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Evaluation of the effects of age-friendly human-machine interfaces on the driver's takeover performance in highly automated vehicles

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A B S T R A C T

The ability to continue driving into old age is strongly associated with older adults' mobility and wellbeing for those that have been dependant on car use for most of their adult lives. The emergence of highly automated vehicles (HAVs) may have the potential to allow older adults to drive longer and safer. In HAVs, when operating in automated mode, drivers can be completely disengaged from driving, but occasionally they may be required to take back the control of the vehicle. The human-machine interfaces in HAVs play an important role in the safe and comfortable usage of HAVs. To date, only limited research has explored how to design age-friendly HMIs in HAVs and evaluate their effectiveness. This study designed three HMI concepts based on older drivers' requirements, and conducted a driving simulator investigation with 76 drivers (39 older drivers and 37 younger drivers) to evaluate the effect and relative merits of these HMIs on drivers' takeover performance, workload and attitudes. Results showed that the 'R + V' HMI (informing drivers of vehicle status together with providing the reasons for the manual driving takeover request) led to better takeover performance, lower perceived workload and highly positive attitudes, and is the most beneficial and effective HMI. In addition, The 'V' HMI (verbally informing the drivers about vehicle status, including automation mode and speed, before the manual driving takeover request) also had a positive effect on drivers' takeover performance, perceived workload and attitudes. However, the 'R' HMI (solely informing drivers about the reasons for takeover as part of the takeover request) affected older and younger drivers differently, and resulted in deteriorations in performance and more risky takeover for both older and younger drivers compared to the baseline HMI. Moreover, significant age difference was observed in the takeover performance and perceived workload. Above all, this research highlights the significance of taking account older drivers' requirements into the design of HAVs and the importance of collaboration between automated vehicle and cooperative ITS research communities.

1. Introduction

The population of the UK is ageing. In 2017, the proportion of the people aged 65 years and over accounts for about 18.2% of the population in the UK, it is predicted to increase to 20.7% by 2027 (ONS, 2018). To many older people, retaining the

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ability to drive safely is strongly linked to maintaining mobility, independent and wellbeing (Guo, Brake, Edwards, Blythe, & Fairchild, 2010; Musselwhite & Haddad, 2010; Li, Blythe, Guo, & Namdeo, 2019b). Despite evidence suggesting older drivers are not necessarily more dangerous than others (Hakamies-Blomqvist, Raitanen, & O'Neill, 2002), there are age-related sensory, cognitive and psychomotor decline that may limit older drivers' safe driving abilities and potentially make them a vulnerable road user group in terms of certain types of road traffic offences and collisions (Ball et al., 1998; Li et al., 2019b). To reduce the risks of such traffic offences and collisions, some older adults adopt self-regulation strategies to limit their expose to specific driving situations that are difficult for them (Charlton et al., 2006). However, the implication of using self-regulation in driving is reduced mobility which could potentially have negative impact on older drivers' independence and well-being (Charlton et al., 2006; Musselwhite & Haddad, 2010).

Fortunately, the fast development of vehicle automation technologies and the potential arrival of automated cars may allow older adults to drive longer and safer. There are several levels of vehicle automation systems, ranging from basic level 0 which refers to the conventional vehicle, through to the ultimate level 5 where the driverless car is capable to perform all safety-critical driving control and to monitor driving for an entire journey under all conditions (SAE, 2014; DfT, , 2015). Before the completely driverless cars become commonplace, the highly automated vehicles (HAVs), such as vehicles equipped with SAE Level 3 automation systems, may potentially become widespread within five to ten years (UKAutodrive, , 2016; Li et al., 2019b). In the HAVs, drivers are permitted to be fully disengaged from driving and also have the freedom to do various types of non-driving activities during automated driving (SAE, 2014; DfT, 2015). However, there are still situations that the HAV would need the drivers to retake the vehicle control, in such situations, drivers need to promptly switch their attention from the non-driving related tasks they were performing to the driving task, regain situation awareness of the driving environment and effectively take over the control of the vehicle within a lead time provided by the HAV system (Gasser & Westhoff, 2012; Gold, Damböck, Lorenz, & Bengler, 2013a; NHTSA, 2013; SAE, 2014). Such system-initiated takeovers are closely associated with the safety usage of HAVs and form an important human–machine interaction in HAVs (Flemisch, Kelsch, Löper, Schieben, & Schindler, 2008; Melcher, Rauh, Diederichs, Widlroither, & Bauer, 2015; Lu, Happee, Cabrall, Kyriakidis, & de Winter, 2016).

1.1. HAVs and older drivers

The potential of the new functionalities of HAVs in supporting older drivers to keep mobile for longer has been recognized (Chan, 2017; Young, Koppel, & Charlton, 2017; Bellet, Paris, & Marin-Lamellet, 2018). A number of studies have attempted to quantify older drivers' interaction with the HAVs especially in the automated driving and takeover situations (Körber, Gold, Lechner, & Bengler, 2016; Miller et al., 2016; Clark & Feng, 2017; Molnar, Pradhan, Eby, & Ryan, 2017; Li, Blythe, Guo, & Namdeo, 2018; Li, Blythe, Guo, & Namdeo, 2019a). Some studies have observed age difference in terms of drivers' behaviour of interacting with HAVs. For example, Körber et al. (2016) investigated the takeover behaviour in HAV among 72 drivers (36 younger and 36 older drivers) on a static driving simulator. They found that older participants exhibited more frequent and stronger braking behaviour as well as kept longer time to collision compared to the younger participants. Clark and Feng (2017) carried out a driving simulator experiment in which participants were enabled to freely select different types of non-driving related tasks based on their own preferences. The study revealed age difference in regard to the liking of non-driving related tasks during automated driving in HAVs, with younger drivers tended to use electronic devices, while older drivers preferred to talk to the researcher. Also, Li et al. (2019a) found older drivers exhibited slower reaction and decision making than the younger counterparts when taking over control from the HAVs. And they also found that bad weather conditions slowed takeover time and worsened takeover quality for the younger drivers, but for the older drivers, their already slowed takeover time did not further increase by bad weathers, however their takeover performance was substantially deteriorated (Li et al., 2018). Apart from those studies focusing on the quantification of takeover performance, previous research has also qualitatively explored older drivers' requirements and opinions towards the human–machine interaction in HAVs. Li et al. (2019b) implemented several semi-structured interviews with 24 older drivers after they had experienced a simulator level 3 HAV. The research yielded a wide range of requirements of older drivers towards the HAVs, for example, older driver would like to maintain physical and potential control over the HAVs; they need an information system and driver monitor system to support them in the HAV; and they want the takeover request in HAVs to be adjustable, explanatory and hierarchical. In addition, Robertson, Woods-Fry, Vanlaar, and Hing (2019) conducted an online survey and eight focus groups to study older drivers' opinions and perceptions towards HAVs, they found that older drivers were significantly more concerned about the safety and usability of HAVs compared to the younger drivers.

1.2. HMI in HAVs

Apart from focusing on exploring the impact of drivers' demographic factors, such as age, on drivers' interaction with HAVs, another popular aspect in the research regarding HAVs is to investigate the impact of the human–machine interfaces (HMI) in HAVs on drivers' takeover performance and behaviour. The HMI plays an important part in enabling the human driver interacts with the high automation systems safely and smoothly (Carsten & Martens, 2019; Naujoks, Wiedemann, Schömig, Hergeth, & Keinath, 2019). A great number of studies have looked at the effect of the modalities of delivering information in the takeover request on drivers' takeover behaviour. Naujoks, Mai, and Neukum (2014) conducted a driving simulator investigation to compare the effect of purely visual takeover requests and visual combined with sound takeover requests on takeover performance among 16 participants. They found that the visual combined with sound takeover request led to a mean reaction time of 2.29 s, while the purely visual modality led to a significantly longer reaction time of 6.19 s. In addition, takeover quality was better with the visual and sound takeover request modality than purely visual. Therefore, it was concluded that the purely visual takeover request modality was not enough, especially for drivers who were performing non-driving-related tasks. This conclusion was supported by later research which suggested that a visual takeover request should be provided together with an acoustic takeover request (Clark & Feng, 2017). In addition, Forster, Naujoks, Neukum, and Huestegge (2017) implemented a driving simulator investigation with 17 participants aged between 22 and 56 years to evaluate the impact of two types of visual and auditory takeover requests, and it was found that the visual and auditory takeover request with additional speech output resulted in faster reaction times and more positive subjective ratings among participants. Previous research has not only been limited to visual and sound takeover requests however, for example, Melcher et al. (2015) evaluated the effect of four types of takeover requests: a visual and sound takeover request, and three enhanced visual and sound takeover requests (integrated with mobile phone, integrated with sudden brake, and integrated with mobile phone combined with sudden brake). The results showed that these types of takeover requests had no significant effect on takeover time, but did have an effect on the driver's type of response. A takeover request with a sudden brake led to reactions of acceleration instead of steering and braking. Also, it was suggested that, as long as the driver is provided with a sufficient lead time of 10 s to reassume control of the vehicle, the designs of the takeover requests would not play a critical role in determining takeover performance. Also, Petermeijer, Bazilinskyy, Bengler, and de Winter (2017) conducted a driving simulator-based study with 24 participants aged 24 to 35 years old to investigate the effects of single-mode (sound or vibration) and double-mode (sound and vibration) takeover requests on participants' takeover performance in an HAV. They found that the double-mode sound and vibration takeover request led to faster reaction times and higher satisfaction among the participants compared to the single-mode sound or vibration takeover requests.

In addition to studying the modalities used to deliver information to drivers in the takeover request, previous research has also explored the designs of takeover requests in the HAV. Gold, Lorenz, Damböck, & Bengler (2013b) evaluated a new form of takeover request which enables drivers to monitor HAV driving for two seconds and then they are asked to take over the control of the vehicle. They found that this type of takeover request slightly speeded up the driver's takeover time by 0.3 s. Also, Merat, Jamson, Lai, Daly, and Carsten (2014) conducted a study on a driving simulator with 37 participants aged 28 to 67 years to assess two designs of HMIs in HAV, including a fixed HMI that transfers control of the vehicle from the automation system to the driver after a fixed duration of 6 min, and a variable HMI that transfers control to the driver as long as it detects that the driver has shifted visual attention away from the road centre. They found that the fixed HMI led to better takeover performance compared to the variable HMI and drivers generally took 35 s to 40 s to stabilise the lateral control of the car. In addition, Lorenz, Kerschbaum, and Schumann (2014) carried out a driving simulator investigation with 46 participants to investigate the effect of integrating augmented reality (AR) technology into the takeover request in an HAV. Two AR takeover requests were examined: one projecting a restricted corridor and another projecting a safe corridor in issuing the takeover request. The results showed that the type of request had no significant effect on takeover time, but the safe corridor projection led to improved takeover quality by leading to more consistent steering action. The findings of the above studies have provided evidence suggesting that carefully designed HMIs for the takeover process in HAVs can play an important role and could have the potential to improve drivers' takeover performance.

1.3. Research gaps

Although previous studies have investigated the impact of age on drivers' interaction with HAVs and realised the importance of involving older adults in the design of in-vehicle system and HAVs (Musselwhite & Haddad, 2007; Guo et al., 2010; Körber et al., 2016; Clark & Feng, 2017; Li et al., 2018; Li et al., 2019b; Li et al., 2019a), knowledge regarding how to incorporate older drivers' requirements into the HMI designs in HAVs and evaluate their impact on drivers' performance is still under-researched. The existing studies regarding the HMI in HAVs mainly focused on testing and evaluating the effects of HMIs from a performance perspective. It is still unclear how these HMIs were designed and whether the designs fully considered the preferences and requirements of the potential end users. As the HAV is potentially to be introduced to the public road, ignoring the needs and requirements of older adults in the HMI designs of HAVs could potentially prevent older adults from accessing and using HAVs and thus reduce the usability and potential benefits of HAVs (Yang & Coughlin, 2014; Li et al., 2019b). Therefore, it is important to develop knowledge in terms of incorporating older drivers' requirements into the design of HMIs in HAVs and evaluation of the effectiveness of these designs, considering if this is good design for older drivers it is good design for all. Such knowledge is important in facilitating a safe and comfortable human–machine interaction in HAVs for older driver end users.

1.4. Purpose of the research

In order to address the above research gaps, this study details a driving simulator investigation that aimed to implement older drivers' requirements into the design of the HMIs in HAVs and then evaluate these HMI concepts by investigating their effects on older driver's takeover performance, workload and attitudes.

Main research hypothesis of this study are:

- Incorporating older drivers' requirements into the design of HMIs improve drivers' performance of taking over control in HAVs.
- Age has significant effects on drivers' performance when interacting with HAVs.

2. Methods

2.1. Highly automated vehicle (HAV) scenario

The HAV scenario of this study involves a system-initiated takeover situation (Li et al., 2018; Li et al., 2019b; Li et al., 2019a), as shown in Fig. 1. It starts with the HAV starting to perform longitudinal and lateral vehicle control and to drive from 0mph to 30mph (13.41 m/s) when driving on the city road or to 60mph (26.82 m/s) on the motorway, and then maintaining an even speed in the central of the left-hand lane of the dual carriageway for a duration of one minute. During the automated driving, the drivers are allowed to take their hands off the steering wheel, and their feet off the pedals, and to be completely disengaged from driving and to safely perform a non-driving related task which requires them to read the material out loud from a tablet mounted 45 degree left to the central line of the steering wheel, as shown in Fig. 6. At one minute, the system detects a stationary red vehicle blocking the driving lane ahead, and then it informs the driver of this using a visual and auditory takeover request. Meanwhile, the HAV system continues to drive at its steady speed. On the city road, the HAV detects the stationary car with an advance range of 268.20 m and informs the drivers with a lead time of 20 s. On the motorway, it detects the stationary car with an advance range of 536.4 m and informs the drivers with a lead time of 20 s. The driver has to reassume the control of the vehicle within the 20 s before the HAV reaches the stationary car. A lead time of 20 s is selected as it was found to be a sufficient lead time for drivers who were disengaged from driving to take over the control of the vehicle when asked by the HAV systems on both the 30mph and 60mph roads (Li et al., 2018; Li et al., 2019a; Li et al., 2019b).

As long as the HAV system detects active input (at least 2 degrees of steering wheel input or/and 10% of pressing accelerator or brake pedals) from the driver (Gold et al., 2013a; Radlmayr, Gold, Lorenz, Farid, & Bengler, 2014; Mok et al., 2015a; Mok, Johns, Lee, Ive, Miller, & Ju, 2015b; Gold, Körber, Lechner, & Bengler, 2016; McDonald et al., 2019), it transfers control of the vehicle to the driver. Then, the driver needs to overtake the stationary car by changing to the next lane. After the driver has passed the stationary car, they are asked to pull over in the left hand lane and the scenario ends.

2.2. Design of HMIs based on the requirements of older drivers

The usability and safety of in-vehicle systems are closely associated with the design of HMIs in these systems and it is important for the design of HMIs to enable the users to feel safe, confident and comfortable when interacting with them (Stevens, 2000). A previous qualitative study by the authors has yielded a wide range of requirements among older drivers concerning a variety of aspects of the human-machine interactions in HAVs (Li et al., 2019b).

Following a mapping exercise, two piece of requirements were chosen because they were not only the two most frequently stated requirements among older drivers but also correspond to the two most important human-machine interactions in HAVs- the takeover control and automated driving processes (Li et al., 2019b). They were:

- Informing drivers about the reasons for takeover in the takeover request in HAVs.
- Providing drivers with information about their journey, vehicle status and road conditions when they are disengaged from driving during the automated driving process in HAVs.

In order to test these two requirements, they would be integrated into the design of the HMI in the HAV. As Fig. 2 indicates, the existing HMI in the HAV of this study is a visual and audible takeover request (Li et al., 2018; Li et al., 2019a). The Baseline HMI was used to refer to this original design.

2.2.1. Design of the R HMI

In terms of the first requirement raised by older drivers, the HAV scenario in this study adopted a HAV system-initiated takeover requiring drivers to perform collision avoidance manoeuvre. Therefore, the reason for takeover refers to a stationary

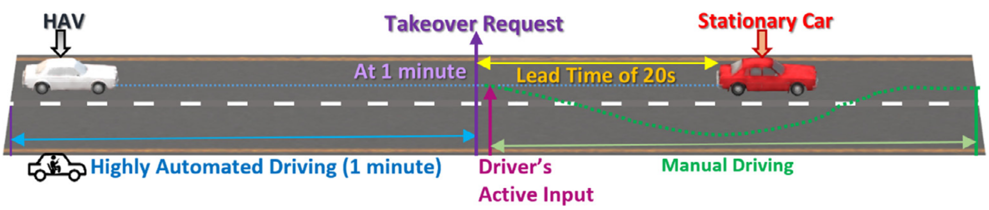

Fig. 1. Illustration of the HAV scenario.

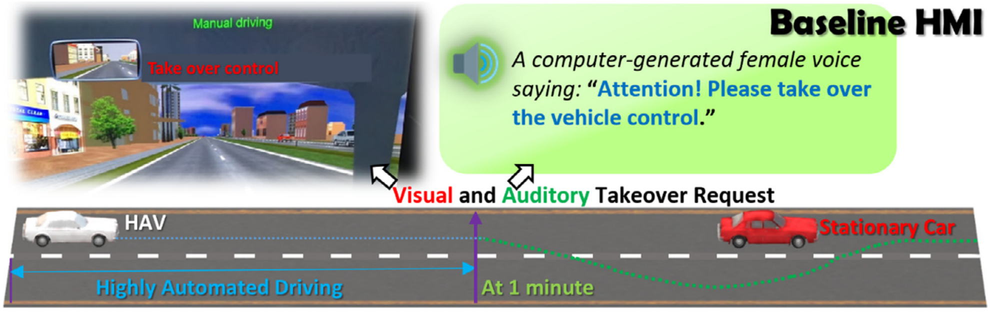

Fig. 2. Illustration of the Baseline HMI in the HAV.

red car suddenly appearing which blocked the driving lane. Such a reason was not mentioned in the Baseline takeover request of the HAV.

When integrating the reason for takeover into the existing baseline HMI, an important consideration is the sequence of the takeover control command and the reason for takeover. As suggested by Li et al. (2019b), a requirement expressed by the older drivers is that there would be no point in the driver knowing what is in front of them before they have completely got the vehicle under control, therefore the takeover request should tell the driver about taking over control of the vehicle first and then explain the reason for requesting this intervention, thus this requirement was built into the HMI. When the existing baseline HMI is followed by the indication of that there is a parked car ahead, a new type of HMI has been formed. An abbreviation of 'R HMI' is used to refer to this HMI, 'R' stands for 'Reasons for takeover' (Fig. 3).

2.2.2. Design of the V HMI

A second requirement from older drivers regarding the HMI was a strong desire to receive some information about their journey from the HAV when they are disengaged from driving while the HAV is performing automated driving (Li et al., 2019b). This requirement is also consistent with the findings previous studies suggesting that more assistance should be offered to drivers who are disengaged from driving during the automated driving mode in order to facilitate the safer and more effective takeover of control from the HAV (Li et al., 2018; Li et al., 2019a). There are three types of information that older drivers would like to be informed when they are disengaged from driving and the HAV is automatically driving the vehicle, these are: vehicle-journey time; traffic conditions and vehicle status (Li et al., 2019b).

When deciding which information should be included in HMI messages, there are several considerations. Firstly, the information provided by the HMI solution needs to correspond with the existing user-case of the HAV scenarios in this research. The HMI that provides the drivers with journey time during the automated driving may be suitable to be evaluated in the HAV scenarios that simulates long-distance journey with the HAV. Since the current user case of the HAV scenarios in this research allows the drivers to have a relatively short duration (one minute) of automated driving before asking them to take over the control of the vehicle (Li et al., 2018; Li et al., 2019b; Li et al., 2019a). The inclusion of journey time in the design of the HMI was not considered in this investigation, which represents a limitation of this study. Similarly, providing drivers with traffic information may be suitable to be tested in scenarios where the HAV is driving in busy traffic. However, in order to minimise the impact of extraneous factors on the drivers' performance, in the existing HAV scenarios used in this study, there is no other traffic, apart from the car which represents the HAV and the stationary red car on the lanes in the direction of driving (Li et al., 2018; Li et al., 2019a). Therefore, this requirement was not considered in this study either, nevertheless it could be tested in future research. The second consideration for designing the HMI was that the information provided by the HMI messages during automated driving should have the potential to improve the drivers' takeover performance. Endsley and Kiris (1995) suggested that providing information about the current status of the system has the potential to enhance

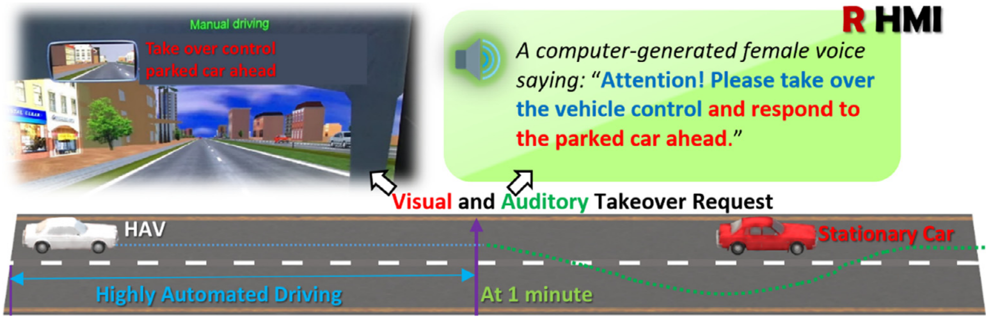

Fig. 3. Illustration of the R HMI in the HAV.

operators' situation awareness and thereby would benefit their performance. And the information of vehicle status of study is the car is highly automated driving at 30mph or 60mph at the time when drivers were disengaged from driving. Such information is used as indications of the status of the HAV in the design of HMI in HAV.

In determining at which time the HMI should present this information to the drivers, an important consideration is that allowing drivers to be completely disengaged from driving is a key feature of HAVs (SAE, 2014; DfT, 2015). Therefore, it is important to ensure that the time point when participants receive the information about vehicle status from the HMI, they should already have been completely disengaged from driving in HAVs. Endsley (1995a) argued that if the operator has been disengaged from the task for more than thirty seconds, they may hardly be able to recall the situation awareness information. Therefore, the information is presented after the drivers have been disengaged from driving task through performing a non-driving reading tasks for 50 s to ensure the status of completely disengagement from driving. The above considerations have shaped a new design of the HMI in HAVs. An abbreviation of 'V HMI' was used to refer to this HMI, 'V' stands for 'Vehicle status', as illustrated in Fig. 4.

2.2.3. Design of the R + V HMI

Finally, it would be worthwhile to design and test an HMI which fulfils both requirements to investigate if this has a more positive impact on user performance or not. Therefore, by combining the R HMI and V HMI, a new type of HMI that provides the reasons for takeover in the takeover request together with giving information about vehicle status was designed. An abbreviation of 'R + V HMI' was adopted to refer to this HMI, which is illustrated in Fig. 5. The overview of the four HMI concepts is summarised in table 1.

2.3. Apparatus

This study was implemented on the Newcastle University fixed-based ST Software Jentig50 driving simulator. As Fig. 6 shows, it consists by five 50-inch Full HD 1080p LCD screens mounted on an aluminium framework, which provides drivers with a high resolution and wide angle vision view. It has all of the controls of a real car, including a dynamic force feedback steering wheel, accelerator pedal, brake pedal, clutch pedal, adjustable car seat and safety belt. The dashboard, rear-view mirror and side mirrors are simulated on the screens. It also has the 5.1 surround sound system which allows the drivers to have an authentic driving experience. The graphical user interface is displayed by an additional monitor to allow researchers to control the driving simulator and monitor the system status. This driving simulator has been adopted by a number of previous studies and has been found to be a useful and valid tool in researching drivers' interaction with in-vehicle technologies and assessing their driving performance (Emmerson, Guo, Blythe, Namdeo, & Edwards, 2013; Guo, Blythe, Edwards, Pavkova, & Brennan, 2013; Edwards, Emmerson, Namdeo, Blythe, & Guo, 2016; Li et al., 2018; Li et al., 2019b; Li et al., 2019a).

2.4. Participants

All the participants of this study have participated two previous driving simulator HAV investigations by the present authors (Li et al., 2018; Li et al., 2019a). They all hold valid UK driving licences and were active drivers during the study. Older drivers (aged 60 years or over) were recruited through a mailing list of an older driver user group (VOICE North) and personal approaches at the local communities in Newcastle upon Tyne. Younger drivers were mainly recruited by personal approaches at Newcastle University. In total, 76 participants aged between 20 and 81 years (mean = 49.21 years, SD = 23.32 years, 33 female, 43 male) participated in this research. 39 of them were older drivers (mean = 71.18 years, SD = 6.06 years; max = 81 years, min = 60 years; 16 female, 23 male). 37 of them were younger drivers (mean = 26.05 years, SD = 4.47 years, max = 35 years, min = 20 years; 17 female, 20 male). Their annual driving mileages are shown in Table 2.

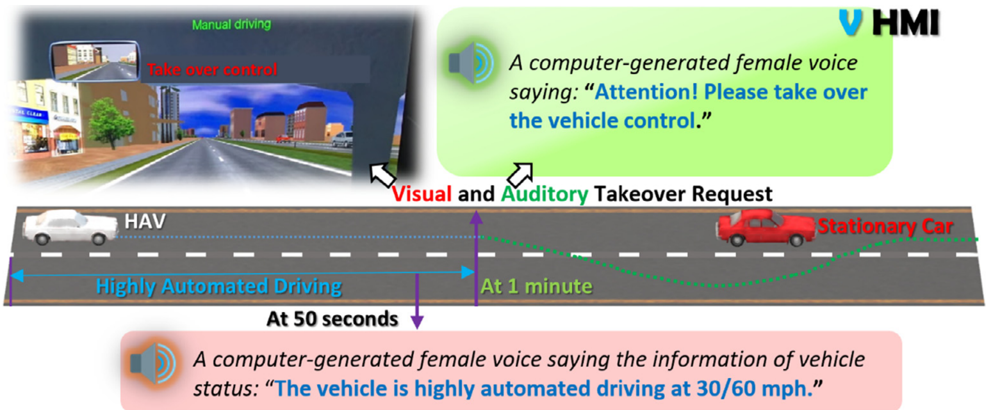

Fig. 4. Illustration of the V HMI in the HAV.

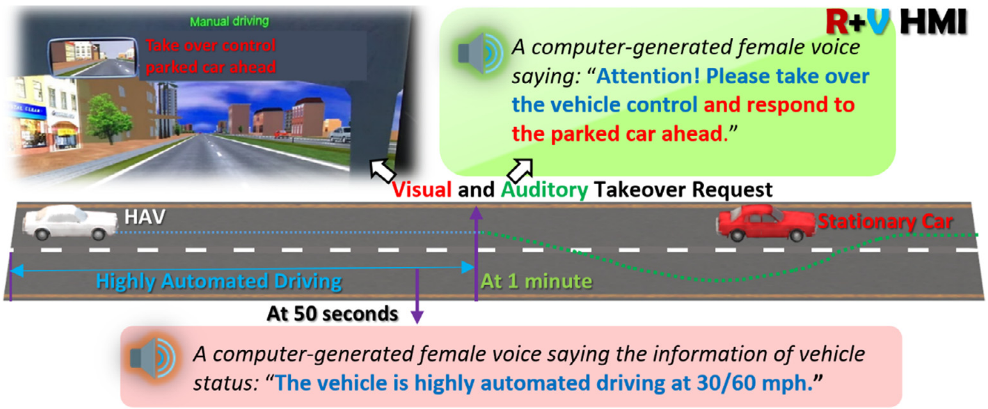

Fig. 5. Illustration of the R + V HMI in the HAV.

Table 1
Overview of HMI concepts.

HMI types	Providing reasons for takeover in the takeover request	Providing information of vehicle status during automated driving
Baseline HMI	N/A	N/A
R HMI	Yes	N/A
V HMI	N/A	Yes
R + V HMI	Yes	Yes

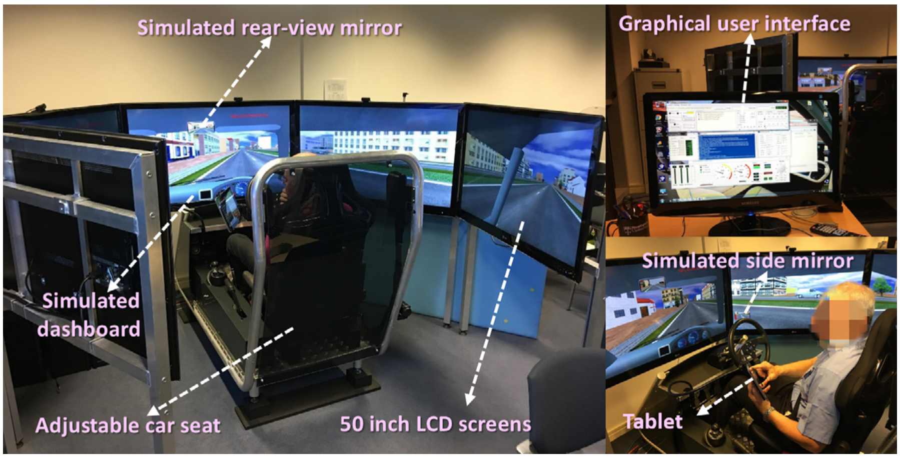

Fig. 6. Fixed-based ST software Jentig50 driving simulator.

Table 2
Annual mileage driven by participants.

Annual mileage (miles)	0–3000	3000–6000	6000–10000	10000–15000	15000+	Total
Younger drivers	15	13	5	2	2	37
Older drivers	6	10	12	10	1	39
Total	21	23	17	12	3	76

2.5. Experimental design

This study adopted a 2 × 2 × 4 between-and within-subjects mixed factor experimental design. The between-subjects independent variables are age (younger drivers, older drivers), road type (city road, motorway). The within-subjects independent variable is HMI (Baseline HMI, R HMI, V HMI and R + V HMI). Each participant experiences all the types of HAV situations. In order to reduce the number of driving sessions for the participants, they were divided into two groups according to the type of road involved. An overview of the experimental design is displayed in Table 3.

Table 3
Experimental design overview.

Between-subjects independent variable		Within-subjects independent variable
Age	Road type	HMI
Older drivers	City road	Baseline HMI, R HMI, V HMI, R + V HMI
Younger drivers	City road	Baseline HMI, R HMI, V HMI, R + V HMI
Older drivers	Motorway	Baseline HMI, R HMI, V HMI, R + V HMI
Younger drivers	Motorway	Baseline HMI, R HMI, V HMI, R + V HMI

2.5.1. Dependent variables

The dependent variables adopted were summarised in Table 4. Drivers' takeover performance is quantified by times aspects of takeover and takeover quality (Li et al., 2018; Li et al., 2019a). In terms of the time aspects of takeover in HAVs, three measurements were selected, consisting of reaction time, takeover time and indicator time. Reaction time attempts to quantify how quickly the driver responds to the takeover request initiated by the HAV. It is defined as the time between the takeover control request and drivers switching back to a safe and ready manual driving position which refers to a position that when subjects move their eyes from the tablet to the road, place their hands on the steering wheel and feet are on the pedals (Li et al., 2018; Li et al., 2019a).

Takeover time measures how quickly drivers execute conscious input to the car. It is the time between the point the HAV sends a takeover request to the driver and the point that the HAV receives an active operation of car controls from the driver. An active operation is defined as a manoeuvre which changes the steering wheel by 2 degrees or/and movement of 10% of accelerator or brake pedals (Gold et al., 2013a; Radlmayr et al., 2014; Li et al., 2018; Li et al., 2019a).

Finally, indicator time attempts to measure the speed of participants' decision-making in terms of avoiding the system limitation in the takeover process in the HAV. It is defined as the time between the points the HAV initiates a takeover request and the point the driver's initiation of an indicator light signal warning fellow road users that the driver intends to change lanes to avoid the stationary red vehicle ahead (Li et al., 2018; Li et al., 2019a).

It is assumed that, the faster their indicator time, the more quickly they have made the decision to change lane.

In regarding to the takeover quality, the minimum time to collision (TTC) is defined as the time required for the HAV to collide with the stationary red vehicle ahead in the driving lane if it continues at its current speed at the point it has successfully avoided the stationary car (Li et al., 2018; Li et al., 2019a). The lane width is 3.6 m and both the HAV and stationary red car have a defined width of 1.8 m and they are located in the centre of the lane as a default. Therefore, the point when the value of the lane position of the HAV is lower than 1.8 m is defined as it having successfully avoided the stationary vehicle following the manual takeover of the driving task. It is calculated as equation (1).

$$MinTTC = (d_s - d_c)/v_c \tag{1}$$

where: d_s is the distance when the stationary car shows up, d_c is the distance when the HAV has successfully avoided the stationary car, and v_c is the speed when the HAV avoided the stationary car.

In addition, as Eq. (2) indicates, the driver's resulting acceleration after the takeover request has been recognised as a valid and effective measure of the quality of a driver's retaking control from automation systems, reflecting the force that the car tyre has to transfer to the ground. The higher this value is, the bigger the chance that it could reach the maximum physical limit of the braking manoeuvres centred on the car tyre; and therefore in this case the driving is considered to be less stable and more dangerous (Gold et al., 2013a; Radlmayr et al., 2014; Li et al., 2018; Li et al., 2019a).

$$Resulting\ \ Acc = \sqrt{MaxLongitudinalAcc^2 + MaxLateralAcc^2} \tag{2}$$

Steering wheel angle is used as a measure of the stability of the driver's takeover. It is quantified as the standard deviation in degrees from the centre-line of the steering wheel. This measure has been widely adopted by previous studies to quantify takeover quality in HAVs (Mok et al., 2015a; Körber et al., 2016; Clark & Feng, 2017; Li et al., 2018; Li et al., 2019a). A higher value represents a less stable takeover performance.

Table 4
Overview of the dependent variables.

	Dependent variables	Unit
Time aspects of takeover	Reaction time	s
Time aspects of takeover	Takeover time	s
Time aspects of takeover	Indicator time	s
Takeover quality	Time to collisions (TTC)	s
Takeover quality	Resulting acceleration	m/s^2
Takeover quality	Steering wheel angle	degree
Takeover quality	Hasty takeover	Count
Workload	NASA RTLX score	N/A
Attitude	7-likert scale score	N/A

Also, previous research has monitored the types of reaction of the driver to check what strategy they used to responses to the system limitations of the HAV (Gold et al., 2013a; Gold & Bengler, 2014). For example, if the system limitation concerns an obstacle in the driving lane, responses to this could be to change lane or to brake and change lane.

Furthermore, the numbers of collisions and critical encounters which occurred were used to assess the success of the takeover (Li et al., 2018; Li et al., 2019a). Number of collisions involves all the crashes which happened during takeover, and the number of critical encounters includes any takeover with a minimum TTC of less than 1.5 s, which is deemed as a time threshold for which human drivers are highly likely to be involved in collisions (van den Beukel & van der Voort, 2013). This reflects potentially dangerous takeover behaviour among the participants.

Moreover, a hasty takeover is defined as any takeover where drivers' takeover time is smaller than the reaction time, reflecting that they execute the first active input to the HAV before they have completely switched to the safe and ready position to manually drive the car, thus representing abrupt and risky takeover behaviours.

Finally, participants' perceived workload was assessed by The National Aeronautics and Space Administration Raw Task Load Index (NASA-RTLX) proposed by Byers, Bittner, and Hill (1989). Their attitudes towards the HMIs was measured by Seven-point Likert scale questionnaires (Symonds, 1924; Cohen, Manion, & Morrison, 2000), see Appendix.

2.6. Research procedure

The ethical approval was granted to the research team from Newcastle University ethics committee before the study. At the start of the research, the driving simulator was set up before the arrival of the participants. When they arrived, their driving licences were checked and they were given a safety briefing. Next, they were informed that the participation of the study is voluntary and they can withdraw from the experiment at any time during the study without giving any reasons, the data collected will be anonymised and access to the data only limited to the research team. If a photograph or video clip is used for demonstration or in a publication, their name will not be made publicly available and their face image will be blurred. Then, they filled the consent form and the participant information questionnaire.

After that, they were given considerable practice time to become comfortable with the simulator until they confirmed verbally that they were ready. The HAV scenario was explained briefly. The participants were told that they needed to put their hands off the steering wheel, with feet off the pedals and to read the material on the tablet out loud when the HAV is performing automated driving. They need to take over control of the vehicle as soon as possible if they perceive any takeover requests. After taking over control, they need to keep driving until being told to stop, obey the speed limit, indicate (using indicator) when changing lanes and drive as they normally would in real life. In addition, they were briefly told the purpose of this study is to evaluate several HMI designs of HAV. Then, the demonstration of the four HMI design concepts were presented to the participants to enable them to become familiar with the HMIs, which would prevent the potential exclusion, difficulty and increased load caused by the participants' unfamiliarity with HMIs (Stevens, Quimby, Board, Kersloot, & Burns, 2002; Bradley, Langdon, & Clarkson, 2016). After that, the experiment started and the participants completed several takeover sessions in the HAV differentiated by different types of HMI. The sequence of the driving sessions for each participant was randomised to avoid the learning effect. After each driving session, participant was given a five to ten-minutes break, and then they completed the NASA-RTLX and 7-Likert scale questionnaires.

2.7. Data analysis

Participants' takeover performance data was collected by the driving simulator with a frequency of 20 Hz (every 0.05 s). The data was in binary form and converted into ASCII format. Continuous data (i.e. time aspects of takeover, TTC, resulting acceleration, and steeling wheel angle) was analysed by mixed ANOVA tests; Nominal data (i.e. hasty takeover and braking and steering behaviour) was analysed by Chi-square tests and McNemar tests; And ordinal data (attitudinal data) was analysed by Mann-Whitney U tests and Friedman tests (McCrum-Gardner, 2008; Field, 2013).

3. Results

3.1. Takeover trajectories

Fig. 7 shows the average trajectories of the older and younger drivers when taking over control from the HAV using different types of HMIs on the two simulated road environment: the city road; and motorway. They could provide a general illustration showing drivers' takeover behaviour.

The average trajectories were generated by positioning each driver's lane position data as vertical coordinates and the driving distance data as horizontal coordinates. The trajectories for each HMI use case are illustrated by lines of different colours, while each figure further divides the experiments parameters by both road type and the cohorts of older and younger drivers. The black vertical arrow and a red car were used to indicate the takeover request and the stationary car. In general, both younger and older drivers were able to take over control of the vehicle and pass the stationary vehicle successfully. Apart from one CCE was recorded among older drivers when using the Baseline HMI, no CCEs were recorded for participants when using the other HMIs.

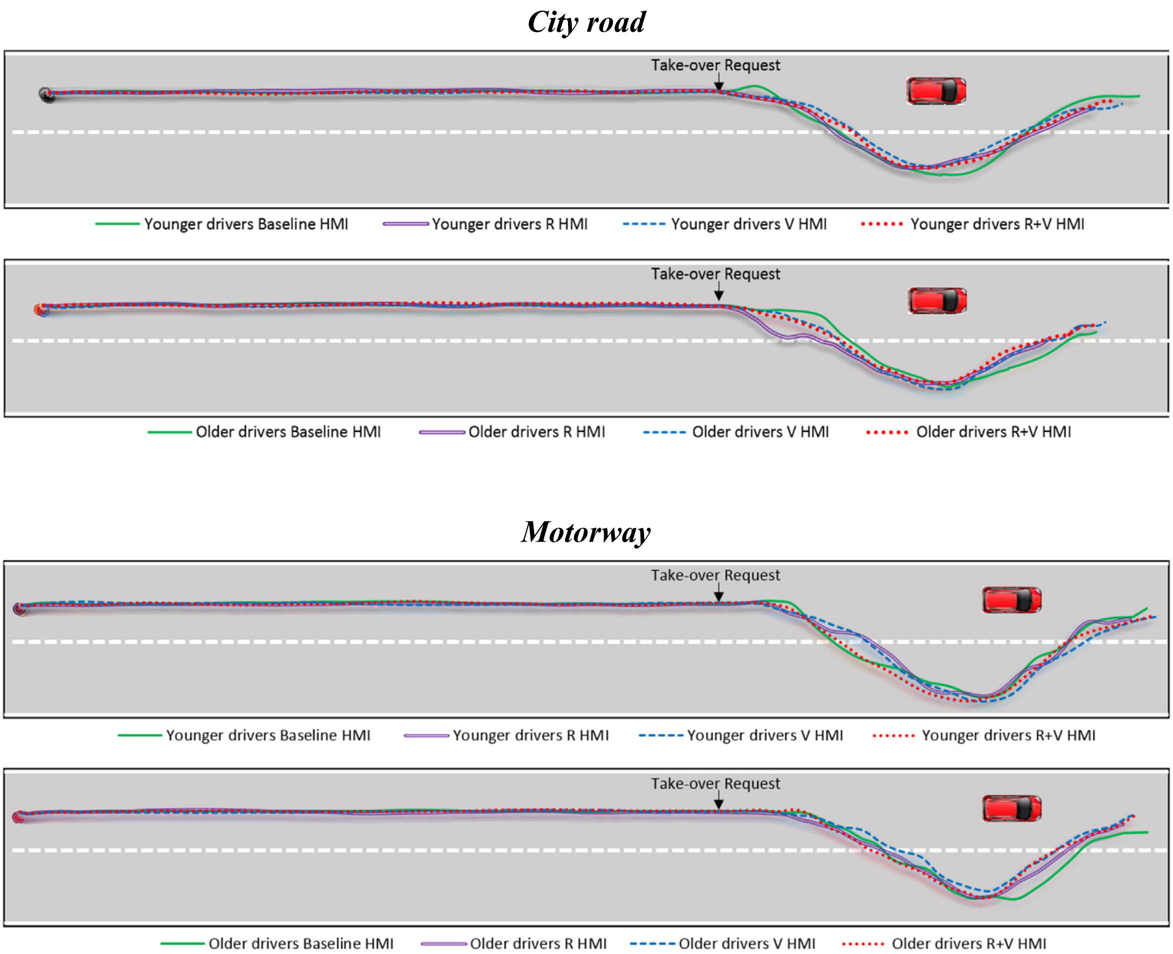

Fig. 7. Average trajectories when older and younger drivers took over control from HAV in different HMI situations.

In general, participants showed similar average trajectories when using different HMIs. The R + V HMI resulted in the smoothest trajectories among the four HMIs. For the younger drivers, on the city road, their mean trajectories under the four types of HMI exhibited similar pattern, with the one using the Baseline HMI showed a slight deviation to the left after take-over request. On the motorway, their average trajectories when using the R and V HMIs were slightly sharper compared to the ones using the Baseline and R + V HMI. For the older drivers, on the city road, their average trajectory when using the Baseline HMI exhibited a slower lane change comparing to those using the R, V and R + V HMIs. In addition, the trajectory when using the R HMI exhibited the earliest lane change. On the motorway, their average trajectories exhibited similar patterns.

3.2. Steering and braking behaviour

As shown in table 5, when using the Baseline HMI, the majority of participants reacted the stationary vehicle by only steering into the next lane. However, when using the R HMI, V HMI and R + V HMI, the majority of participants avoided the stationary vehicle by breaking and steering into the next lane.

When using the Baseline HMI, 67 drivers (34 older and 33 younger drivers) avoided the stationary vehicle only steering to the next lane, but not using the brake. 9 drivers (5 older and 4 younger drivers) reacted by steering and braking. A Chi-square test ($p = 0.768$) showed that there is no significant difference in the steering and braking behaviour between older and younger drivers in the clear weather.

When using the R HMI, 71 drivers avoided the stationary car by braking and steering into the next lane, including all the older drivers and the majority of younger drivers. 5 younger drivers reacted by only steering into the next lane. A Chi-square test ($p = 0.018$) showed that there is significant difference in the steering and braking behaviour between older and younger drivers when using the R HMI. In addition, a McNemar test ($p < 0.001$) showed that there is a significant difference in the steering and braking behaviours among participants when using the Baseline HMI and the R HMI.

Table 5
Steering and braking behaviour.

	Baseline HMI		R HMI		V HMI		R + V HMI	
	Steer only	Steer & brake	Steer only	Steer & brake	Steer only	Steer & brake	Steer only	Steer & brake
Older drivers	34	5	0	39	3	36	1	38
Younger drivers	33	4	5	32	5	32	9	28
Total	67	9	5	71	8	68	10	66

When using the V HMI, 68 drivers (36 older and 32 younger drivers) reacted to the stationary vehicle by braking and steering into the next lane. 8 drivers (3 older and 5 younger drivers) reacted by only steering into the next lane. There was no significant difference in the steering and braking behaviour between the older and younger drivers as assessed by a Chi-square test ($p = 0.409$). A McNemar test ($p < 0.001$) revealed that there is a significant difference in the steering and braking behaviours among the participants when using the Baseline HMI and the R HMI. Also, there was no significant difference in the steering and braking behaviours when using the R HMI and the V HMI, as tested by a McNemar test ($p = 0.453$).

Finally, when using the R + V HMI, 66 drivers (38 older and 28 younger drivers) avoided the stationary vehicle by braking and steering into the next lane. 1 older driver and 9 younger drivers reacted by only steering into the next lane. A Chi-square test ($p = 0.005$) revealed that there is significant difference in the steering and braking behaviour between the older and younger drivers. A McNemar test ($p < 0.001$) showed that there is a significant difference in the steering and braking behaviours among the participants when using the Baseline HMI and the R + V HMI. In addition, McNemar tests revealed that there is no significant difference in the steering and braking behaviour when using the R + V HMI compared to the R HMI ($p = 0.063$) and V HMI ($p = 0.774$).

3.3. Hasty takeover

The participants' hasty takeovers were illustrated in Fig. 8. The red dotted lines in the Fig. 8 are $y = x$. If a data point falls on the left-hand side of the $y = x$ line, it suggests a driver has exhibited a longer reaction time than takeover time. Drivers of this type generated active input to the vehicle before they had completely switched to the manual driving position. A hasty takeover could reflect an abrupt and potentially risky takeover behaviour.

In the Baseline HMI condition, 3 drivers exhibited hasty takeover. All of them were older drivers. A Chi-square test ($p = 0.085$) showed there is no significant difference in the hasty takeover between the older and younger drivers. When using the R HMI, 13 drivers (8 older and 5 younger drivers) exhibited hasty takeover. A Chi-square test ($p = 0.418$) revealed that there is no significant effect of age on hasty takeover in R HMI condition. In addition, a McNemar test ($p = 0.013$) revealed that R HMI led to significantly greater number of participants with hasty takeover compared to the Baseline HMI.

When using the V HMI, 9 participants (7 older and 2 younger drivers) exhibited hasty takeover. A Chi-square test ($p = 0.091$) revealed that there is no significant effect of age on hasty takeover in V HMI condition. Also, there is no significant difference in the number of participants with hasty takeover in the V HMI condition compared to in the Baseline HMI condition ($p = 0.070$) and the R HMI condition ($p = 0.454$) as assessed by McNemar tests.

Finally, when using the R + V HMI, 4 participants (3 older and 1 younger drivers) exhibited hasty takeover. There is no significant effect of age on hasty takeover as tested by a Chi-square test ($p = 0.330$). In addition, there is no significant difference in the number of participants with hasty takeover in the R + V condition compared to in the Baseline HMI condition as examined by a McNemar test ($p > 0.999$). However, a McNemar test ($p = 0.022$) revealed that the R + V HMI led to significant fewer participants with hasty takeover compared to the R HMI. There was no significant difference on hasty takeover between the R + V HMI and the V HMI as tested by a McNemar test ($p = 0.227$).

3.4. Reaction time

Fig. 9 shows that participants exhibited the longest reaction time when using the Baseline HMI and the fastest reaction time when using the R + V HMI. The results of a mixed factorial ANOVA with Greenhouse-Geisser correction revealed that the HMI had a significant effect on reaction time (see Table 6). Post-hoc test using the Bonferroni correction revealed that significant differences were between:

- Baseline HMI ($M = 2.53$ s, $SD = 0.73$ s) to V HMI ($M = 2.07$ s, $SD = 0.60$ s,), a decrease of 0.45 s (95% CI, 0.21 s to 0.69), $p < 0.001$.
- Baseline HMI ($M = 2.53$ s, $SD = 0.73$ s) to R + V HMI ($M = 2.02$ s, $SD = 0.62$ s), a decrease of 0.49 s (95% CI, 0.23 s to 0.75 s), $p < 0.001$.
- R HMI situation ($M = 2.30$ s, $SD = 0.69$ s) to V HMI, a decrease of 0.23 s (95% CI, 0.20 s to 0.44 s), $p = 0.024$.
- R HMI to R + V HMI, a decrease of 0.27 s (95% CI, 0.06 s to 0.49 s), $p = 0.006$.

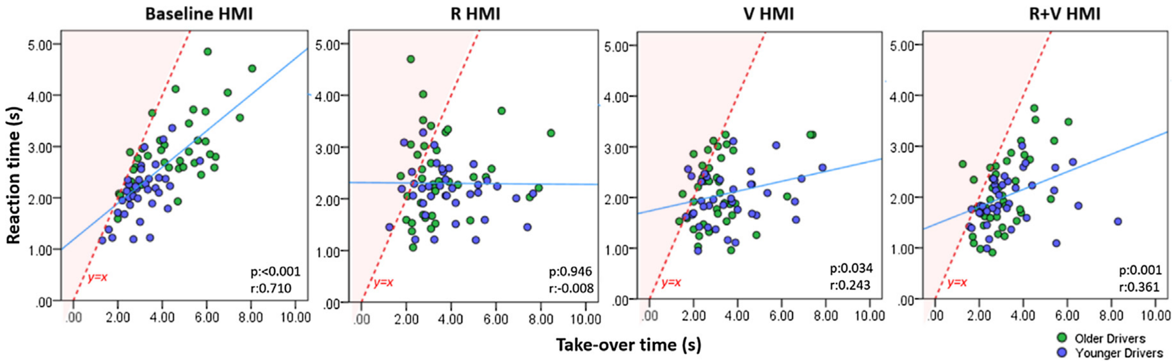

Fig. 8. Scatter plot of reaction time (s) relative to takeover time (s) for different age groups in the four HMI situations.

In addition, age had a significant effect on reaction time, with older drivers (M = 2.41 s, SD = 0.79 s) needing significantly longer reaction times than younger drivers (M = 2.04 s, SD = 0.50 s), a significant difference of 0.37 s (95% CI, 0.16 s to 0.58 s). In addition, there was a significant interaction effect between age and HMI. For the older drivers, their reaction time showed a trend of consistent reduction from the Baseline HMI (M = 2.91 s, SD = 0.70 s) to the R HMI (M = 2.45 s, SD = 0.81 s), V HMI (M = 2.16 s, SD = 0.67 s) and R + V HMI (M = 2.11 s, SD = 0.73 s) conditions. For the younger drivers, their reaction time showed a slight increase from Baseline HMI (M = 2.12 s, SD = 0.52 s) to R HMI (M = 2.14 s, SD = 0.50 s) and then exhibited a consistent decrease from R HMI to V HMI (M = 1.97 s, SD = 0.50 s) and R + V HMI (M = 1.93 s, SD = 0.48 s).

3.5. Takeover time

Fig. 10 shows that, in general, participants had the longest takeover time when using the Baseline HMI (M = 3.79 s, SD = 1.47 s) and the fastest takeover time in the R + V HMI situation (M = 3.26 s, SD = 1.30 s). The mixed factorial ANOVA with Huynh-Feldt correction revealed that HMI showed a significant effect on participants' takeover time (Table 6). A post-hoc test using the Bonferroni correction revealed that takeover times in the R HMI situation (M = 3.75 s, SD = 1.60 s, p = 0.045) were significantly longer than in the R + V HMI situation; a significant difference of 0.49 s (95% CI, 0.01 s to 0.98 s). There were no significant differences in takeover time among the other HMI conditions. Age did not have a significant effect on takeover time, although older drivers (M = 3.59 s, SD = 1.52 s) exhibited slightly slower takeover time compared to the younger drivers (M = 3.51, SD = 1.43 s).

In addition, there was a significant interaction effect between age and HMI on takeover time. For older drivers, their takeover time highest when using the Baseline HMI (M = 4.46 s, SD = 1.61 s), and then showed a trend of consistent reduction when using the R HMI (M = 3.61 s, SD = 1.65 s), V HMI (M = 3.17 s, SD = 1.34 s) and R + V HMI (M = 3.12 s, SD = 1.07 s). For the younger drivers, they exhibited the shortest takeover time in the Baseline HMI (M = 3.09 s, SD = 0.89 s) and then it showed sharp increase to in the R HMI situation, after that it showed a consistent decrease across the R HMI (M = 3.89 s, SD = 1.55 s), V HMI (M = 3.64 s, SD = 1.60 s) and R + V HMI (M = 3.40 s, SD = 1.51 s).

3.6. Indicator time

Fig. 11 shows the participants' mean indicator time when taking over control from the HAV in different HMI situations. A mixed factorial ANOVA with Huynh-Feldt correction yielded a significant effect of HMI on the indicator time (Table 6). Post-hoc test using the Bonferroni correction revealed that significant difference were between:

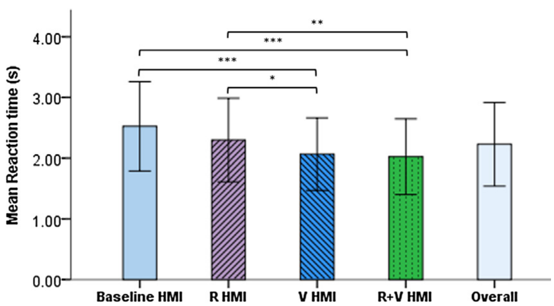

Fig. 9. Mean reaction times for different HMI conditions (error bars = ±1 SD, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

Table 6
ANOVA results; DVs: reaction time, takeover time, indicator time, TTC, resulting acceleration, steering wheel angle and workload; IVs: HMI and Age.

	df	f	p	ηp2	Differences between HMI conditions and age groups
Reaction time (s)					
HMI	1.989147.184	16.678***	<0.001	0.184	Baseline HMI to R HMI: ↓0.23 s
Age	174	11.941***	0.001	0.139	Baseline HMI to V HMI: ↓0.45 s***
HMI × Age interaction	1.989147.184	6.768**	0.002	0.084	Baseline HMI to R + V HMI: ↓0.49 s***
					R HMI to V HMI: ↓0.23 s*
					R HMI to R + V HMI: ↓0.27 s**
					V HMI to R + V HMI: ↓0.05 s
					OD to YD: ↓0.37 s**
Takeover time (s)					
HMI	2.470182.779	2.963*	0.043	0.039	Baseline HMI to R HMI: ↓0.04 s
Age	174	0.177	0.675	0.002	Baseline HMI to V HMI: ↓0.39 s
HMI × Age interaction	2.470182.779	8.381***	<0.001	0.102	Baseline HMI to R + V HMI: ↓0.53
					R HMI to V HMI: ↓0.35
					R HMI to R + V HMI: ↓0.49 s*
					V HMI to R + V HMI: ↓0.14
					OD to YD: ↓0.08
Indicator time (s)					
HMI	2.315171.305	3.067*	0.042	0.040	Baseline HMI to R HMI: ↓0.19 s
					Baseline HMI to V HMI: ↓0.43 s
Age	174	5.594*	0.021	0.070	Baseline HMI to R + V HMI: ↓1.29 s
HMI × Age interaction	2.315171.305	2.261	0.099	0.030	R HMI to V HMI: ↓0.24 s
					R HMI to R + V HMI: ↓1.11 s*
					V HMI to R + V HMI: ↓0.86 s*
					OD to YD: ↓1.33 s*
Time to collision (s)					
HMI	2.356174.348	2.168	0.108	0.028	Baseline HMI to R HMI: ↑1.59 s
					Baseline HMI to V HMI: ↓0.22
					Baseline HMI to R + V HMI: ↑0.19 s
Age	174	0.742	0.392	0.010	R HMI to V HMI: ↓1.81 s
					R HMI to R + V HMI: ↓1.40 s
HMI × Age interaction	2.356174.348	2.055	0.122	0.027	V HMI to R + V HMI: ↑0.41 s
					OD to YD: ↓0.78 s
Resulting acceleration (m/s^2)					
HMI	2.473182.975	14.451***	<0.001	0.163	Baseline HMI to R HMI: ↑0.64 m/s^2
					Baseline HMI to V HMI: ↓0.69 m/s^2*
Age	174	7.794**	0.007	0.095	Baseline HMI to R + V HMI: ↓0.72 m/s^2*
					R HMI to V HMI: ↓1.34 m/s^2***
HMI × Age interaction	2.473182.975	0.610	0.578	0.008	R HMI to R + V HMI: ↓1.37 m/s^2***
					V HMI to R + V HMI: ↓0.03 m/s^2
					OD to YD: ↓0.61 m/s^2**
Steering wheel angle (degree)					
HMI	2.556189.128	4.990**	0.004	0.063	Baseline HMI to R HMI: ↑1.25 degrees
					Baseline HMI to V HMI: ↓1.04 degrees
					Baseline HMI to R + V HMI: ↓0.74 degrees
Age	174	30.282***	<0.001	0.290	R HMI to V HMI: ↓2.25 degrees*
					R HMI to R + V HMI: ↓1.96 degrees**
HMI × Age interaction	2.556189.128	1.294	0.278	0.017	V HMI to R + V HMI: ↑0.30 degrees
					OD to YD: ↓3.43 degrees***
Workload (NASA-RTLX score)					
HMI	2.515186.125	23.391***	<0.001	0.240	Baseline HMI to R HMI: ↑2.05**
					Baseline HMI to V HMI: ↓1.68
Age	174	4.614*	0.035	0.059	Baseline HMI to R + V HMI: ↓3.05***
					R HMI to V HMI: ↓3.67***
HMI × Age interaction	2.515186.125	8.682***	<0.001	0.105	R HMI to R + V HMI: ↓5.10***
					V HMI to R + V HMI: ↓1.45
					OD to YD: ↓3.00*

Note: ↑ = increase, ↓ = decrease, OD = older drivers, YD = younger drivers, significant differences were highlighted by * = $p \le 0.05$, ** = $p \le 0.01$, *** = $p \le 0.001$.

- Baseline HMI (M = 8.79 s, SD = 3.44 s, p = 0.087) to R + V HMI (M = 7.50 s, SD = 3.08 s), there is no significant difference, but p value (p = 0.087) shows a certain trend towards significant.
- R HMI (M = 8.60 s, SD = 3.99 s) to R + V HMI, a significant decrease of 1.11 s (95% CI, 0.11 s to 2.10 s), p = 0.021.
- V HMI (M = 8.36 s, SD = 3.52 s) to R + V HMI, a significant decrease of 0.86 s (95% CI, 0.11 s to 1.6 s), p = 0.016.

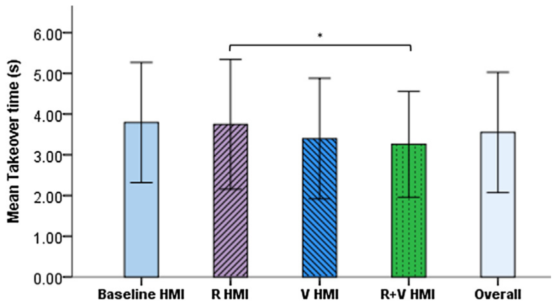

Fig. 10. Mean takeover times for different HMI conditions (error bars = ±1 SD, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

Age had a significant effect on indicator time, with older drivers (M = 8.96 s, SD = 3.75 s) exhibiting significantly longer indicator times than younger drivers (M = 7.63 s, SD = 3.17 s); a significant difference of 1.33 s (95% CI, 0.21 s to 2.46 s).

3.7. Time to collision (TTC)

Fig. 12 illustrates that in general, participants exhibited similar TTCs in different HMI situations. The TTC for R HMI (M = 10.96 s, SD = 6.80 s) was higher than when using the Baseline HMI (M = 9.37 s, SD = 5.05 s), V HMI (M = 9.15 s, SD = 6.17 s) and R + V HMI (M = 9.56 s, SD = 4.67 s). A mixed factorial ANOVA indicates that there were no significant effect of HMI type on the TTC (Table 6). In addition, there was no significant effect of age on TTC. Although, in general older drivers exhibited longer TTC (M = 10.14 s, SD = 5.93 s) than the younger drivers (M = 9.36 s, SD = 4.16 s).

3.8. Resulting acceleration

Fig. 13 illustrates that participants exhibited the greatest resulting acceleration when using R HMI. Also, participants had higher resulting acceleration in the Baseline HMI and R HMI situations than in V HMI and R + V HMI situations. And participants had similar resulting acceleration when using the V HMI and R + V HMI. A mixed factorial ANOVA with Huynh-Feldt correction revealed that HMI had a significant effect on the resulting acceleration (Table 6). Post-hoc test using the Bonferroni correction revealed that significant difference were between:

- Baseline HMI (M = 2.72 m/s^2, SD = 1.86 m/s^2) to V HMI (M = 2.02 m/s^2, SD = 1.39 m/s^2), a significant decline of 0.69 s (95% CI, 0.001 s to 1.37 s), p = 0.049.
- Baseline HMI to R + V HMI (M = 1.99 m/s^2, SD = 1.11 m/s^2), a significant difference of 0.72 s (95% CI, 0.12 m/s^2 to 1.32 m/s^2), p = 0.011.
- R HMI (M = 3.36 m/s^2, SD = 1.98 m/s^2) to V HMI, a significant decline of 1.34 m/s^2 (95% CI, 0.63 m/s^2 to 2.05 m/s^2), p < 0.001.
- R HMI to R + V HMI, a significant decline of 1.37 m/s^2 (95% CI, 0.69 m/s^2 to 2.05 m/s^2), p < 0.001.

Age showed a significant effect on the resulting acceleration, with older drivers (M = 2.82 m/s^2, SD = 1.80 m/s^2) exhibiting significantly greater resulting acceleration than younger drivers (M = 2.21 m/s^2, SD = 1.56 m/s^2), a significant difference of 0.61 s (95% CI, 0.17 s to 1.04 s).

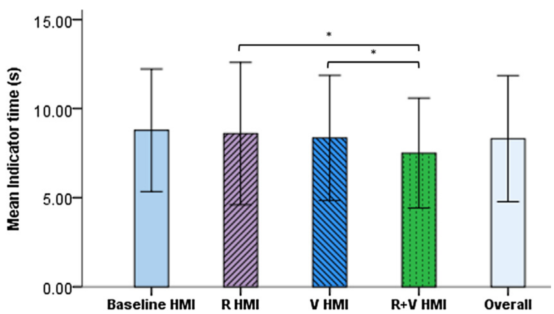

Fig. 11. Mean indicator time for different HMI conditions (error bars = ±1 SD, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

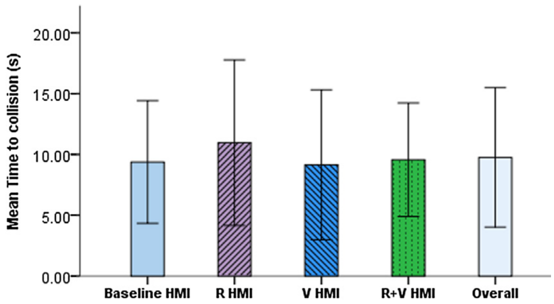

Fig. 12. TTCs for different HMI conditions (error bars = ±1 SD, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

3.9. Steering wheel angle

Fig. 14 shows the steering wheel angles that participants had during taking over control from the HAV in the four types of HMI situations. Overall, participants showed the greatest steering wheel angle when using R HMI. Also, participants' steering wheel angle was higher when using Baseline HMI and R HMI compared to when using V HMI and R + V HMI. And V HMI and R + V resulted in similar steering wheel angles. A mixed factorial ANOVA with Huynh-Feldt correction showed that the HMI resulted in significant effect in the steering wheel angle (Table 6). Post-hoc test using the Bonferroni correction revealed significant difference between:

- R HMI (M = 8.52 degrees, SD = 5.72 degrees) to V HMI (M = 6.26 degrees, SD = 4.18 degrees), a significant decline of 2.25 degrees (95% CI, 0.36 degrees and 4.14 degrees), p = 0.011.
- R HMI to R + V HMI (M = 6.56 degrees, SD = 3.57degrees), a significant decline of 1.96 degrees (95% CI, 0.52 degrees to 3.41 degrees), p = 0.003.

In addition, age also showed a significant effect on steering wheel angle, with older drivers (M = 8.83 degrees, SD = 5.50 degrees) showing significantly greater steering wheel angles than the younger drivers (M = 5.41 degrees, SD = 2.85 degrees); a significant difference of 3.43 degrees (95% CI, 2.17 degrees to 4.67 degrees).

3.10. Workload

Fig. 15 shows that overall workload was perceived to be highest when using R HMI. A mixed factorial ANOVA with Huynh-Feldt correction showed that HMI had a significant effect on the perceived workload (Table 6). A post-hoc test using the Bonferroni correction revealed significant difference between:

- Baseline HMI (M = 28.27, SD = 9.53) to R HMI (M = 30.24, SD = 6.87), a significant increase of 2.05 (95% CI, 0.49 to 3.63), p = 0.004.
- Baseline HMI to R + V HMI (M = 25.14, SD = 6.07), a significant decrease of 3.05 (95% CI, 1.14 to 4.96), p < 0.001.
- R HMI to V HMI (M = 26.59, SD = 5.70); a significant decrease of 3.67 (95% CI, 2.04 to 5.29), p < 0.001.
- R HMI to R + V HMI, a significant decrease of 5.10 (95% CI, 3.64 to 6.56), p < 0.001.

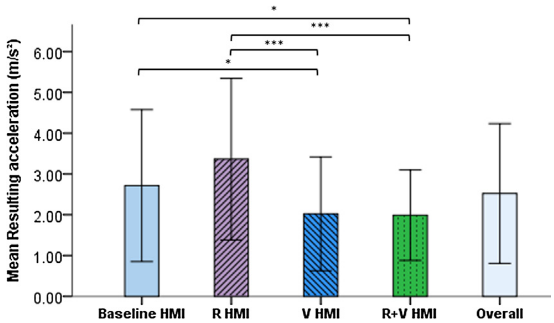

Fig. 13. Resulting acceleration for different HMI conditions (error bars = ±1 SD, * = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$).

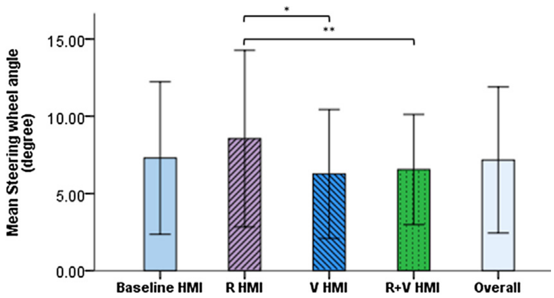

Fig. 14. Steering wheel angle for different HMI conditions (error bars = ±1 SD, * = $p \le 0.05$, ** = $p \le 0.01$, *** = $p \le 0.001$).

Age also had a significant effect on the workload score, with older drivers (M = 29.02, SD = 6.78) perceiving significantly higher workload than younger drivers (M = 26.02, SD = 7.75); a significant difference of 3.00 (95% CI, 0.22 to 5.79). In addition, there was a significant interaction between age and HMI type on the workload score. This interaction indicates that the four types of HMI influenced the workload scores of older and younger drivers differently. For the older drivers, they perceived the highest workload when using the Baseline HMI (M = 31.64, SD = 8.83) then their perceived workload showed a consistent decreasing trend from R HMI (M = 30.87, SD = 6.26), V HMI (M = 27.79, SD = 4.84) and R + V HMI (M = 30.87, SD = 6.26). For the younger drivers, their perceived workload exhibited a sharp increase from the Baseline HMI (M = 24.71, SD = 9.03) to the R HMI (M = 29.58, SD = 7.48), and then it showed a trend of a consistent decline from R HMI to V HMI (M = 25.33, SD = 6.31) and R + V HMI (M = 24.46, SD = 7.10).

3.11. Attitude towards HMIs

Participants' attitudes towards the four types of HMI were examined using a 7-Likert scale questionnaire. As Table 7 indicates, for the Baseline HMI, 51.3% of the participants showed positive attitudes. This percentage becomes much larger for the R HMI (82.9%). Then it continues to increase to 93.4% for the V HMI and 98.7% for the R + V HMI.

The results of a Friedman test show that there was a statistically significant difference in participants' attitudes towards the different types of HMI, $\chi 2$ (3) = 108.746, $p < 0.001$. The post-hoc Wilcoxon signed-rank test with Bonferroni adjustment showed that participants' attitudes towards the R HMI (Mdn = 5, $p < 0.001$), V HMI (Mdn = 6, $p < 0.001$) and R + V HMI (Mdn = 6.5, $p < 0.001$) were statistically significantly different compared to the Baseline HMI (Mdn = 5). Also, participants' attitudes toward the V HMI (Mdn = 6, $p < 0.001$) and R + V HMI (Mdn = 6.5, $p < 0.001$) were statistically significantly more positive compared to the R HMI (Mdn = 5). Moreover, the attitudes towards R + V HMI (Mdn = 6.5, $p < 0.001$) were statistically significantly more positive than the attitudes towards V HMI (Mdn = 6).

Moreover to investigate age differences in attitudes towards the four types of HMI, several Mann-Whitney U tests were administered. For the Baseline HMI, older drivers showed lower medians in their attitudes (Mdn = 4) than the younger drivers (Mdn = 5), but the difference was not significant, U = 629.000, p = 0.323. For the R HMI, older drivers had a higher median (Mdn = 6) attitudes than younger drivers (Mdn = 5); however, the difference was again not statistically significant, U = 668.500, p = 0.560. For the V HMI, younger and older drivers exhibited the same median (Mdn = 6) attitude and so there was no significant age effect on attitudes, U = 680.500, p = 0.652.Similarly, for R + V HMI, despite older drivers having a higher median score (Mdn = 7) in their attitudes than younger drivers (Mdn = 6), the difference was not significant, U = 640.000, p = 0.354.

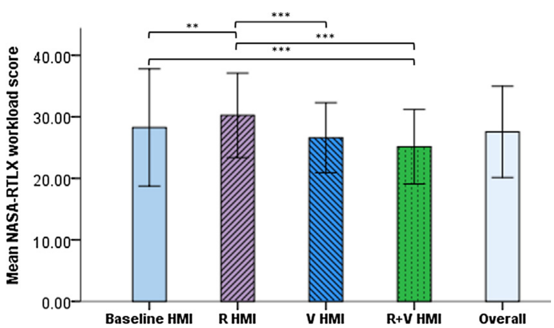

Fig. 15. NASA-RTLX workload for different HMI conditions (error bars = ±1 SD, * = $p \le 0.05$, ** = $p \le 0.01$, *** = $p \le 0.001$).

Table 7
Summary of participants' attitudes towards different types of HMI in the HAV.

"I would like to have the following HMI in my HAV"	Median	Mode	% Positive attitude
Baseline HMI	5	5	51.3
R HMI	5	5	82.9
V HMI	6	6	93.4
R + V HMI	6.5	7	98.7

Note: Positive attitude refers to the drivers' answering 5, 6 or 7 on the scale.

4. Discussion

This study has investigated the effects of three HMI types and age on drivers' performance, workload and attitudes when retaking driving control from a HAV operating in automated driving mode.

4.1. Effect of HMI on takeover performance

The takeover performance in HAV was quantified by the time aspects of takeover and takeover quality. The time aspects of takeover consist of reaction time, takeover time and indicator time. These variables were used to measure how quickly the participants responded to the HAV system's takeover request, when they executed the first conscious input to the vehicle and made the decision to conduct the lane change to avoid the stationary vehicle ahead on the road during the process of taking over manual driving control from the HAV.

For the reaction time, the results show that participants reacted to the takeover request significantly faster when using the V HMI and R + V HMI compared to the Baseline HMI and R HMI. The reaction time of R HMI was also slightly faster than that of the Baseline HMI, but the difference was not statistically significant. Regarding to the takeover time, the results revealed that the time that participants took to generate the first active input to the vehicle was significantly faster in the R + V HMI situation compared to the R HMI situation. Although there was no statistically significant differences between the takeover times for other HMI situations, the data seems to indicate some potential differences. For instance, participants generated the first active input to the vehicle much more quickly when using the V HMI (M = 3.40 s, SD = 1.48 s) and R + V HMI (M = 3.26, SD = 1.30 s) compared to when using the Baseline HMI (M = 3.79 s, SD = 1.47 s) and R HMI (M = 3.75 s, SD = 1.60 s).

These findings suggest that, when using the V HMI and R + V HMI, disengaged drivers might feel more confident and reacted quicker, so that both reaction time to the takeover request and time to execute the first active input to the vehicle were shortened. This could be explained as that in the current research drivers who were fully concentrated on reading with little awareness of what was happening driving during the automated driving period, little or no interaction between the operator and the HAV system could substantially reduce the human's situation awareness. As an result of this, when the system requires the operators to reassume control, the time taken by the operators to shift their focus, understand what is going on, recognise the problems and be ready for execution can be much longer than when they are constantly involved in the system's control loop (Endsley & Kiris, 1995; Kaber & Endsley, 1997). Providing the indications of the current mode or status of the system, which incorporated in both V HMI and R + V HMI, is an understandable way of enhancing operators' situation awareness (Endsley, 1995b). Audible information on vehicle status, including automation mode followed by the speed prior to the takeover request, may have enhanced the participants' perception of the relevant information and elements in the environment (Level 1 situation awareness) and made the understanding of the current situation (Level 2 situation awareness) easier and enabled a 'projection' (Level 3 situation awareness) of the likely consequence (Endsley, 1995b; Stanton, Chambers, & Piggott, 2001). The enhanced situation awareness may have compensated for the negative effect of the 'out-of-the-loop' issue to some extent and thus resulted in faster reaction times and takeover times among participants. The outcomes of the current research are in line with an earlier study by Seppelt and Lee (2007), who found that providing continuous information about the functionality of the in-vehicle system potentially enhanced the driver's situation awareness.

In terms of indicator time, the results show that the time that the participants took to make the decision concerning lane change was significantly faster in the R + V HMI situation than with R HMI and V HMI. Although no significant difference was found between other HMI situations, the data suggests that participants' indicator time was similar among the Baseline HMI, R HMI and V HMI situations. However, the indicator time when using R + V HMI was much faster than when using the Baseline HMI, and the difference showed a certain trend towards statistically significant ($p = 0.087$). These results provide an indication that, when the information concerning vehicle status and reasons for takeover are presented to participants separately, such as in the R HMI and V HMI, their effects on speeding up indicator time are not obvious. However, when combining these two types of information together in the HMI of the HAV, such as in R + V HMI, this may have the potential to make the indicator time faster, which reflects a more rapid decision about the lane change to overcome the stationary car ahead among the participants after taking back control from the HAV. Thus, it can be suggested that providing the information of the critical cues has the potential to enhance the operators' situation awareness during critical events (Endsley, 1995b). In the context of the takeover control process in the HAV, the drivers need to firstly take back control of the vehicle and then respond to whatever critical events lie ahead of them. Thus, despite verbally informing them of the reasons for takeover may have some effect on helping them to better understand the critical event (stationary car ahead), they may have spent extra time while obtaining the vehicle control due to the ‘out-of-the-loop’ performance decrement in the HAV (Endsley & Kiris, 1995). When verbally informing the drivers of the vehicle status together with the reasons for being requested for intervention in the takeover request, this may have a more comprehensive effect on enhancing participants’ perceptions and comprehension of the tasks of taking over control of the vehicle as well as overtaking the stationary car ahead, and therefore their enhanced situation awareness may have a substantial contribution in speeding up the time that participants take to make the decision to change lane to overtake the stationary vehicle.

In terms of the effect of different types of HMI on takeover quality, the results provide a clear indication that solely providing participants with the information about HAV status (V HMI) as well as providing information of HAV status together with the reasons for takeover (R + V HMI) yielded a smaller resulting acceleration and steering wheel angle among the participants compared to the Baseline HMI and R HMI. This reflects that both V and R + V HMIs have similarly positive effects on longitudinal and lateral input to the vehicle. These findings could be possibly explained as that tasks of operating the longitudinal and lateral control of the vehicle essentially require the perception and understanding of the driving environment (Matthews, Bryant, Webb, & Harbluk, 2001). Providing information about the HAV status (automation mode and speed) before the takeover request may have enhanced drivers’ perception (Level 1 situation awareness) and comprehension (Level 2 situation awareness) of the takeover task (Endsley, 1995b) and thus lead to more stable longitudinal and lateral input to the vehicle among the participants. From the drivers’ attentional perspective, this finding could be explained if we consider that providing information of HAV status to the drivers before a takeover request may have helped them to maintain their attention capacity close to the optimal levels (Young & Stanton, 2002b; Young & Stanton, 2002a), which would improve the performance of operators of the automation systems(Young & Stanton, 2002b).

In addition, the results did not yield any significant differences in the measurements of takeover quality in the R HMI and the Baseline HMI situations. However, the data showed that R HMI gave rise to the strongest resulting acceleration and the largest steering wheel angle among the four types of HMI. This may provide an indication that solely providing the participants with the reasons for takeover in the request, such as in the R HMI, results in sharper and less stable longitudinal and lateral input to the vehicle, and therefore worse takeover quality among the participants. A possible explanation of this could be that solely warning drivers about the stationary car ahead in the takeover request may have panicked the participants and negatively affected their takeover quality. The impact of R HMI will be discussed more together with its impact on workload in the next section.

4.2. Effect of HMI on workload and attitudes

The results for participants’ perceived workload and subjective attitudes suggest that the R + V HMI approach of providing information about HAV status before the takeover request together with the reason for takeover during the takeover request leads to the lowest workload and highest acceptance. Considering this together with the results of takeover performance, a clear indication is provided that the R + V HMI design concept is beneficial to drivers of the HAV. The R + V HMI concept may have helped to maintain drivers’ workload demand to an optimizing level and therefore improved their performance in reassuming control of the vehicle (Stanton & Young, 1998). Moreover, this finding corresponds with previous findings which suggest that inadequate feedback about the status of an automation system causes difficulties among human operators (Norman, 1990) and drivers of automated vehicles should be informed about the current mode of the system in order to avoid confusion (Debernard, Chauvin, Pokam, & Langlois, 2016). In addition, results show the R HMI concept resulted in the highest perceived workload among the four HMI concepts. When considering this together with the results that the R HMI also led to worse takeover quality, a possible explanation could be that when solely providing the reasons for takeover in the takeover request, the drivers had to assemble and process more information within the limited time available for takeover (a maximum 20 s in this research). This suddenly increased demand may have exceeded the drivers’ attentional capacity and caused a mental overload which could lead to deteriorating driving performance (Young & Stanton, 2002a). Besides, when drivers were suddenly informed about the stationary vehicle ahead of them in the takeover request, they may have become stressed, which may worsen the negative effect of mental overload on performance (Matthews & Desmond, 1995).

4.3. Effect of age on takeover performance, workload and attitudes

In terms of the influence of age on the time aspects of takeover, the results reveal that older drivers exhibited significantly longer reaction times and indicator times compared to the younger drivers. These findings correspond to the findings by previous studies (Houx & Jolles, 1993; Dykiert, Der, & Deary, 2012; Li et al., 2018; Li et al., 2019a). Again, these findings could be possibly explained in terms of a number of age-related functional changes, involving impairments in visual and aural senses, cognitive abilities, and longer reaction times as well as deteriorating psychomotor abilities which may have resulted in delaying the time taken to switch to the manual driving position and generating the turn signal indicator for the lane change among the older drivers compared to the younger drivers when resuming control from the HAV (Stelmach & Goggin, 1988; Brouwer, Waterink, Van Wolffelaar, & Rothengatter, 1991; Attebo, Mitchell, & Smith, 1996; Helzner et al., 2005; Myerson, Robertson, & Hale, 2007; Pollatsek, Romoser, & Fisher, 2012; Ferreira, Simões, & Marôco, 2013). In addition, results of this study show there were no significant differences in the takeover time of older and younger drivers, which is in accordance with previous research (Körber et al., 2016; Clark & Feng, 2017; Molnar et al., 2017). However, this is in contrast to the findings of the previous two investigations by the authors (Li et al., 2018; Li et al., 2019a). A possible explanation for this could be that the simulated HAV in this chapter incorporated four types of HMIs, whereas the simulated HAV in the previous two investigations only used the baseline HMI. The new types of HMIs may have compensated the age difference in the takeover time to some extent. This results could be explained by the significant interaction effect between age and HMI type on the takeover time, which is discussed in the next section. In terms of the effect of age on the takeover quality, the results show that older drivers generated significantly greater input to the brake and accelerator pedals and had significantly less stable operation of the steering wheel compared to the younger drivers, which is in accordance with the findings previous research (Körber et al., 2016; Clark & Feng, 2017; Li et al., 2018; Li et al., 2019a).

Concerning the age differences in perceived workload, the results show that older drivers (M = 29.02, SD = 6.78) perceived a significantly greater workload than younger drivers (M = 26.02, SD = 7.75) when reassuming control from the HAV. This finding is in accordance with those of previous studies that older drivers perceived significantly higher workload than younger drivers when interacting with advance driver-assistance systems (ADAS) as well as automated vehicles (Kim & Son, 2011; Molnar et al., 2017). Regarding the effect of age on subjective attitudes towards the HMIs of the HAV, the results show that older and younger drivers had similar attitudes towards the HMIs of the HAV, and no significant age differences were found. Considering that the three HMIs tested in this study-R HMI, V HMI and R + V HMI were designed based on older drivers' requirements derived from the findings by Li et al. (2019b), this provides an important evidence supporting the idea of designing in-vehicle technologies for older drivers which may also benefit drivers of all ages (Czaja, Rogers, Fisk, Charness, & Sharit, 2009).

4.4. Interaction effect between HMI and age

The results show a significant interaction effect between age and HMI on participants' reaction time and takeover time, which indicates that older and younger drivers were affected differently by different types of HMIs. For the older drivers, both measurements showed a trend of consistent reduction from using the Baseline HMI, to the R HMI, V HMI and the R + V HMI. However, those for the younger drivers exhibited a trend of increasing time from the Baseline HMI to the R HMI, and then they showed a trend of progressive decline in time when using V HMI and R + V HMI. In addition, the results reveal a significant interaction effect on workload. This shows that the perceived workload of older and younger drivers were affected differently by the four types of HMI. The workload of older drivers showed a trend of consistently sharp decreases from using the Baseline HMI, to the R HMI, V HMI and the R + V HMI. However, for younger drivers, it exhibited a trend of sharply increasing from the Baseline HMI to the R HMI, and then showed a sharp reduction from the R HMI to V HMI. Then they declined slightly from the V HMI to the R + V HMI.

When considering the above results together, there is a clear indication that the R HMI affected older and younger drivers in opposite ways. This finding could be possibly explained by that the fact in this research, after the HAV system initiated a takeover request, drivers have to stop the reading task they were performing and then to perceive and comprehend the situation in order to effectively take over control of the vehicle. However, age-related visual and cognitive functional impairments may negatively affect older drivers' ability of perceiving and understanding the takeover situation. Providing them with information that there is a vehicle ahead in the takeover request may have compensated for any such age-related visual and cognitive impairments, and thus resulted in slightly faster reaction times and takeover times as well as a lower perceived workload. However, for the younger drivers, this same information about the HAV status may just represent an additional distraction and add to the workload, which may have resulted in delayed responses to the takeover request as well as a higher perceived workload.

Generally, these findings provide new evidence to support the hypothesis that older drivers react to HMIs in HAVs in different ways compared to the younger drivers. Therefore, the needs and requirements of both sets of drivers should be carefully considered during the design process of new technologies (Emmerson et al., 2013; Guo et al., 2013; Edwards et al., 2016).

5. Conclusion

This study aimed to investigate the effect of different types of HMI with different levels of information which results in a request for the driver to retake over manual control of a HAV that is currently operating in automatic mode, on the driver's takeover performance, and perceived workload as well as attitudes.

The four types of HMI used in this investigation included one baseline HMI and three HMI concepts (R HMI, V HMI, R + V HMI) which were developed based on two of the older drivers' stated requirements for the human-machine interface of HAV that were identified in a previous study (Li et al., 2019b). This investigation has found that the HMI informing drivers of vehicle status together with the reasons for takeover (R + V HMI) resulted in good takeover performance, lower perceived workload and highly positive attitudes, and it is clearly the most beneficial and optimal HMI approach to the drivers of HAVs. Furthermore, this investigation has found that verbally informing the drivers about the vehicle status, including automation mode and speed, before the takeover request (V HMI) also had a positive effect on takeover performance, workload and attitudes. Specifically, it had a similar positive effect to that of the R + V HMI in terms of reaction time, takeover time, resulting acceleration and steering wheel angle. It led to lower perceived workload than the Baseline HMI and significantly lower workload than the R HMI. It also resulted in significantly higher positive attitudes compared to the Baseline HMI and R HMI. Moreover, this investigation has found that the R HMI affected the older and younger drivers in different ways in terms of reaction time, takeover time and the workload score. Although it reduced reaction time, takeover time and workload compared to the Baseline HMI among the older drivers, it resulted in a rise in all the three parameters among the younger drivers. In addition, for the participants overall, it resulted in the highest resulting acceleration, and steering wheel angle and the largest number of risky takeovers among the four HMIs. Therefore, the R HMI design should be considered with caution and subject to further evaluation.

In addition, this investigation has found significant age differences in drivers' takeover performance and perceived workload. Compared to younger drivers, older drivers took longer to switch back to the manual driving position after receiving the takeover request. They were also slower to take the decision to change lane to overtake the stationary car ahead. Moreover, older drivers were recorded to have harder braking and accelerating patterns, less stable steering control, and more critical and risky takeover, higher perceived workload than among the younger drivers.

This study has several important implications. Firstly, this study is an important example of testing the requirements of older drivers in the context of vehicle automation. The knowledge yielded by this study not only has the potential to improve the safety and comfort of older drivers' interaction with HAVs but also potentially increase their trust, confident and potential acceptance in using automated vehicles, thereby facilitating their adoption of HAVs and ultimately to enhance their mobility, independence and wellbeing. Secondly, the findings of this study provide an important understanding of how to design the HMI of HAV based on the specific requirements of older driver coherent with clear evidence underpinning this knowledge. Thirdly, the study provides additional evidence to support the importance of involving older drivers and fully considering their performance, capabilities and requirements during the design, test and development of the human-machine interaction for automated vehicles, and supporting the idea that designing for older people can benefit people at all ages. Finally, this study has important implications on the safety of HAVs. The findings lead to an emphasis on the need for HAVs to be in communication with an intelligent infrastructure to enable them to have accurate understanding and recognition of the driving environment, so that they can effectively detect system limitations, provide drivers with sufficient time to take over the vehicle control, update drivers with information concerning road and traffic conditions. This adds additional complexity to road vehicle automation with the requirement for vehicle-to-vehicle and vehicle-to-infrastructure communication. Therefore, it is important to build collaboration between the automated vehicle research community and the Cooperative ITS (CITS) research community, in order to fully assess the potential for deployments of CITS and automated systems to deliver a range of safety and operational benefits to drivers, passengers, fleet operators and network operators (Edwards et al., 2018; Li et al., 2019a).

This study has generated important knowledge with regard to HMIs in HAVs and older drivers. This following sections discuss the limitation of this study and propose a number of directions so that the findings of this study could be developed and extended in the future.

This study tested older drivers' requirements towards the human-machine interactions in HAVs (Li et al., 2019b) by evaluating the effectiveness of several HMI design concepts in HAVs. Future research could study and explore the HMI design in HAVs in more depth. To begin with, an important direction is to explore the optimum location of the visual interfaces, which would have important implications for safety, usability and acceptance of HAVs (Stevens et al., 2002; Naujoks et al., 2019). In the current study, the visual information related to the HMIs was projected in the front LCD screen of the driving simulator. In a real HAV, such visual information can be presented by an Augmented Reality Head-Up Display when drivers are manually driving the car or monitoring the driving environment (Stevens et al., 2002; Naujoks et al., 2019). When the drivers are disengaged from driving and the HAV is in automated driving mode, the visual information related to the HMI could be presented via the same display used by drivers to perform the non-driving related activities (Naujoks et al., 2019). Future research could evaluate the effectiveness of these locations of HMIs and investigate their impact on the users' performance when interacting with HAVs.

Secondly, this study has found 'R + V HMI' is the most beneficial approach. This HMI could be modified and enhanced in further design iterations. The second iteration of this HMI could be designed to coordinate with the different non-driving related tasks, which would potentially enhance user comfort of HAVs (Li et al., 2019b; Naujoks et al., 2019). For example, if the HAV is driving normally without encountering any critical situations and the drivers were performing tasks that they would not like to be interrupted frequently, such as napping or watching a movie, the HMI could adjust itself to reduce the frequency of sending routine vehicle status information. It could also be designed to be adaptive to the urgency of the driving situations. In critical situations, such as a system failure requiring immediate takeover, the HMI should adjust itself to prioritise the urgent information (takeover request) and ignore the routine information (vehicle status) to ensure it can promptly and effectively capture the drivers' attention, which would potentially guarantee the safety of HAVs (Stevens et al., 2002; Li et al., 2019b; Naujoks et al., 2019). In addition, the HMI should also use different modes of delivery between routine and critical information, for example, using lower volume notification-style to deliver routine information and higher volume command-style to deliver critical information (Naujoks et al., 2019).

Thirdly, the present study did not assess participants' functional capabilities prior to interacting with the HMIs in HAVs. Future research could explore the impact of drivers' functional abilities, such as visual and hearing abilities, psychomotor abilities, reaction time, and cognitive abilities, on their performance and acceptance when interacting with HMIs in HAVs as well as investigate how the HMI could coordinate with driver monitoring systems to better facilitate drivers' interaction with HAVs (Carsten & Martens, 2019; Louw et al., 2019; Naujoks et al., 2019).

Finally, the findings yielded from this study are based on investigations and experiments conducted on a driving simulator, future research has been planned to modify the design of HMIs and evaluate their compliance with applicable standards, guidelines and best practices using an authentic full-scale HAV in a real-world environment (Stevens et al., 2002; Naujoks et al., 2019).

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Declaration of interest

The authors report no conflicts of interest.

Appendix A. HMI attitude questionnaire

The human–machine interface (HMI) in HAVs refers to the interface that allows you to interact with HAVs, including any information and feedback you receive during automated driving, as well as the takeover request.

Please indicate how much do you agree with the following statement, please put a tick (✔) on the line.

I would like to have this HMI in my HAV.

	1	2	3	4	5	6	7	
Strongly Disagree	____	____	____	____	____	____	____	**Strongly Agree**

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