 7.33 m/s^2, $P < .05$).

Standard deviation of lane position

As shown in Figure A9 (see online supplement), the results of the Kruskal-Wallis tests indicated significant differences in SDLP between older and younger drivers during road monitoring and NDRTs for both the first, $\chi^2_{(df=3)}$ = 33.987, $d = 1.650$, $P < .001$, and second, $\chi^2_{(df=3)}$ = 15.462, $d = 0.906$, $P < .001$, takeover operations.

In the first takeover operation, older drivers exhibited higher SDLP during both road monitoring (O-R: 0.51 m > Y-R: 0.35 m/s, $P < .001$) and NDRTs (O-V: 0.62 m > Y-V: 0.48 m, $P < .01$). The results of within-group Wilcoxon matched-pairs tests revealed that only young drivers engaged in road monitoring exhibited a significant increment in SDLP in the second takeover operations compared to the first one (first: 0.35 m < second: 0.44 m, $P < .05$), whereas there were no significant variations observed for other drivers.

In the second takeover operation, there were no significant differences in SDLP between older and younger drivers during road monitoring. However, older drivers exhibited significantly higher SDLP when engaged in NDRTs (O-V: 0.60 m > Y-V: 0.47 m, $P < .001$).

Collision

As shown in Figure A10 (see online supplement), the Pearson's chi-square tests indicated that age and NDRTs had a significant effect on the collision rate during both takeover operation: First: $\chi^2_{(df=3)}$ = 6.872, $d = 0.513$, $P < .05$; second: $\chi^2_{(df=3)}$ = 7.005, $d = 0.520$, $P < .05$. Older drivers had higher collision rates while performing NDRTs, but younger drivers did not exhibit an increase in collision rates. There were no significant differences in the rate of collision between the 2 takeover operations for drivers in both age groups, regardless of whether they were engaged in road monitoring or NDRTs.

Discussion

Age-related effect on takeover performance during partially automated driving

After experiencing a short period of road monitoring during automated driving, aging would not necessarily lead to significant longer reaction time during control transitions, despite the numerical higher values in older drivers compared to younger drivers. However, when it comes to MRA and SDLP, older drivers exhibited significantly poorer takeover performance than younger drivers. This finding support the validation of Hypothesis 1. Older drivers applied a higher MRA compared to younger drivers, possibly because the decline in cognitive function among older drivers, observed via the MMSE scores, led to a decrease in their ability to respond to complex situations. As a result, when faced with the need to make quick decisions, older drivers may tend to put in extra effort to ensure safety (such as applying heavier braking or faster steering velocity to avoid a crash).

Older drivers had a larger SDLP than younger drivers. This presents a result contrary to that of the findings of Clark and Feng (2017), who observed a lower SDLP among older drivers. One potential explanation is the increased difficulty of the takeover scenarios in our study. In these situations, the driver not only needed to react to the obstacles ahead but also needed to pay attention to the oncoming traffic in the adjacent lane to choose the correct direction of lane change. Another plausible explanation is that older drivers had lower use rates of ACC and, consequently, they had to exert more effort to maintain longitudinal vehicle stability compared to younger drivers. The reduced cognitive resources for lateral control among older drivers resulted in poorer lateral stability of the vehicle.

Although older drivers did not exhibit higher collision rates in the experiment, their poorer driving stability, inferred from an indicator of lateral control-SDLP, during their takeover operations would also affect the efficiency of traffic flow. Moreover, the road situations in the real world are more complex than that in our experiment, and the drastic lateral and longitudinal movement of vehicles among older drivers would increase the risk of collisions such as rear-end, sideswipe, or broadside collisions. It can be inferred from drivers' visual search behaviors that aging may lead to a degradation of visual processing capacity. A feasible way to help older drivers obtain situation awareness would be extending the TOR lead time or providing real-time dynamic road information. These would mitigate perceived risk and thus avoid aggressive driving maneuvers.

After a long period of automated driving, the road monitoring task produced more intense drowsiness in younger drivers than in older drivers. Younger drivers exhibited higher use rates of ADAS and were less engaged in driving tasks compared to older drivers. The "boring" and "monotonous" road monitoring condition during automated driving was potentially less demanding for younger drivers, which would promote drowsiness. However, older drivers had lower usage rates of ADAS and were more actively engaged in driving tasks to deal with monotony and maintain vigilance.

Driving drowsiness led to a decline in takeover performance among younger drivers, as evidenced by the longer takeover time and increased MRA and SDLP. Scheduled, or non-emergency, takeover operations will help maintain their sense of driving engagement and vigilance (Wu et al. 2019) as well as situation awareness of road conditions during long utilization of automated driving. However, the long period of road monitoring tasks was not associated with significant changes in takeover performance among older drivers. Although older drivers exhibited shorter takeover times during the second hazardous event than younger drivers, there was no significant difference in MRA, SDLP, and collision rate between the 2 groups of drivers, which does not confirm that older drivers have an advantage in regaining vehicle control during prolonged automated driving and thus Hypothesis 2 is invalid.

Age differences in the impact of voluntary NDRTs on takeover performance

In the first phase of automated driving, older drivers exhibited a lower percentage of fixation times on NDRTs, indicating a lower initial trust in automated driving (Pan, He et al. 2023; Pan, Xu et al. 2023; Payre, Perelló-March, Sriranga, and Birrell 2023) or lower ADAS use. After the first hazardous event, there was an increase followed by a subsequent decrease in the fixation time on the NDRT. This pattern may be a compensatory measure adopted by older drivers to avoid excessive immersion in NDRTs. After maintaining a relatively lower NDRT engagement, there was a subsequent upward trend, which could be attributed to the increase in trust building up through experience with and use of automation (Payre, Perelló-March, and Birrell 2023).

In the second hazardous event, young drivers who were involved in NDRTs had shorter takeover times and lower MRAs than those performing road monitoring tasks. These results confirm the validity of Hypothesis 3 that NDRTs improved the takeover performance of younger drivers. NDRTs decreased the boredom induced by road monitoring. Contrary to younger drivers, the NDRTs resulted in poorer takeover performance for older drivers in both hazardous events. The positive effects of NDRTs on young people were not identified in older people during prolonged automated driving conditions. The result completely supports the validity of Hypothesis 4.

Drivers needed to allocate their visual attention between the in-vehicle entertainment system and the road environment, and the NDRTs led to an increased visual workload for both groups of drivers. Whether they were performing road monitoring or NDRTs, older drivers had longer durations of fixation point times than younger drivers. This can be partially attributed to the more cautious driving style among older drivers; they had a more detailed observation of the road environment. Importantly, it is also related to the natural decline in visual perception and cognitive function associated with aging (Folli and Bennett 2023). Older drivers have relatively slower visual information processing speed and need more time to interpret the road environment elements.

The switching costs imposed by dual-task execution were more pronounced among older drivers. The LDA system was more frequently activated to correct their driving maneuvers while driving with ADAS; on the other hand, when the automated system reaches its limits and the vehicle needs to be taken over, older drivers engaging in NDRTs had longer reaction times, worse vehicle control stability, and higher collision rates than those performing road monitoring tasks.

In the later stage of the second phase of automated driving (P.2), older drivers spent a similar percentage of fixation time on NDRTs as younger drivers, which indicated an increased trust in the automation system among older drivers. Furthermore, this highlights the reduced selective attention and inhibition abilities in older adults (Depestele et al. 2020; Gasne et al. 2022); thus, older drivers are also prone to the issue of excessive immersion in NDRTs. To some extent, automation technology allows individuals to delegate some of the driving tasks and engage in NDRTs, but it may lead to visual overload for older drivers. As a result, it can hinder their ability to safely resume control of the vehicle when the ADAS cannot operate anymore. Therefore, it is not recommended for older drivers to engage in NDRTs during short or long uses of automated driving.

To cope with the issue of decreased fitness to drive among older drivers, adequate training and education programs should be implemented to help them to gain an understanding of the functionality and limitations of automated driving systems, as well as to develop appropriate trust in these systems (Payre et al. 2016, 2017). Overreliance on automation systems would lead to more severe consequences, and it is essential to emphasize the self-awareness of older drivers, which includes encouraging them to be attentive to their surroundings and constantly prepared to assume control of the vehicle in response to emergencies and system failures.

Age-related cognitive declines can impair the driving performance of older drivers. Though older drivers were less prone to driving drowsiness compared to younger drivers, it does not compensate for the differences in takeover performance with younger drivers. Older drivers exhibited slower reaction times, decreased hazard perception, and decreased motor coordination, which affected their driving performance and safety. Therefore, it is necessary to implement appropriate measures such as fitness to automated driving assessments, takeover training, and the utilization of intelligent automated driving assistance technologies to ensure their safe participation in road traffic.

Though older drivers had lower trust and use of ADAS technology, it is noteworthy that ADAS technology effectively enhances driving safety among older drivers, particularly during NDRT engagement. Consequently, it is imperative to increase acceptance toward automated driving technologies among older drivers. Firstly, it is critical to furnish them with comprehensive information pertaining to the functionalities and safety of such technologies. On the other hand, it is essential to implement age-friendly feature settings that are tailored to their distinct requirements and preferences. Furthermore, adjustments and improvements should be made based on their experiences and feedback following their utilization of ADAS technology.

Compared to younger drivers, older drivers have lower engagement in NDRTs. NDRTs appeared to alleviate driving drowsiness and improve takeover performance in prolonged automated driving conditions for younger drivers, but they did not significantly affect the drowsiness of older drivers. Voluntary NDRTs would impair takeover performance for older drivers, both after short and long exposures to automated driving. Therefore, it is crucial to prevent information overload associated with NDRTs in older drivers and ensure their focus is on the driving task, enabling them to better handle sudden control transitions.

Limitations

The current study has several limitations. First, for safety concerns, we conducted our research in a driving simulator. This means that in case of operational errors, there was no real threat to the driver's safety. Therefore, we may have overestimated drivers' NDRT engagement. Second, to assess the participants' subjective drowsiness, we asked about their KSS levels every 4 to 5 min. It should be noted that this may have had an impact on the results because it would temporarily reduce their level of drowsiness. Finally, simulated driving studies often face the inherent challenge of limited sample size. Future research could investigate the effect of NDRT engagement and age on takeover performance by conducting an on-road experiment with a larger sample size.

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Data are available upon reasonable request from the authors subject to agreement by the funder.

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