EMPOWERMENT THROUGH TRUSTED SECURE MOBILITY

FLOURISH WP3 Task 3.1.4b

Literature Review: Human-Machine Interface

UWE Bristol
University of the West of England

Document authors

The authors of this literature review are as follows:

Phillip L. Morgan (UWE-Bristol), Praminda Caleb-Solly (UWE-Bristol and Designability), Alexandra Voinescu (UWE-Bristol), and Craig Williams (UWE-Bristol)

With contributions from: Chris Alford (UWE-Bristol), Graham Parkhurst (UWE-Bristol), and Tony Pipe (Bristol Robotics Laboratory)

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Please address any queries or comments in relation to this document to the lead author:

Dr Phillip L Morgan
Senior Lecturer in Cognitive and Human Factors Psychology
Department of Health and Social Sciences
Faculty of Health and Applied Sciences
The University of the West of England
Frenchay Campus
Coldharbour Lane
Bristol
BS16 1QY
Email: phil.morgan@uwe.ac.uk

Or to the FLOURISH lead on User Needs and Experience:

Dr Chris Alford
Associate Professor in Applied Psychology
Department of Health and Social Sciences
Faculty of Health and Applied Sciences
The University of the West of England
Frenchay Campus
Coldharbour Lane
Bristol
BS16 1QY
Email: chris.alford@uwe.ac.uk

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The FLOURISH Project

The FLOURISH project runs from June 2016 – May 2019 and was developed in response to Innovate UK's *Connected and Autonomous Vehicles Collaboration Research & Development competition*. It sets out to identify innovative solutions that address two distinct but related topics within the connected and autonomous vehicle (CAV) market which will help to realise market readiness of CAVs:

- Customer Interaction focusing on the customers' needs and experience when using the technology; and
- Connectivity focusing on effective data analytics and ensuring that the cyber security and wireless connectivity elements of CAVs are safe by design.

The project has the following principal objectives:

1. Develop an understanding and articulation of user needs and expectations of CAVs in order to maximise the mobility potential they offer.
2. Develop usable adaptive interfaces, performance certification processes, products and services that enable secure, trustworthy and private technology within CAVs.
3. Capitalise on the large volume of data created by CAVs to develop innovative new tools and products.
4. Leverage existing investment in the Bristol City-Region to expand validation and test capabilities in both urban and interurban networked environments and enhance the commercial opportunities this will deliver.

There are there four strands of research in FLOURISH, each contained in a work package (WP). These elements are:

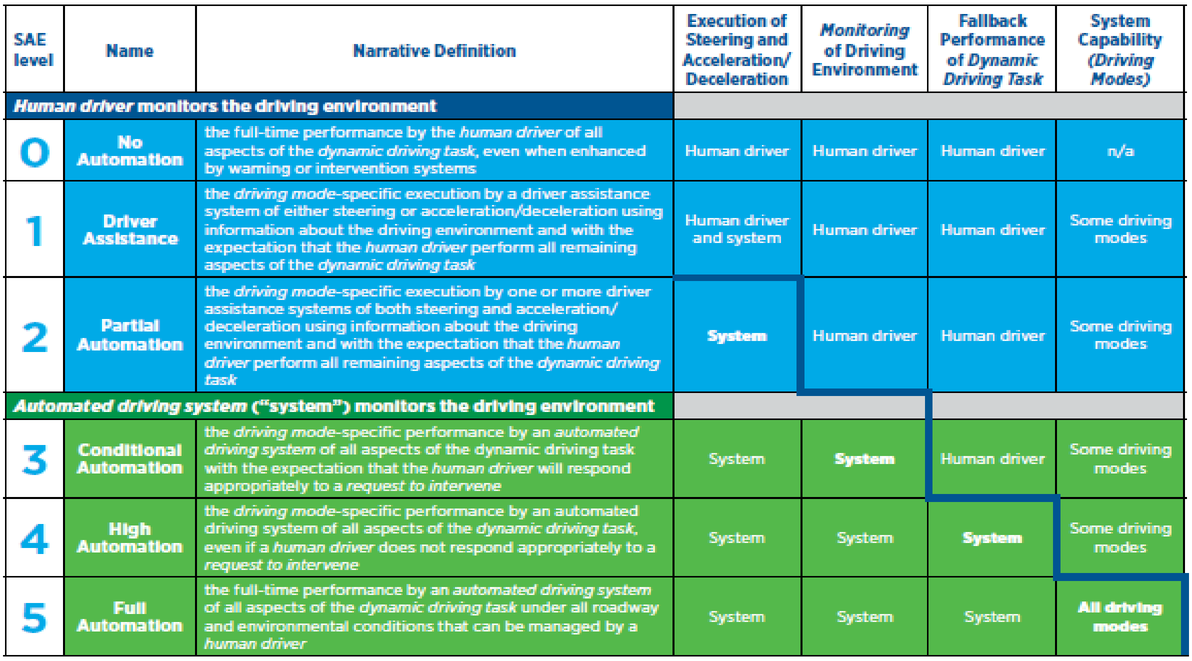
- WP3: User Needs and Experience. Gaining an understanding of customers' needs and experiences when using CAVs. Older adults with ageing-related impairments are seen to be particular beneficiaries of such technology, allowing them to continue to be active contributors to the economy and society. As a consequence, there is a deliberate focus on the needs of this group, hopefully accelerating their ability to become early adopters of CAVs. It is expected that by addressing the needs of this demographic, the knowledge, services and capabilities that will be developed are intended to enable exploitation by all sections of society. The current HMI review forms part of this WP although also informs other WPs.
- WP4: Data Capture, Fusion and Visualisation. This strand of work focuses on how data within the CAV ecosystem will be harnessed and converted into intelligent outputs for use by both the vehicles themselves but also users and third parties. Filtering the vast amounts of data generated within the CAV ecosystem, solutions will be developed to process this data in real time into clear actionable tasks.
- WP5: Secure, Trustworthy and Private Communications. A critical factor for public acceptance and adoption of CAV technology relies on CAV's being secure. The project will undertake simulated and real work tests of communications systems in order to develop products and services for the market, and a performance benchmarking methodology and certification process for CAVs that will be scalable and replicable across the UK and internationally.
- WP6: Scenario Development and Testing of Project Outputs through Real World Trials. Two types of trials will be undertaken – the first type will likely use a LUTZ Pathfinder Pod, and the

second using a traditional car. The Pod based trials will focus on understanding the needs of end users, particularly older adults (linked closely to WP3). The pods will be equipped with a range of sensor technologies capturing data necessary for autonomous driving as well as prototypes of human state monitoring and HMI technologies. The car-based trials will focus on the connectivity between vehicles, infrastructure, the cloud, and network operators (linked closely to WP5).

The Current Review

The major objective of this literature review is to examine the current literature (theoretical as well as empirical) on human-machine interfaces (HMIs) for autonomous vehicles (AV) designed for older adults, including those with undiagnosed mild cognitive impairments and/or physical impairments. The particular focus will be on accessibility, usability, functionality and adaptability issues. Key HMI design principles and recommendations that might inform the design and development of Connected Autonomous Vehicles (CAV) HMIs will be proposed, whilst our research programme will test these and many other principles throughout the FLOURISH project.

In relation to the taxonomy for autonomous vehicles (AV) we will use the one proposed by SAE International[1] (see Figure 1). The current literature review aimed to focus on HMIs for AV Levels 4 and 5, but considered also lower levels of automation due to limited studies and resources that are available for higher levels of autonomous driving.



SAE level	**Name**	**Narrative Definition**	**Execution of Steering and Acceleration/ Deceleration**	***Monitoring* of Driving Environment**	**Fallback Performance of *Dynamic Driving Task***	**System Capability *(Driving Modes)***
***Human driver* monitors the driving environment**						
0	**No Automation**	the full-time performance by the *human driver* of all aspects of the *dynamic driving task*, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	**Driver Assistance**	the *driving mode*-specific execution by a driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	Human driver and system	Human driver	Human driver	Some driving modes
2	**Partial Automation**	the *driving mode*-specific execution by one or more driver assistance systems of both steering and acceleration/ deceleration using information about the driving environment and with the expectation that the *human driver* perform all remaining aspects of the *dynamic driving task*	**System**	Human driver	Human driver	Some driving modes
***Automated driving system* ("system") monitors the driving environment**						
3	**Conditional Automation**	the *driving mode*-specific performance by an *automated driving system* of all aspects of the dynamic driving task with the expectation that the *human driver* will respond appropriately to a *request to intervene*	System	**System**	Human driver	Some driving modes
4	**High Automation**	the *driving mode*-specific performance by an automated driving system of all aspects of the *dynamic driving task*, even if a *human driver* does not respond appropriately to a *request to intervene*	System	System	**System**	Some driving modes
5	**Full Automation**	the full-time performance by an *automated driving system* of all aspects of the *dynamic driving task* under all roadway and environmental conditions that can be managed by a *human driver*	System	System	System	**All driving modes**

Figure 1. SAE International standard J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems. (Copyright © 2014 SAE International).

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[1] SAE International is a global association of engineers and technical experts in the aerospace, automotive and commercial-vehicle industries. The organisation has as a key function the development of 'voluntary consensus' standards in its fields of interest.

Review Process

A number of search terms were used to guide the review with 37 different combinations. Terms included: human machine interface, display design, autonomous vehicle, driverless car, automation, elderly and older adults. The search stage had three stages: (1) using the University of the West of England/UWE-Bristol online library database, (2) using a general scholarly search engine (*Google Scholar*), and, (3) using a general internet search engine (*Google*). The search and shortlisting procedure resulted in 207 records that were reviewed and scored in terms of relevance to the research questions outlined below. A scoring criteria was adopted using a scale ranging from 0 (not relevant) to 5 (very relevant/key reference). Those references rated 3 or above were regarded as very relevant and were included as important references whilst some references rated 1 and 2 are included within the review but have a lower status.

Research Questions

The current FLOURISH systematic literature review aims to answer to five main research questions.

1. What are the current leading HMI design principles that could inform the development of a CAV in-vehicle HMI?
2. What ageing-related impairments should be considered in regards to the usability and accessibility of a CAV in-vehicle HMI?
3. What ageing-related impairments should be considered in regards to the functionality and adaptability of a CAV in-vehicle HMI?
4. What are the key evaluation criteria and approaches when assessing user interaction with in-vehicle CAV HMIs?
5. Which other categories of the population – other than older adults – are likely to benefit from CAVs and what are the design recommendations for in-vehicle HMI design?

1. What are the current leading HMI design principles that could inform the development of a CAV in-vehicle HMI?

Human-machine interfaces and human-computer interaction: A brief history

Human-computer interaction/HCI involves observing and measuring how humans interact with computers and informing the design of future interfaces (Card, Moran, & Newell, 1980). Cognitive psychology, neuroscience, human factors, engineering, computer science, and artificial intelligence are amongst the key areas that offer insights into HCI evaluation, design and development.

Human-machine interface/HMI describes the interface between a human user(s) and computer system(s). Examples include computer monitors, tablet devices and mobile/cell telephones. Historically speaking, some of the early HMIs violated many contemporary interface design principles such as ‘providing too many features to perform the same function or similar functions’ (e.g., ‘find’, ‘search’, ‘locate’). Some also contained features that did not seem to represent the functions that they served to perform (e.g. filing cabinet icon that could involve an ‘open’ or ‘save’ function). However, game changing HCI/HMI frameworks emerged such as those by Shneiderman (1987), Nielsen (1994), and Wickens et al. (2004) to better guide the design of HMIs and improve HCI by putting human user experiences, needs and capabilities at the heart of the design process.

For example, principles from Shneiderman's (1987) Golden Rule framework include:

- Strive for consistency (e.g., identical terminology for menus, prompts and help options);
- Enable frequent users to use shortcuts (i.e., reduce the number of interactions required to perform an action when it is something that the user engages with on a regular basis);
- Offer informative feedback (with the degree of feedback varying in terms of the frequency of the action and the severity of the outcome);
- Design dialogues to yield closure (e.g., provide feedback when task completed);
- Offer simple error handling (e.g., serious mistakes can be avoided by requiring the user to go through 'checking steps' that do not simply involve clicking the same button multiple times);
- Permit easy reversal of actions (e.g., undo and reverse that should reduce anxiety about executing an action in the first place);
- Permit internal locus of control (e.g., a system that regularly requires a user response may reduce locus of control unless commands are designed to remind users to perform important actions at the most appropriate time);
- Reduce short-term memory load (e.g., HMIs should be as simple as possible in terms of information load, not contain multiple display pages unless necessary, and have reduced window-motion frequency).

Nielsen (1994) took into consideration factors such as the importance of the match between the system and the real world, establishing and adhering to conventions and standards, maintaining visibility of system status, and simplicity and aesthetic integrity. Together with other interface design principles and frameworks (e.g., Gould & Lewis, 1985; Heckel, 1984, Mayhew, 1992), Nielsen (1994) and Shneiderman & Plaisant (2010) continue to lead the way in terms of informing 'effective' generic interface design principles for the majority of knowledgeable to expert frequent HMI users.

Wickens, Lee, Liu, & Becker (2004) developed another set of principles with a key focus on human cognitive capabilities and limitations. These include:

- Perception (e.g., make displays legible and/or audible, maximise bottom-up perceptual features unless top-down is processing important such as when human intervention is required);
- Attention (e.g., minimise the cost of accessing important information, minimise features that compete for the same modality due to limited resources);
- Memory (e.g., replace memory load by including key 'to-be-remembered' information within the display and/or make it easily accessible);
- Mental models (e.g., try to achieve pictorial realism between display item and item in real world, ensure that parts move/flow in a logical manner);
- Situation awareness - SA (e.g., supporting users to predict future events and reminding them of past events, through understanding of the current situation).

Principles to guide the design of in-vehicle HMIs

We discovered that many general leading principles derived over the past 30 years or so, including some of those described above, can be tentatively applied to the design of in-vehicle HMIs. Some can be directly applied (e.g., Green, Levison, Paelke, & Serafin, 1995) to areas such as: manual controls; spoken input and dialog guidelines; guidelines for visual and auditory displays, and; traffic information guidelines. These and other principles will be discussed in more detail below. In terms of specific principles, recent work by Weir (2010) stresses that in-vehicle interfaces should be designed to meet requirements related to key factors such as usability, driver comfort, and acceptable levels of attentional demands in dual task conditions. It is also important to try and strive for optimal functionality and usability in terms of comfort (e.g., temperature adjustments), entertainment (e.g., music, news), telematics (e.g., network communications and updates), and driver support (e.g., updates regarding driving conditions).

Another key factor was noted at this stage of the review. Vehicle technology is developing rapidly with a rise in different types of display-based systems (e.g., heads-up displays) – as well as the development of more sophisticated automated systems that can control functions and tasks that would have in the past been controlled by the driver (e.g. maintaining constant speed, parking, staying in lane). Thus, many older HMI design principles might need to be modified to meet contemporary in-vehicle "challenges" related to partially, highly and fully autonomous vehicles.

Principles to guide the design of in-vehicle HMIs for automated vehicles

Work in this area has spanned the past two decades although a key surge in research has appeared over the past 10-years or so. Due to technology advancement in road vehicles, many display principles for vehicles with minimal automated functions (e.g., Level 1-2) might not apply to vehicles with higher levels (e.g., Levels 3-5) of automation (Häuslschmid, Bengler, & Olaverri-Monreal, 2013), including those that allow 'hand off controls' and/or 'eyes off road' and/or 'mind off driving'.

Over a decade ago, Cuevas (2004) suggested that the four most important factors to consider include within the design of HMIs for vehicles with high levels of autonomy include:

- Ethnographic/anthromorphic qualities: e.g., attributing human qualities to automated system displays and functions;
- Cognitive factors: e.g., looking to theories and models of perception, attention, memory and mental models;
- Predictive modelling: e.g., step-by-step modelling of human interactions with new interfaces informed by established models and architectures);
- Empirical testing: i.e., the most effective systems are likely to be those developed through testing with human participants and ideally target end-user groups.

More recent work in this area picks-up on the HMI design issues of information overload (Jämsä & Kaartinen, 2015) and situation awareness/SA (Baxter, Besnard, & Riley, 2007). Essentially, '…design needs to focus on communicating the information needs of drivers in order to give them the best chance of behaving appropriately for the situation' (Walker, Stanton, & Salmon, 2015, p. 143) as well as communicating the limits of the system in a dynamic ongoing (not static) manner (Seppelt & Lee, 2007).

Examples of recent activity in the area of HMI design for automated vehicles are adaptive cruise control (ACC), parking assistance and lane keeping assistance. These tend to be known as *Automation Displays* (Walker, Stanton, & Salmon, 2015). For example, one study conducted by Stanton, Dunoyer, and Leatherland (2011) compared three different methods of displaying 'stop and go' (S&G) ACC information to drivers under a range of driving conditions. The methods involved: a standard static icon (vehicle ahead icon, distance lines and arrow), a flashing icon (same as static but changed colour when getting too close to vehicle ahead), and a radar display (displaying distance ahead and position on road information). Whilst icon-based interfaces were simple, they did not seem to contain enough information to support better driver SA whereas the radar display was complex but perhaps provided too much information that put strain upon driver workload. In another example from the aviation domain, Waldron, Patrick, Morgan, and King (2007) also found that complex radar displays were more effective than simple icon-based displays in terms of supporting situation awareness.

Overall, there is little in the way of research on HMI design principles for AVs and CAVs in comparison to the wealth of research and literature concerning general HMI design principles that *could* inform the development of in-vehicle CAV HMIs. Nevertheless, some of the general HMI principles should prove fruitful for informing the design of early generation HMIs for CAVS. Whilst there has been a recent surge in work involving HMIs to support partial autonomous functions (e.g., Levels 1 and 2) such as ACC and S&G with further emerging principles that can guide the design of HMIs for integration into connected fully autonomous connected vehicles, there is far less on HMIs designed for Level 3 and 4 autonomous vehicles. In general, we found a dearth in literature concerning HMI design for fully autonomous ‘Level 5’ vehicles thus further highlighting the importance of the work being conducted through the current FLOURISH CAV research project and other projects that are beginning to consider fully autonomous CAVs.

2. What ageing-related impairments should be considered in regards to the usability and accessibility of a CAV in-vehicle HMI?

Ageing tends to be associated with a series of psychological, physiological and mobility impairments (Deary, 2009; Freedman, Martin, & Schoeni, 2002; Glisky, 2007). Ageing often relates to a decline in physical mobility and sensory function (e.g., vision and hearing). Cognitive ageing refers to a decline of cognitive processes (e.g. perception, attention, and memory) and it appears in normal and pathological ageing (Deary, 2009).

Interfaces intended to be used by older adults with different needs and abilities should match usability requirements of this specific population (Charness & Boot, 2009; Fisk, Rogers, Charness, Czaja & Sharit, 2009). In a broad sense (and in line with recommendations from e.g., Nielsen, 1994) usability refers to:

- Learnability: design interfaces to be easy to learn and quickly implemented;
- Efficiency: design interfaces to allow for maximum productivity;
- Memorability: design interfaces with information that is easy to remember with minimal learning and memory load requirements;
- Errors: design interfaces to minimise error rates, and when errors do occur; ensure that they are not catastrophic;
- Satisfaction: Design interfaces that encourage and support subjective satisfaction with the system.

With these high-level principles in mind, we need to consider them in light of cognitive ageing. Attention is a cognitive function that is quite prone to age-associated impairment in terms of e.g., maintaining focus on a stimuli and/or switching or dividing focus between stimuli. A number of design recommendations have been proposed to increase older adults’ usability of a system whilst aiming to alleviate some of the implications of age related decline in attention (e.g., Czaja & Lee, 2009; Farage, Miller, Ajayi & Hutchins, 2012; Zaphiris, Kurniawan & Ghiawadwala, 2007). These include:

- Use simple displays;
- Important and relevant information should be highlighted differently;
- Minimise the amount of screen clutter;
- Minimise the number and frequency of distractor stimuli, especially when it is not important to the task(s) at hand.

Working memory is another cognitive function described as the ability of the cognitive system to actively retain and manipulate information from the environment in a flexible way over relatively short periods of time not usually greater that 30-45 seconds (e.g., Glisky, 2007; Bizon, Foster, Alexander, & Glisky, 2012). To overcome age-associated decreases in working memory function, recommendations for HMI design include the following principles (e.g., Farage et al., 2012; Mulvenna et al., 2011; Sharit, Czaja, Nair & Lee, 2003; Zaphiris et al, 2007):

- Avoid complex or long instructions to avoid memory/information overload;
- Use graphical aids to support tasks (especially those that are complex);
- Label items (especially those that are complex) clearly;
- Use familiar conceptual models and/or metaphors (e.g. red for 'stop' and green for 'go').

One of the most documented cognitive process prone to the effects of cognitive ageing is long-term memory (e.g., Farage et al., 2012; Fisk et al., 2009; Glisky, 2007; Spencer, & Raz, 1995). Long-term memory is often thought of as a system or store capable of holding memories permanently such that they are available (not necessarily easily accessible) for future activation and retrieval. Principles for effective HMI adaptation to support possible long-term memory issues include:

- Use simple, minimal and intuitive steps in order to perform tasks;
- Allow a sufficient amount of practice delegated to learn the procedure(s);
- Avoid using time based instructions (e.g., perform x in 2 minutes) and instead use event based instructions with a context specific memory cue(s).

Also, as people grow older, sensory changes may occur. Visual and auditory perception impairments, as well as mobility and balance issues tend to appear in normal ageing (Dickinson, Arnott, & Prior, 2007; Lee, & Scudds, 2003; West et al., 1997). For example, visual impairments tend to increase rapidly with advancing age.

There is a vast amount of previous work on HMI design recommendations taking into account sensory impairments (e.g., Echt & Morrell, 2002; Farage et al., 2012; Hawthorn, 2000; Morrell & Echt, 1997; Kosnik, Winslow, Kline, Rasinski & Sekuler, 1988; Rubin, Roche, Prasada-Rao, & Fried, 1994; Watson & Maylor, 2002; West et al., 1997). Example sensory related principles include:

- Where possible, use large screens with large buttons (approximately 15-20 mm minimum);
- Make information clearly visible using size, colour and contrast features;
- Space buttons at a distance of at least 3.17 mm and up to 12.7 mm;
- Use warm colours and matte surfaces;
- Use static (not moving/dynamic) text presentation formats.

Hearing loss is another common condition reported among older populations, again with much associated research related work leading to HMI design principles (e.g., Archer, Head, Wollersheim & Yuan, 1996; Fisk et al., 2009; Gordon-Salant, 2005; Pak & McLaughlin, 2010; Strawbridge, Wallhagen, Shema, & Kaplan, 2000; Zajicek & Morrissey, 2001). Example principles include:

- Sound signals should be at least 60dB;
- Discriminable sounds (e.g., pitch) should have a frequency range of between 500-1000Hz;

- The voice of a system should not be robotic or synthetic;
- Messages, particularly those providing instructions, should be short and simple with visual text displayed alongside an auditory voice.

Some older adults also have difficulties adapting to different interfaces. Cognitive and sensory decline, the absence of prior knowledge of computers, and/or reduced computer skills can negatively affect their interaction with technology. To support individuals with such requirements, Darejeh and Singh (2013) suggest principles such as:

- Reduce terminology;
- Present clear and simple navigation paths;
- Include descriptive text and guidelines for tools.

Input and output devices designed for older adults

Input devices are mechanisms that help users to communicate their actions or intentions to a technology system. The typical example of an input system is the standard keyboard or touchscreen button. Output devices are mechanisms that communicate with the users. An example of output device is the voice from a navigation system that communicates directions (e.g., Fisk et al. 2009).

Two basic recommendations for designing input and output devices for older adults are minimising steps and maintaining consistency (Fisk et al., 2009). Fisk et al. (2009) also recommend provision of training in device-use to improve general and device specific computer skills.

General input and output devices recommendations for older adults (e.g., Findlater et al., 2013; Fisk et al. 2009; Gao & Sun, 2015; Holzinger et al., 2002) include:

- Use touchscreen devices with large buttons;
- Minimise the need for screen scrolling;
- Avoid long menus with multiple submenus;
- Use multimodal feedback.

HMI physical usability/accessibility requirements for older adults with physical impairments

Physical usability requirements for older adults often arise due to age-related changes in motor control, which can affect fine motor movement and coordination (Charness & Boot, 2009). To improve accessibility to a HMI amongst older adults (e.g., if unable to comfortably reach an interface), which in turn would impede its usability, the following recommendations have been made (e.g., Aslan et al., 2008; Farage et al., 2007; Page, 2014; Zaphiris, Kurniawan & Ghiawadwala, 2007):

- Haptic displays should ideally involve touchscreen devices; although ideally not for use by people with visual impairment;
- Avoid tasks that require double-click actions and reduce tasks that require dragging;
- Use horizontal scrolling for shorter scrolling tasks and vertical scrolling for longer scrolling tasks;
- Use light pens for touchscreen interaction;
- Provide grip balustrades or handles to support users to keep their balance whilst in a dynamic situation.

HMI physical usability/accessibility requirements for driving age adults with physical impairments

Generally, users with motor impairments can have difficulties in using some interfaces and software applications. Therefore, the following recommendations have been made by researchers including Darejeh and Singh (2013), Dieudonné et al. (2003), Fink, Kobsa, and Nill (1998), Hwang et al. (2004), and, Trewin & Pain (1999):

- Avoid pointing and dragging tasks;
- Use tasks that require less physical movement;
- Limit difficult or long successive actions;
- Reduce required movement of the mouse pointer;
- Offer a wide range of action buttons;
- Offer a wide range of different access points within the interface.

This section of the review has highlighted key ageing-related impairments that should be considered in regards to the usability and accessibility of a CAV in-vehicle HMI ranging from physical, sensory and cognitive needs. Some are quite intuitive (e.g., design HMIs that can be used using auditory and physical/visual based responses for those with varying degrees of auditory and/or visual impairment) whereas others tend to be based on minimal requirements to ensure that a HMI is accessible and usable (including screen and button sizes and the intensity of sound and voice commands). It is also clear that adaptability is a key factor when designing HMIs for older adults with individuals likely to have a very different set of physical, sensory and mobility (including accessibility) needs and requirements where bespoke adaptable systems are likely to offer the greatest level of usability. The issue of adaptability also features within the next section of the review.

3. What ageing-related impairments should be considered in regards to the functionality and adaptability of a CAV in-vehicle HMI?

Functionality

Age-related impairments can result in older-adults experiencing a series of driving related problems. Availability of some functions might increase the usability and acceptance of an in-vehicle CAV HMI and aid a positive user-experience for such individuals. Several in-vehicle functions that maintain and enhance safe mobility have already been developed (with some undergoing redevelopment) such as: navigation aids (e.g., route guidance), visual aids (e.g., night vision enhancement), attentional and cognitive aids (e.g., distraction-management system), and crash avoidant aids (e.g., collision warnings).

For CAV in-vehicle technology, in-vehicle functions can increase safety because they provide the user with valid and reliable driving information. As recommended by a synthesis of work by several authors (e.g., Eisses, 2011; Emmerson, Guo, Blythe, Namdeo, & Edwards, 2013; May, Ross & Osman, 2005; Pauzie, 2003) effective in-vehicle functions should, for example:

- Use a step-by-step route guidance generated by a navigational system;
- Provide information on vehicle speed and journey time;
- Remove complex interfaces and integrate traditional navigation methods (e.g., road atlas);

- Use landmark information alongside a step-by-step navigation instruction.

Other functions that might provide a positive experience and keep users engaged with the system have been recommended by a number of researchers (e.g., Arnaout & Bowling, 2014; Bekiaris, Panou, & Touliou, 2013; Eby, Molnar, Liang Zhang, Zanier & Lidia, 2006; Iulian & Leonte; 2014; Kramer, Cassavaugh, Horrey, Becic & Mayhugh, 2007; McMellon & Schiffman, 2002; Reimer, 2014; Reimer, Mehler, Pohlmeyer, Coughlin, & Dusek, 2006; Xie, Watkins, Golbeck & Huang, 2012). Example principles include:

- Night vision enhancement (NVE) function;
- Forward collision warnings (FCW);
- “Stop and Go Adaptive Cruise Control” (S&G ACC);
- HMI health monitoring functions (e.g. sensors that monitor heart rate, blood pressure, and blood oxygen levels) that provide feedback regarding emergency situations;
- Infotainment systems providing e.g., news updates.

Adaptability

Interface adaptability refers to designing interfaces that adjust to the user’s individual needs. Some interfaces are now becoming more adaptable (e.g., Alvarez-Cortes, Zayas-Perez, Zarate-Silva, & Uresti, 2007; Gonzalez-Rodriguez, Manrubia, Vidau, & Gonzalez-Gallego, 2009; Kurschl, Augstein, Burger, & Pointner, 2014). Designing accessible interfaces and interaction paradigms that correspond to specific needs must also take into consideration that as an individual’s ageing-related impairments change, the system should lend itself to being easily adapted to ensure continued usability. An effective adaptation process takes into account intermediate levels of adaptation based on the type of task (e.g., routine vs non-routine), level of task difficulty (e.g., complex vs simple), and users (e.g., younger vs older adults) (Lavie & Meyer, 2010).

To support adaptability and personalisation, the system needs to have information regarding the user’s ability and limitations which can be captured in a user model and/or through use of a reliable and valid set of tests and measures of factors (see Browne, Norman, & Riches, 2016; Mejía et al., 2012). These include: cognitive ability (e.g., mental processing speed, attention, working memory), perceptual abilities (e.g., vision, hearing), and physical abilities.

General recommendations for adaptability have been proposed by many researchers (e.g., Chung, Lee, & Jeong, 2011; Ferreira et al., 2014; Hanson, 2004; Lavie & Meyer, 2010; Mejía et al., 2012; Rice & Alm, 2008; Sloan, Atkinson, Machin, & Li, 2010; Verwey, 2000). Examples include:

- Consider intermediate levels of adaptation;
- Provide the option to zoom-in and out;
- Provide text-to-speech option;
- Consider using persona-based user modelling.

Cultural adaptability, which relates to the ability of the system to adapt to a user’s culturally different concepts of space, time and communication, have also been considered as a significant aspect of the system design. These include factors such as (Heimgärtner, 2007): preferred type of routes, average speed, default tours, short or long tours, travelling along rivers or hills, and preferred interaction styles.

This section of the review has highlighted ageing-related impairments that should be considered in regards to the functionality and adaptability of a CAV in-vehicle HMI with an element of crossover to the previous section. Functions appear to relate to those that involve in-vehicle information such as vehicle speed and journey time (e.g., from location) and physiological monitoring (particularly important for individuals with e.g., age related health conditions), as well as outer-vehicle information such as distance between own and other vehicles and infotainment news updates. Some of these functions represent a move from traditional manual vehicle functions such as external light setting options, traction control, and engine rev data and extend the types of information that people can engage in given the ability to relinquish driving controls to the autonomous system. Adaptability is a key factor that must be given paramount consideration in the design of effective in-vehicle HMIs for CAVs. Key examples involve the ease of switching between information modalities (e.g., text-to-speech) and zooming in and/or out of information sources (e.g., linked to different sensory impairments). However, it is noted that there is little in the way of research on adaptive in-vehicle HMIs for use amongst older adults in highly and/or fully autonomous vehicles such as CAVs. This again emphasises the importance of the work being conducted through the FLOURISH CAV research project.

4. What are the key evaluation criteria and approaches when assessing user interaction with in-vehicle CAV HMIs?

Relevant evaluation criteria should be adopted to determine the usability of the in-vehicle CAV HMI and improve user experience. As such, the evaluation approach needs to assess higher-level task-related measures from the users' perspective.

Kharchenko, Orekhova, and Orekhov (2014) have defined five key principles which could be used within the context of evaluating in-vehicle experience:

- User model compatibility;
- Situational awareness (SA);
- Cognitive compatibility;
- Cognitive workload;
- Timeliness.

Kirmani and Rajasekaran (2007) have also defined some key aspects to be considered as well as corresponding evaluation criteria:

- Information architecture: e.g., is the information structured into meaningful units/groups best matching the mental model of users to aid findability?
- Interaction design: e.g., is information regarding the current state of the system provided in a clear and understandable way to the user?
- Visual design: e.g., is the layout of the interface consistent?
- Labelling: e.g., have appropriate labels been used for menus, menu items, and controls as per user vocabulary?
- Functionality: e.g., can tasks be completed in an optimal number of steps?
- Content: e.g., is information appropriately presented in terms of comprehensibility for the target user group?

Additionally, key usability questions defined in the previous sections of this literature review have been collated into the following evaluation criteria:

- Can people easily access, learn and remember the system?

- Can people use the system simply and effectively?
- Do people feel that they have a sense of being in control, knowing what to do and how to do it?
- Do the system components comply with safety standards?
- Do the components integrate into personal contexts in a way that suits people?
- Does the system help meet the person's "experience goals"?

Acceptability is another aspect to be explored in terms of assessing user interaction with in-vehicle CAV HMIs. Four dimensions that relate to accessibility are described by Sharp, Roger and Preece (2007):

- Political acceptability (social sensibilities): e.g., do people see it as enhancing their abilities or are they threatened by it?
- Convenience: e.g., is the design acceptable within a given context?
- Cultural and social habits: e.g., is it non-intrusive to people's social lives?
- Usefulness: e.g., does it meet the needs of everyday living?
- Economic: e.g., does it represent value for money?

Ensuring the selection of relevant evaluation criteria and ecologically valid evaluation approaches will play a major role in determining the acceptance, adoption, and continued usage of the final FLOURISH in-vehicle CAV HMI as well as other CAV HMIs. As such, in addition to assessing the HMI in relation to specific accessibility usability, functionality and adaptability criteria, the evaluation approach needs to effectively, accurately and comprehensively evaluate the users' needs, requirements, expectations and experiences in order to inform the continued design process and cycle.

5. Which other categories of the population are likely to benefit from CAVs and what are the design recommendations for in-vehicle HMI design?

As well as older adults, other sectors of the population might benefit most from the early development and deployment of CAVs and the mobility possibilities they afford. These include individuals with identified cognitive and learning impairments (e.g. learning difficulties, autism spectrum disorders, traumatic brain injury, stroke, Alzheimer's disease, Parkinson's disease) (e.g., Fryia et al., 2009). Some of these conditions might have comorbidities (e.g. physical or sensory impairments) that should also be taken into account in the process of designing HMI interfaces for CAVs. As a result, some will not be able to drive a non-automated vehicle or find it difficult; thus minimising mobility options and potentially negatively impacting upon social and societal interactions.

Basic HMI recommendations for people with identified mild-severe cognitive and learning disabilities are displayed below and are derived from researchers such as Darejeh and Singh (2013), Fryia et al. (2009), Holzinger (2002), Lin et al. (2009); and Liu et al. (2008):

- Reduce interface complexity;
- Eliminate clutter and unnecessary features;
- Avoid using computer terms and names that are not familiar to all users for naming tools;
- Use appropriate graphical objects like avatar or icons for increasing software attraction;
- Use touchscreen technology wherever possible;
- Use large size icons with larger distances between icons/objects;
- Reduce cognitive load by reducing the number of interactions at one time.

Younger adults (e.g., 17-25 year olds) represent another category that are likely to benefit from early deployment of CAVs, including specific in-vehicle CAV interface design features (Brovold et al., 2007; Dotzauer, De Waard, Caljouw, Pöhler, & Brouwer, 2015; Rudin-Brown & Jamson, 2013). Several interface adaptations for e.g., teen drivers of non-autonomous vehicles have been developed such as:

- Teen Driver Support Systems (TDSS) (e.g. RoadSafety RS-1000, SignalTrac, NetworkCar, see Brovold et al. (2007) for a complete review) that rely on behaviour modification functions;
- Advanced Driver Assistance Systems (ADAS) (e.g., Lee, 2007; Rudin-Brown & Jamson, 2013) that include a navigation device, sensor suites plus control systems that enhance safety driving features for younger drivers (e.g. Intelligent Speed Adaptation (ISA); Alcohol Interlock, Data Logger, and Driver Identification).

Taking into consideration the needs of other high- risk drivers and how this may be informed by work with older adults within the current FLOURISH project – is a very important endeavour. These populations are likely to represent other important early adopters of CAVs and we need to think about the design of CAV HMIs for use amongst such individuals. Designing in-vehicle HMIs for CAVs for those not only with the greatest levels of needs and requirements (i.e., older adults, younger individuals with cognitive and learning impairments) as well as for those likely to have the highest levels of technological prowess (i.e., younger adults *per se*) but the lowest level of vehicle usage experience – will likely lead to robust systems with adaptive capabilities that can extend to most other population sectors in the future.

Conclusions and Recommendations

The current review set out to explore theoretical and empirical literature on the design of human-machine interfaces (HMIs) for autonomous vehicles (AV) and connected autonomous vehicles (CAVs) designed for older adults, including those with undiagnosed mild cognitive impairments and/or physical impairments. One key theme is that there are numerous generic HMI and in-vehicle HMI design principles that relate to four general categories:

- Accessibility: e.g., being able to reach it, being able to control it using touch and/or speech;
- Usability: e.g., human cognitive capabilities as well as input and output devices;
- Functionality: e.g., warnings, guidance systems, visual aids, attentional and cognitive aids;
- Adaptability: taking into consideration individual user requirements and capabilities.

These categories have not only guided the structure of the current review but are also shaping design principles for HMIs being developed as part of the FLOURISH CAV project.

The review has highlighted the importance of effectively designed in-vehicle CAV HMIs for older adult users, in terms of the current role that a car plays in providing a key mode of mobility for them. It has also highlighted some of the challenges that may be faced in terms of technology acceptance and use amongst this population. The review highlighted that experience and training in the resultant systems, as well as the ability to adapt systems and create bespoke individual user-focussed solutions, are likely to play a key role in overcoming many of the possible barriers associated with an older user group.

The HMI design principles identified and described throughout the current review can guide the design and development of an in-vehicle HMI for use in CAVs amongst older adults. However, it has been identified that there is a crucial need for much more concentrated research on the design and testing of in-vehicle HMIs for CAVs amongst older adults as well as other population sectors. Specifically, there is a dearth of direct research in this area. Nevertheless, many existing generic and driving specific (although not necessarily autonomous driving specific) HCI and HMI principles can be incorporated and tested within early iterations of HMIs for CAVs, such as those being designed as part of the current FLOURISH project.

The FLOURISH project represents a major effort to inform this gap in knowledge and to offer effective design solutions. This involves taking into account key design principles and evaluation criteria informed by the current review in designing an effective HMI for CAVs and for use amongst older adults. Additionally, this process will be strengthened by incorporating expert information from multiple FLOURISH partners concerning e.g., the needs of older adults (e.g., AgeUK, Designabilty) and developing computer and engineering solutions designed for older adults (e.g., Designability, Dynniq, TSC). Ultimately, our design solutions will be tested and validated through a series of simulator and road based CAV experiments involving older adult participants, with multiple iterations of a HMI developed throughout the FLOURISH project. Importantly, our work puts the key user group – older adults – at the centre of informing the design of effective HMIs for integration into CAVs. We strongly believe that this integrated approach is crucial not only to the success of the design of HMIs for CAVs used by older adults but also to inform the design of CAV HMIs developed for all other sectors of the population.

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