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Other road users' adaptations to increase safety in response to older drivers' behaviour

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ABSTRACT

Changes in physical and cognitive abilities not only challenge the driving ability of older adults, in some situations age-related changes in driving behaviour require other road users to adapt their behaviour to maintain a safe traffic situation. In this study, we aimed to map age-related differences in driving behaviour and assess the impact on other road users. A group younger and a group older adults drove four different routes containing challenging situations (e.g., merging into motorway traffic) in a driving simulator while measures of driving behaviour were collected. Other road users' deceleration responses to the driver's behaviour were also collected as a measure of behavioural adaptation. Our results showed similar driving performance between young and older drivers when task complexity was low, but reduced performance in older drivers when tasks requirements increased. Lower driving speed and longer waiting times that were observed in older drivers can be interpreted as compensatory behaviour aimed at creating more time to lower task requirements. Crucially, in a non-time critical situation this compensatory behaviour was found to be successful, however in a time-critical situation (merging onto a motorway) this strategy had negative side effects because other road users had to decelerate in order to keep a safe distance. Our results show the importance of anticipation and adaptation by other road users for the success of older driver's strategies and traffic safety.

1. Introduction

Ageing has been related to a multitude of changes in both physical and cognitive abilities that can impact driving performance (Shinar, 2017). These changes do not inevitably lead to reduced driving safety, as driving is a highly cooperative activity and road users take each other into account and react to each other when participating in traffic (e.g., Kraft, Maag, & Baumann, 2019). Also, older adults are usually experienced drivers that have been shown to be able to compensate for age-related changes by adapting their driving behaviour, reducing the elevated crash risk due to impairments (Brouwer & Ponds, 1994; De Raedt & Ponjaert-Kristoffersen, 2000; Dykstra et al., 2020). Behavioural compensatory strategies during driving have been frequently studied, yet the impact of changes in older driver's behaviour on other road users have only been explored to a limited extent. The present study is aimed at mapping differences in driving behaviour between younger and older drivers in challenging traffic situations, and assessing the impact of compensatory behaviour on other road users.

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Driving behaviour can change with age under the influence of alterations in sensory, perceptual-motor, and cognitive abilities, and accumulated experience (Brouwer & Ponds, 1994; Karthaus & Falkenstein, 2016; Shinar, 2017). Reduced joint flexibility for example can lead to reduced neck rotation causing problems when looking over your shoulder during a lane change, and diminished information processing speed can limit the ability to navigate busy traffic situations. However, although age-related changes in brain structure may cause a decline in cognitive abilities, these processes are also counteracted by processes of brain reserve, brain maintenance, and neural compensation that limit the impact on behaviour (Cabeza et al., 2018). Reuter-Lorenz and Cappell (2008) described how compensatory brain activation is effective at lower levels of task demands, but may prove insufficient when tasks become increasingly complex. This is in line with older adults performing similarly to younger adults in simpler driving situations (Horberry et al., 2006), whereas they display altered driving performance in more complex situations, such as changing lanes, making left turns at un-signalized intersections and merging into motorway traffic (Karthaus & Falkenstein, 2016; Romoser et al., 2013; Staplin & Lyles, 1991). It also is in line with the fact older adults are more often involved in accidents that involve a complex environment or time pressure (Hakamies-Blomqvist, 2003).

When task demands become too high for neural compensation, older drivers may attempt to reduce the task demands through compensation at the behavioural level by, for example, slowing down. Driving can be divided into three behavioural levels: the strategical level (planning), tactical level (manoeuvring), and operational level (control) (Michon, 1985), of which the first two allow for compensation. At the strategical level, the general planning stage of a car ride, older adults have been found to drive less in high-risk situations and under adverse conditions such as at night time, during peak hours, high-speed roads, and bad weather (Charlton et al., 2006; Hakamies-Blomqvist & Wahlström, 1998; Shinar, 2017). At the tactical level, the level of manoeuvre control, older adults may compensate by driving more slowly, maintaining longer headways towards a leading vehicle, and accept larger gaps when passing through traffic (Dissanayake et al., 2002; Evans & Wasielewski, 1983; Porter & Whitton, 2002; Staplin & Lyles, 1991; Wasielewski, 1984).

Although behavioural compensatory strategies are aimed at decreasing risks and task complexity, their success in terms of safety outcomes might be partly dependent on other road users' behaviour. In some situations, compensatory strategies might increase accident risk and require other road users to adapt their driving behaviour to maintain a safe traffic situation (Keskinen et al., 1998; Smiley, 1999). For example, when merging onto the motorway a lower driving speed provides the older adult with more time to process the complex traffic situation and find an appropriate gap to filter in, however, at the same time it increases the speed differential with motorway traffic, creating a riskier situation and potentially requiring rear traffic to respond by adapting their driving speed in order to maintain distance to the merging car (De Waard et al., 2009). Hence the success of compensatory strategies is presumably partly depending on other road users' ability to adapt their driving behaviour in order to maintain a safe traffic situation. Even though distance to the car in front is a common focus in traffic research (e.g., Reinolsmann et al., 2021), research on the effect of driving behaviour on rear traffic is limited. While the response of other traffic to older driver's behaviour has been studied (Davidse et al., 2009), that study focussed on urban driving behaviour. In particular in challenging high-speed conditions, it is important to know the impact of compensatory strategies of older drivers on other road users. This knowledge may also be very relevant for giving support to older drivers, in other words, for the development Advanced Driver Assistance Systems (ADAS) for this group of drivers (Davidse, 2006). Although the effects of ADAS have been found to be helpful for older drivers (e.g., Davidse et al., 2009), beneficial effects were not observed in all cases. In an earlier study (De Waard et al., 2009) it was shown that a simple support system actually was counter-effective for older drivers in terms of safety effects under these more demanding high-speed motorway traffic conditions. Also, additional information presented to the driver may add demands imposed and distract from the primary task of driving (e.g., Weeks & Hasher, 2014).

In this study, a group of younger and older drivers drove four different rides, containing challenging traffic situations, in a driving simulator. Age-related differences in driving behaviour and utilisation of tactical compensatory strategies were investigated, as well as the impact of these compensatory strategies by examining behavioural adaptation of other road users. Older drivers were expected to display altered driving behaviour and compensatory behaviour in complex traffic situations, for example by adhering to lower driving speeds and preferring more spacious gaps when crossing through traffic compared to young drivers. The compensatory driving behaviour of older drivers was expected to require more frequent and more extensive adaptations of other road users in order to preserve traffic safety.

2. Method

2.1. Participants

Thirty-seven younger (18–26 years (M = 21.3, SD = 2.1), 16 female) and 46 older adults (59–71 years (63.4, SD = 3.0), 25 female) participated in this study. All participants were right-handed, had normal or corrected-to-normal vision, held a driving licence (average time holding driving licence [SD]: younger = 4.2 [3.8] years, older = 41.1 [8.5] years), did not have history of neurological or psychiatric diseases and did not use any psychoactive medication. The younger participants were students at a university or university of applied sciences. The older participants worked for at least 20 h/week in a paid and/or volunteering job. The study was conducted according to protocols approved by the Ethical Committee of the University of Groningen, and all participants gave written informed consent. Participants were recruited via advertisements, personal contacts and a recruitment agency. They received € 20 as compensation for their time plus compensation for their travel expenses.

2.2. Procedure

This study was part of a larger study consisting of two testing days composed of a cognitive assessment, a structural Magnetic Resonance Imaging scan and a driving simulator session. In addition, participants were asked to fill out questionnaires at home regarding driving experience and driving preference. The driving simulator session always took place at the end of the morning following the cognitive assessment.

Following an explanation about simulator sickness, participants were instructed on the operation of the driving simulator and drove a short practice ride on a rural winding road to get accustomed to controlling the simulator. Subsequently, participants drove six test rides which were each followed by the subjective assessment of mental effort on the Rating Scale Mental Effort (RSME, Zijlstra, 1993). This scale runs from 0 to 150 with several labels provided alongside the axis to guide participant's decision, running from 'absolutely no effort' to 'extreme effort'.

2.3. Materials

A Jentig50 driving simulator (ST Software) placed on a two degrees of freedom moving base platform (CKAS) was used. The simulator set-up consisted of an open cabin mock-up including a driving seat, steering wheel, gear box, accelerator and brake pedal and indicators. The participant was surrounded by five 60-inch diagonal LED screens to enable the participant to view the surrounding and traffic within a 270 degrees field of view. The car windows, rear-view and sideview mirrors, as well as the dashboard were displayed on the screens. StRoadDesign (STSoftware) was used to design the graphical interface of the rides and scenarios were programmed using StScenario (STSoftware). To promote a realistic driving experience simulated traffic was responsive to the participant's behaviour (van Winsum & van Wolffelaar, 1993). All rides were driven in automatic transmission.

2.4. Driving simulator rides

2.4.1. Route ride

During this ride participants had to drive a route in a rural environment by turning left or right at Y-junctions they encountered along the way. The speed limit on this route was 80 km/h. The scenario was driven in two different conditions, once using auditory navigation information provided during the ride 200 m before each Y-junction (turn-by-turn condition; e.g., 'On the next junction go left'), and once after listening to an audio fragment providing all route information prior to driving (pre-listen-condition). In the latter condition all route instructions had to be memorized and subsequently retrieved while driving the route. Participants were allowed to listen to the pre-listen route-instruction as many times as they needed prior to driving.

For both conditions, the routes consisted of five consecutive instructions (left or right turns), with a maximum of two identical turns in a row (e.g., left-left). This resulted in 14 possible routes that were counterbalanced between participants and conditions. The end of the route was either indicated by an audio clip informing the participant that they reached the end of the route (in the turn-by-turn condition) or participants parked their car at the end of the route in accordance with the memorized instructions (pre-listen condition).

The impact of different types of route instructions (pre-listen vs. turn-by-turn) and age (younger vs. older) was examined by inspecting route accuracy (number of mistakes), driving speed (km/h), lateral position on the road (metres, road centre = 0, towards the right-hand road edge line gives negative values), and mental effort ratings (0–150 on the RSME scale). Average driving speed, the standard deviation of driving speed and standard deviation of lateral position (SDLP) were measured for each of the four 850 m sections between the Y-junctions, and averaged before analysis. The pre-listen condition was predicted to have a higher dual task load compared to the turn-by-turn condition, as the route has to be kept and be updated in memory in addition to driving the car, while participants could solely focus on driving the car in the turn-by-turn conditions as navigation instructions were presented at the moment they could be used.

2.4.2. Gap acceptance ride

In the gap acceptance ride, participants drove on a rural road (max speed 80 km/h) where they encountered three intersections which they had to cross straight ahead. Cars, approaching from the left and the right, crossed the intersection, creating gaps for the participants to pass through. The gap size increased as time passed, rewarding waiting with more spacious gaps and therefore more time to cross the intersection. The first gap presented was one second, and the maximum gap size offered was ten seconds. Gaps increased in steps of one second, and every gap was offered three times before a larger gap was presented. The series of three gaps of the same size were separated by two one-second-gaps. The accepted gap size on each intersection was used in the analyses.

To examine the degree of required driving behaviour adaptation of other road users, caused by the participants driving behaviour, a measure of deceleration was used. Surrounding traffic in the simulator environment was programmed to respond to the participant by adapting their speed based on a set of decision rules, regarding the driving speed difference between the participant and the modelled car, and the distance between the two cars. The maximum deceleration of approaching cars (in m/s^2) in response to the crossing participant was registered per intersection and compared between the age groups.

2.4.3. Merge ride

Participants started a merge ride on a road leading to a busy 120 km/h speed limit dual lane motorway with the task to merge. The ride was driven twice, during which participants' driving speed (in km/h) and deceleration of the rear car (in m/s^2) directly after merging were taken as main outcome measures. Average outcome measures were used for analyses. Similar to the gap acceptance ride, a deceleration measure was used to examine the degree of required adaptation of driving behaviour of other road users, in this case, the rear car at the moment of merging. The distance between this rear car and the participant was the same for all participants at the start of the merging lane, and deceleration was dependent on the participants' driving speed and location of merging. This meant that if a participant filtered in closer to the front of the rear car, the time headway (THW) was smaller (by definition) causing the rear car to decelerate more. Similarly, if the participants' driving speed was lower than that of the rear car, the rear car decelerated in order to create sufficient distance. If the participant's speed was higher than that of the rear car and the time headway to the rear car > 1 s, the rear car did not decelerate.

2.4.4. Rural road ride

In the rural road ride, participants drove on a road with a speed limit of either 60 or 80 km/h. At some point along the route, a car would unexpectedly pull out of a parking lot onto the road with just two seconds time-headway from the participant. The response strategy to this event (i.e. braking and staying behind the car or passing the car via the other lane) was taken as a dependent measure, as well as the minimal time headway to this car (THW in seconds), and whether there was a collision (yes or no). Lastly, mean driving speed (in km/h) on four road sections (two 60 km/h and two 80 km/h sections) was measured, and averaged per speed limit before analysis to give an indication of adherence to speed limits.

2.5. Analysis

Statistical analyses were performed using R version 1.2 (R Core Team, 2020). One younger and eight older participants dropped-out during the practice ride because they experienced simulator sickness. During the experimental sessions two additional younger participants and eight additional older participants ceased participation after experiencing sickness symptoms. The rides in which the symptoms started were excluded from the analysis. In addition, one older participant was excluded from analysis of the gap ride because of insufficient vehicle control Due to technical problems the data from one merge ride of an older participant and the data of a rural road ride from a different older participant are missing. At least data of 30 participants per age group per ride were included in the analyses. Even though the number of participants varied per ride (34–36 young participants, 30–38 older participants), the number of completed rides was not significantly related to age (r_s = -0.21, p = .07), and did not differ significantly between males and females (U = 768.5, p = .14).

Proportions were calculated to describe performance per age group and condition or intersection for route accuracy (route ride; proportion of participants that drove error free), behavioural adaptation of other traffic (gap acceptance and merge ride), and strategy to the unexpectedly merging car (rural road ride). Two-sample t-tests were used to compare performance between age groups. In the absence of homogeneity of variance the Welch two-sample *t*-test was applied. When assumptions of parametric tests were violated, Mann-Whitney tests were used to compare the age groups and Friedman tests were used to compare conditions. Levene's test was used to compare variation between age groups (route ride and merge ride), and Spearman's correlation was calculated to assess the relation between driving speed and deceleration rate within each age group (merge ride).

3. Results

3.1. Route ride

Route accuracy in the turn-by-turn condition was very high in both age groups, with all younger participants and 97% of the older participants driving the route error free. In the pre-listen condition more errors were made, and older participants made more errors compared to younger participants. The route was driven error free by 84% of older and 97% of younger participants. Types of errors in the pre-listen condition included taking the wrong turn (5 times), route stopped to early (3 times) and route stopped too late (3 times).

Standard deviation of driving speed measurements of four sections were excluded from analysis due to a measurement error. Younger adults, on average, drove significantly faster during the route rides compared to older adults, and their driving speed was

Table 1
Comparison of younger and older participants on driving simulator variables. Median per group and Mann-Whitney test statistics.

	Younger	Older	U	p
Route ride				
Mean Driving speed (km/h)	75.8	72.3	3842	< 0.001
SD of driving speed (km/h)	1.22	1.94	1530	< 0.001
SDLP (m)	0.22	0.29	939	< 0.001
(Normalised) RSME prelisten	−0.63	−0.40	383.5	0.001
(Normalised) RSME turn-by-turn	−0.95	−0.57	388	0.001
Gap acceptance ride				
Maximum deceleration approaching cars (m/s^2)	0.43	0.25	567	0.103
Merge ride				
Maximum deceleration rear car (m/s^2)	0.9	1.77	153.5	0.031
Rural road ride				
Driving speed at 60 km/h speed limit (km/h)	63.8	62.4	602.6	0.216
Driving speed at 80 km/h speed limit (km/h)	78.9	74.4	734.0	0.002

found to vary less as reflected by a smaller standard deviation of driving speed compared to older adults (See Table 1). Furthermore, younger adults swerved less on average during driving, as reflected by a lower SDLP compared to older adults (See Table 1**)**. The type of route instruction did not impact average driving speed, average standard deviation of driving speed or SDLP (χ^2 (1) = 0.87, p = .35, χ^2 (1) = 0.05, p = .82 and χ^2 (1) = 0.69, p = .41, respectively).

Self-reported mental effort ratings were found to differ between the route instruction conditions, with higher levels of mental effort reported in the pre-listen condition compared to the turn-by-turn condition (median $RSME_{pre\text{-}listen}$ = -0.57, median $RSME_{turn\text{-}by\text{-}turn}$ = -0.77 ; χ^2 (1) = 9.98, p = .002). Furthermore, younger adults rated the required mental effort during both route rides as relatively lower than the other rides compared to older adults (See Table 1).

3.2. Gap acceptance ride

The majority of participants were able to cross the busy intersections without collisions, but one younger participants collided with two cars on the third crossing. Data from this specific participant and crossing were excluded from further analyses, as they would skew the data. Furthermore, measurements of two intersections were excluded for one older participant, as no traffic was presented at the intersections due to a software error.

Although both younger and older adults on average passed through a five second gap, younger adults used the first five second gap offered while the older adults used the third five second gap presented (U = 3084.5, $p < .001$).

In order to gain insight in the extent to which passing traffic was required to adapt its driving speed when crossing the intersections, maximum deceleration of the approaching cars from left and right was analysed. The majority of crossing manoeuvres was executed without requiring other road users to decelerate (66% of all crossings). The percentage of crossing where passing traffic could maintain their driving speed was, however, higher in older compared to younger adults (81% vs. 53%, respectively). In case of deceleration, the average maximum deceleration of approaching cars was found not to differ between younger and older adults (See Table 1 and Fig. 1A).

3.3. Merge ride

Driving speed at the moment of merging onto the motorway was significantly higher for younger adults compared to older participants (mean speed [SD]: younger = 99.6 [6.4] km/h, older = 80.6 [9.0] km/h, t(65) = 2.98, p = .004). Moreover, driving speed varied less in the younger group compared to the older group ($\sigma^2_{younger}$ = 41.4, σ^2_{older} = 80.6; F(1,65) = 3.97, p = .05).

When merging onto the motorway, the car behind the participant had to decelerate to some extent in 23% of cases in younger and 33% of cases in older adults, suggesting that older adults on average more often caused other road users to adapt their driving

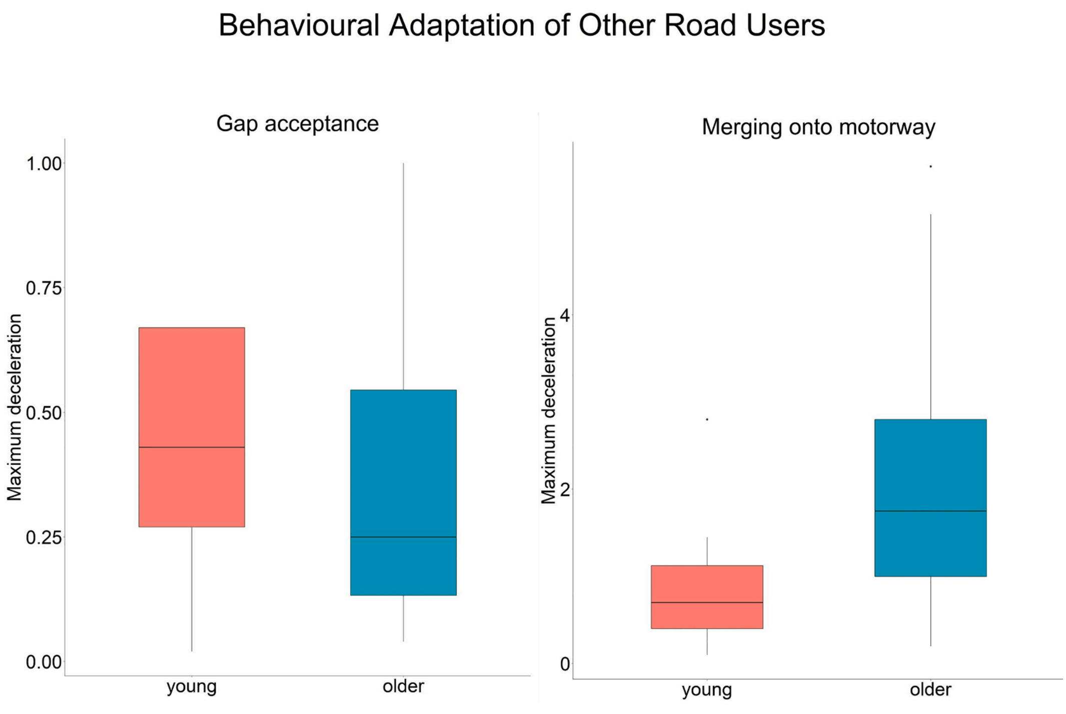

Fig. 1. Behavioural adaptation of other road users. **(A)** Maximum deceleration of approaching cars when crossing an intersection (gap acceptance ride); **(B)** Maximum deceleration of the rear car when merging onto the motorway (merge ride). Whiskers represent the most extreme values within 1.5 interquartile range of the 25th and 75th percentile of each group.

behaviour compared to younger adults. Contrary to the findings in the gap acceptance ride, the degree of adaptation in these cases was found to be higher in older compared to younger adults (See Table 1 and Fig. 1B) as indicated by a higher deceleration rate. This deceleration rate was found to correlate significantly with driving speed at the moment of merging in the older adult group ($r_s = 0.64$, $p < .01$), whereas this relation was not found for the younger adult group (r_s = -0.07 , p = .79).

3.4. Rural road ride

Average driving speed of younger and older adults on a rural road was found to not differ when the speed limit was 60 km/h, however, when the speed limit was 80 km/h older adults drove significantly slower, deviating more from the speed limit, compared to younger adults (See Table 1).

In response to the car unexpectedly pulling out of a parking lot onto the road, 47% of younger participants and 62% of older participants drove around the car via the oncoming lane. The other participants braked, and stayed behind the car in their driving lane. In three cases the situation resulted in a collision with the merging car (2 younger, 1 older adult). Minimal time to collision to the merging car and brake reaction time of those who did not collide were found not to differ between younger and older adults ($t(25) = -1.00$, $p = .33$; and $U = 111$, $p = .42$, respectively) for cases where participants braked and stayed behind the car.

3.5. Mental effort

To statistically compare mental effort ratings between the age groups, RSME scores were normalized within participants to correct for individual differences in terms of average ratings and distribution ($(RSME_{specific\ ride} - RSME_{individual\ mean})/RSME_{individual\ standard\ deviation}$). Reported differences therefore reflect differences in perceived mental effort relative to the other rides. Only participants who provided mental effort ratings for all simulator rides were included in the analysis (n = 64).

Average mental effort ratings were found to differ between younger and older adults for the route and merge rides (Route Prelisten: $U = 242$, $p < .001$; Route TBT (Turn-By-Turn): $U = 262$, $p < .001$, Merge 2: $U = 710$, $p = .007$; Merge 1: $t(62) = 2.66$, $p = .010$), with younger adults rating the route rides as requiring relatively less mental effort compared to older adults, while older adults rated the merge rides as requiring relatively less mental effort compared to younger adults. Both age groups rated their easiest ride with a score between 'almost no effort' to requiring 'a little effort' on the RSME scale (See Fig. 2).

No evidence was found that mental effort ratings differed between younger and older adults for the gap acceptance and rural road ride (Gap: $U = 575$, $p = .39$; Rural Road: $t(62) = 0.94$, $p = .35$). These two rides were rated by both age groups as requiring the most mental effort, with an average RSME-score between 'some effort' and 'rather much effort' (See Fig. 2).

4. Discussion

Age-related changes in cognitive and physical functions have been reported to lead to altered driving behaviour and the

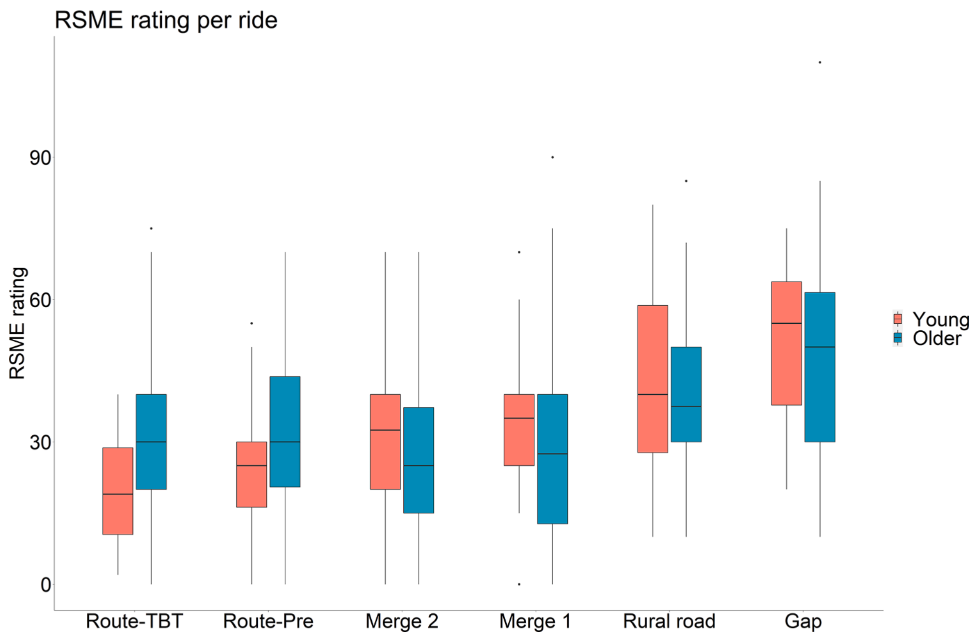

Fig. 2. Median Effort (RSME) rating per simulator ride for younger and older adults. Whiskers represent the most extreme values within 1.5 interquartile range of the 25th and 75th percentile of each group. TBT = Turn By Turn condition, Pre = Prelisten condition.

implementation of compensatory strategies by older adults (Brouwer & Ponds, 1994; Shinar, 2017). The implications of these alterations on other road users, however, have thus only been studied to a limited extent. The present study therefore not only aimed to map age-related differences in driving behaviour in challenging driving situations (i.e., merging onto the motorway), but also to gain insight in the impact of altered driving behaviour on other road users.

4.1. Age-related differences in driving behaviour

Age-related differences in driving behaviour, and potential use of compensation strategies are expected in more complex situations, where compensatory brain activation is insufficient (Reuter-Lorenz & Cappell, 2008). In this study, in line with Reuter-Lorenz and Cappell and findings by other researchers (Brundell-Freij & Ericsson, 2005; De Waard et al., 2009; Malfetti & Winter, 1987), we indeed found that in the relatively low demanding condition, that is at a lower speed limit of 60 km/h, driving speed did not differ between the age groups. However, when driving on a rural road with a speed limit of 80 km/h (route ride and rural road ride) and when merging onto a motorway, older adults were found to adopt a lower driving speed compared to younger adults. The fact that older adults also varied more in their driving speed and swerved more compared to young adults at the higher speed limit, could indicate that task requirement in this situation exceeded the capabilities of the older drivers. Similarly, when required to drive a route, route accuracy was comparable between younger and older drivers in the low mental demand (turn-by-turn) condition, while older participants made more mistakes in the route they had to drive from memory. Driving behaviour as measured by driving speed and SDLP was not found to differ between high and low mental effort conditions, suggesting that older adults prioritized driving behaviour above remembering the route in a situation when task demands were too high to maintain optimal performance in both tasks. These findings suggest that, while tactical compensation was not required at lower levels of task complexity (lower speed limit and receiving route instructions while driving), older adults used different compensation strategies depending on the situation at higher levels of task complexity (higher speed limits, merging manoeuvre and driving a route from memory) to reduce task demands (Brouwer & Ponds, 1994; Brundell-Freij & Ericsson, 2005).

In contrast to studies using real life data that suggest that older adults have more difficulty selecting a safe gap when crossing an intersection (Oxley et al., 2006), and choose a larger gap compared to younger adults when passing through a two-stop controlled intersection (Dissanayake et al., 2002), our results indicated that younger and older participants accepted the same gap size on average when crossing a busy intersection. However, older adults were found to take more time before crossing (they waited on average 10 s longer than younger participants), possibly reflecting a tactic compensation strategy to create more time.

Notably, when confronted with a car unexpectedly pulling out of a parking lot at a critical distance, a situation where creating more time is not an option, both young and older drivers were able to adequately respond to the acute situation and were able to prevent a collision, despite strategy differences. These differences in collision avoidance strategy might also reflect compensatory behaviour. Previous research has shown that braking is the most common response towards an unexpected event where collision needs to be avoided, but steering is more often observed when the situation is more critical (lower TTC values) (Adams, 1994; Lee et al., 2007). This suggests that in a situation with a comparable time to collision, such as in our task, participants' collision avoidance strategy is co-determined by their ability to react quickly, as a reduced reaction time would deem an identical TTC as more critical and increase the chance of steering. Diminished reaction time with increasing age (Salthouse, 2000) in combination with a demanding traffic situation could therefore offer an explanation for the fact that older participants more often opted for steering around the car via the oncoming driving lane compared to younger participants. It is however important to stress that both strategies were prevalent in both age groups, and both groups managed to avoid an accident.

If collision avoidance strategy is indeed related to general reaction times, it can be expected that drivers who steered also have longer reaction times in response to other traffic situations compared to braking drivers, and they might adhere more to tactic compensation strategies such as lower driving speeds to create more time. The finding that response times for participants that braked did not differ between younger and older participants, might be in line with this as it suggests that this subgroup of older adults were not delayed in compared to younger participants. Our dataset however, does not lend itself for a more detailed analysis of this relation, and thus this association remains speculative and would need to be confirmed by future research.

4.2. Required behavioural adaptation of other road users

So far, we focussed on compensation mechanisms used by the drivers themselves. However, a safe traffic environment is characterized by the efficient interplay between different road users, and at times requires other road users to adapt their driving behaviour, as in the case of the car unexpectedly pulling out of a parking lot. To gain more insight in the effects of participants' driving behaviour on other road users we explored whether and to what extent they were required to adapt their driving behaviour, by measuring their deceleration to maintain a safe traffic situation in response to the participant crossing a busy intersection and merging onto the motorway.

At the busy intersection, traffic coming from the left and right was more frequently required to decelerate in response to younger participants crossing compared to older participants. However, the extent to which the other road users had to decelerate in those cases was similar for both age groups. As stated before, older adults waited longer before crossing through a gap, likely reflecting compensatory behaviour. These results may suggest that, when crossing a busy intersection, younger drivers rely more often on other road users to keep the traffic situation safe. The results may also reflect less experience of the younger drivers, being less capable to predict how hazards develop or overestimating their skills (e.g. Vlakveld, 2011), leading to other traffic having to adapt to their crossing behaviour. For older adults, the extra time taken before crossing the intersection results in a more desirable traffic situation for surrounding traffic.

When merging onto the motorway a different picture arises, as older drivers were found to more often and more heavily rely on rear traffic to adapt their driving speed in order to maintain a safe traffic situation. Given that the extent to which the rear car had to decelerate depended on the participants driving speed at the moment of merging in the older group, it seems that the lower driving speed older adults adopted as a means of compensation imposes higher adaptation requirements on other road users to keep the traffic situation safe. Thus, although older adults rated merging onto the motorway as requiring less mental effort compared to young adults indicating that reducing driving speed is a successful compensation strategy in that it reduces mental load and facilitates executing the merging manoeuvre for them, this does come at the cost of higher levels of required behavioural adaptation by other road users.

Hence, the extent to which older adults rely on other road users to adapt their driving behaviour is dependent on the traffic situation. Some situations offer room for compensatory behaviours by which older adults create more time, and do not require other road users to adapt, like waiting for a gap to cross a busy intersection. In these cases, taking more time leads to a more desirable traffic situation. Whereas in other situations, creating more time seems to counteract the intention and results in a, sometime challenging, situation for other road users. In these situations, adaptation of other road users is crucial in preventing collisions and maintain a safe traffic situation.

4.3. Alternative support

Apart from the response by other road users that increases traffic safety, other measures that increase safety are conceivable. Self-explaining roads that elicit desirable behaviour and realistic traffic expectations on the basis of road layout, are an effective infrastructural measure (Theeuwes, 2021). On the basis of this study, extended acceleration lanes, or at least the avoidance of short acceleration lanes, can also be recommended.

Support systems, ADAS, provided these are tailored to the older user and not simplistic as the one used by De Waard et al. (2009), should also facilitate driving for older drivers and reduce human error (see Davidse, 2006). What becomes clear from the present study is that support is particularly needed in complex, time-critical situations, as in simpler situations, older drivers perform just as well as younger drivers.

4.4. Limitations

There are a few considerations to take into account with regard to this study. The study was performed in a driving simulator, which has as major benefit large experimental control, but as drawback that sometimes participants, in particular participants over the age of 70, can become simulator sick (Classen, Bewernitz, & Shechtman, 2011). In particular the difference in susceptibility between age groups makes driving simulator research difficult. In the present study however, the older participants came from a 'younger-older' age group, which is likely to have limited negative simulator sickness effects. Functional and physical changes increase with age, and therefore older drivers than those who participated in this experiment, might be more affected in their behaviour, which makes it desirable to include this group in future studies. Finally, the selection of the younger participant group could be criticised in the sense that drivers were relatively young, and potentially their hazard perception was not as developed as in more experienced drivers. Nevertheless, we did find important differences in behaviour between the present groups of participants, in particular in high-speed demanding conditions.

4.5. Conclusions

To conclude, we found confirmation for age-related differences in driving behaviour, especially in traffic situations where task requirements are high. These changes reflect altered performance when task requirements exceed the capabilities of older adults, as well as differences that can be interpreted as tactile compensatory behaviour aimed at creating more time in order to lower task requirements (e.g. reducing driving speed). In a non-time critical situation this compensatory behaviour was found to be successful, however in a time-critical situations (merging onto a motorway) this strategy had negative side effects in that it calls upon other road users to adapt their driving behaviour in order to maintain a safe traffic situation. Our results show the importance of anticipation and adaptation by other road users for the success of compensatory driving strategies and traffic safety.

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CRediT authorship contribution statement

Tineke de Haan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Project administration. **Arjan Stuiver:** Methodology, Software, Writing – review & editing. **Monicque M. Lorist:** Conceptualization, Writing – review & editing, Supervision. **Dick de Waard:** Conceptualization, Methodology, Writing – review & editing, Supervision.

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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