Challenges for automated vehicle driver training:

A thematic analysis from manual and automated driving

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Abstract

Considerable research and resources are going into the development and testing of Automated Vehicles. They are expected to bring society a huge number of benefits (such as: improved safety, increased capacity, reduced fuel use and emissions). Notwithstanding these potential benefits, there have also been a number of high-profile collisions involving Automated Vehicles on the road. In the majority of these cases, the driver’s inattention to the vehicle and road environment was blamed as a significant causal factor. This suggests that solutions need to be developed in order to enhance the benefits and address the challenges associated with Automated Vehicles. One such solution is driver training. As drivers still require manual driving skills when operating Automated Vehicles on the road, this paper applied the grounded theory approach to identify eight “key” themes and interconnections that exist in current manual vehicle driver training. These themes were then applied to the limited literature available on Automated Vehicle driver training, and a ninth theme of trust emerged. This helped to identify a set of training requirements for drivers of Automated Vehicles, which suggests that a multifaceted approach (covering all nine themes and manual and Automated Vehicle driving skills) to driver training is required. This framework can be used to develop and test a training programme for drivers of Automated Vehicles.

*Keywords***:** Automated Vehicles, Driver Training, Attention, Situation Awareness, Trust, Mental Models

1. **Introduction**

On the 18th March 2018, a female pedestrian named Elaine Herzberg was fatally struck by an Uber Level 2 Automated Vehicle (defined in section 1.1) as she was crossing the road in Tempe Arizona. According to the US National Transportation Safety Board, there was a software flaw in the vehicle which meant that the vehicle did not identify Elaine as a pedestrian (Cuthbertson, 2019). The safety driver was supposed to monitor the road and the vehicle and respond and takeover control of the vehicle in an emergency, however she was watching “The Voice” at the time of the crash (Cuthbertson, 2019). Footage from the crash showed that the pedestrian was visible from around two seconds before the collision occurred, leading one expert to suggest that if the safety driver had been alert, she may have been able to react to the pedestrian and swerve and/or brake to avoid her (Levin, 2018).

Although extreme, this collision demonstrates an apparent gap between what drivers assume the vehicles are capable of and what they are actually capable of. By definition, Automated Vehicles (AVs) are changing drivers’ tasks from actively controlling and handling the vehicle to passively monitoring the road environment and supervising the vehicle (Society of Automotive Engineers International, 2018). However, in the example above, the driver did not appear to be performing these tasks. It will never be known why, but it does appear that the driver’s role in AVs needs to be made clearer.

Despite these high-profile accident reports, there are many potential benefits for AVs. They have the potential to improve safety (fewer and less serious road accidents (Schoettle & Sivak, 2014)), efficiency, mobility (Choi & Ji, 2015) and convenience on the road (Nordhoff, de Winter, Kyriakidis, van Arem, & Happee, 2018), reduce the skill divide between novice and experienced drivers (Young & Stanton, 2004), reduce the physical (controlling the vehicle) and mental workload (reduce driver decision-making) that driving imposes on the driver (Endsley, 2017; Stanton, Young, & McCaulder, 1997) and reduce the energy and greenhouse gas emissions that are produced by vehicles (Greenblatt & Shaheen, 2015). Therefore, despite many people being skeptical about AVs (Schoettle & Sivak, 2014) and the potential benefits that AVs can bring (e.g. believing that there will always be accidents on the road (Nordhoff, et al., 2018)), many people are also in favour of AVs. For example, in a survey involving 925 respondents, Hulse, Xie and Galea (2018) found that only 3% had negative views towards the future use of AVs.

**1.1 Levels of Driving Automation**

How these societal benefits are realised, depends on the capability of the driving automation. The level of driving automation under consideration therefore needs to be clearly understood. Many different classifications of Driving Automation exist. This includes the Society of Automotive Engineers’ (SAE) six levels of driving automation, which is the most commonly used taxonomy to-date (Inagaki & Sheridan, 2019).

The Society of Automotive Engineers (SAE) decomposes driving automation into six levels (Society of Automotive Engineers International, 2018), ranging from Level 0 (No Automation- The driver performs all dynamic driving tasks (e.g. steering, acceleration, deceleration) and monitors the road environment) to Level 5 (Full Automation- The automation performs all driving tasks under all road and environmental conditions). In Level 1 Automation (Driver Assistance), the automation supports the steering or braking and acceleration of the vehicle, however the driver must perform the remaining dynamic driving tasks and monitor the road environment and the driving automation. In Level 2 automation (Partial Automation), the automation controls the steering, braking and acceleration of the vehicle in certain circumstances, however the driver must monitor the road environment and the automation and takeover control of the vehicle when the limitations are reached or when a system failure occurs. In Level 3 automation (Conditional Automation), the automation controls all dynamic driving tasks in certain road conditions. The driver is no longer required to monitor the automation or the road environment, however he/she must perform all dynamic driving tasks or achieve a minimal risk condition when the limitations are reached or a system failure occurs. In Level 4 automation (High Automation), the automation performs all dynamic driving tasks under certain road conditions. The driver is no longer required to take over control of the vehicle or achieve a minimal risk condition as the automation can automatically transition to a minimal risk condition (e.g. turns on the hazard lights and parks the vehicle in the hard shoulder).

Many of the benefits to society described above will only be realised at full automation (SAE Level 5), whilst the vehicle described in the case study is categorised as partial automation (SAE Level 2). As technology, policy and infrastructure advances to support full automation, it is imperative to minimise the challenges that drivers and other road users face from partial and conditional levels of automation (AVs).

**1.2 Challenges of Automated Vehicles**

There are many challenges associated with AVs. As drivers have to monitor a Level 2 AV and the road environment, research suggests that this can increase their mental workload and reduce their situation awareness (Endsley, 2017; Endsley, 2019; Stanton & Young, 2000; Stanton, Young, & Walker, 2007a) of the road environment. Additionally, AVs can degrade drivers’ manual driving skills (control and manoeuvring skills) over time, impairing their ability to manually takeover control of the vehicle when required (Bainbridge, 1983; Parasuraman, 2000). Finally, as AVs are taking the physical driving tasks away from drivers (Banks, Stanton, & Harvey, 2014), drivers will have to complete passive tasks instead (monitoring and sustained attention tasks) and research has consistently shown that humans are poor at completing these tasks, especially when automation is involved (e.g. Molloy & Parasuraman, 1996; Parasuraman, Molloy, & Singh, 1993). For example, Carsten, Lai, Barnard, Jamson and Merat (2012) found that as the level of car automation increased (from no automation (SAE Level 0), to semi-automation (lateral or longitudinal control was automated, SAE Level 1) to high automation (lateral and longitudinal control was automated, SAE Level 2)), the drivers’ monitoring and attention to the road and traffic decreased. This is because when humans are not actively involved in a task, they find it hard to sustain their visual attention on the task over a long period of time (Bainbridge, 1983) and their vigilance drops quickly due to boredom, fatigue and mind-wandering (Casner & Hutchins, 2019). As a result, their reaction time to events slows down (Dozza, 2013). This can be problematic when driving AVs as drivers may not react to emergency situations or unplanned takeover requests on time (Endsley, 2017; Stanton, et al., 1997), leading to disastrous consequences (e.g. crashes, injury or death) (Stanton, et al., 2007a). Therefore solutions need to be developed in order to enhance the benefits and eliminate the problems associated with AVs. Options include better design, user interfaces and driver training. The designs of AVs and their interfaces are not standardised (Richardson, Revell, Kim, & Stanton, 2020), and as it may take a long time for an agreement to be made between manufactures about what the designs should be, these vehicles could come out onto the market before this agreement is made. Therefore in the meantime, driver training can help to ensure drivers use AVs safely on the road, regardless of these manufacturer-specific designs. The nature and content of this training, however, is still up for debate.

As demonstrated in section 1.1, drivers of Level 0 and Level 1 Automation have to control and handle their vehicle on the road at all times, therefore the current driver training for manual vehicles will cover all the skills they need to drive these vehicles on the road. By way of contrast, drivers of Level 5 Automation are effectively passengers; they do not perform any driving task and they do not have to monitor the vehicle or the road environment. Future concepts of Level 5 AVs may not even have manual controls (e.g. steering-wheels, gear sticks, clutch and brake pedals) to emphasise that the responsibility of the driving task lies completely with the automation. Therefore drivers will not have to undergo driver training in order to “drive” these vehicles on the road. However, drivers of Level 2 AVs are required (when these features are activated) to actively monitor the road environment, supervise the vehicle and takeover control of the vehicle when the automation reaches its limits or a system failure occurs. Similarly, drivers of Level 3 AVs are required to takeover control of the vehicle when asked and drivers of Level 4 AVs can still (although it is not compulsory) takeover control of the vehicle when asked. These are all skills and tasks that drivers have not been formally trained to perform (as this lies outside the requirements of current driving tests) and as literature shows that these tasks are challenging for drivers to perform well (Molloy & Parasuraman, 1996; Parasuraman, et al., 1993; see above), a new approach to driver training is required to ensure drivers have the appropriate skills to perform their role as a ‘co-driver’ of an AV. Additionally, as drivers may still have to manually control the vehicle, this suggests that driver training for both manual and AVs will be required. As shown in the introductory case study presented and other fatal accidents (e.g. Banks, Plant, & Stanton, 2018), Levels 2, 3 and 4 Automation are particularly problematic for drivers, therefore the focus of this review will be on how best to support these three levels of driving automation. Throughout the rest of this review, these three levels will be referred to as AVs.

**1.3 Current Driver Training for Manual Vehicles (Level 0)**

Each country has a different training programme for teaching drivers how to drive manual vehicles. In the United Kingdom, learner drivers (first-time drivers) have to pass two tests before they can drive unaccompanied on the road. The first is a theoretical test which has two components; a 50-item multiple choice test which tests their knowledge on the Highway Code, traffic signs and essential driving skills and a hazard perception test which tests their hazard perception ability. The second test is a practical driving test on the road. This tests their general driving ability in different road and traffic conditions, their ability to perform manoeuvres (e.g. bay parking) and their ability to follow directions using either an in-car navigation system or road signs (GOV.UK, 2017).

From this point on, advanced driver training courses are then optional. These include the Pass Plus Scheme which is designed to increase drivers’ driving experience in towns (navigating around pedestrians), on rural roads (navigating around animals, blind bends and slow moving vehicles), at night (problems with visibility and glare), on dual carriageways and motorways (use of slip roads, lanes, overtaking and dealing with breakdowns) and in different weather conditions (e.g rain which affects stopping distance) (GOV.UK, 2017). Defensive driving courses, such as the Institute of Advanced Motorists RoadSmart’s (IAM) Advanced Driver Course, are also available. By reading a logbook and undergoing on-road driver coaching, drivers learn how to improve their ability to gather information on the road (through effective observation, anticipation and planning) and use that information to be in the correct position, at the right speed and in the right gear when approaching hazards on the road, so that they can deal with them effectively (IAM RoadSmart, 2016). The majority of people take and pass their driving test at ages 17 and 18 years (Department for Transport, 2020) and rarely do any additional training throughout their driving career.

In Germany, first-time drivers have to complete an eye test and a first aid course before they can learn how to drive. Just like the United Kingdom, two tests have to be taken; a theoretical test consisting of 30-multiple choice questions and a practical driving test on the road. However, unlike the United Kingdom, drivers have to undertake both theory and practical driving lessons (at night, on the motorway and on country roads) with a driving school before they can take these two tests. They cannot be taught how to drive by friends or family (I AM EXPAT, 2020; Toytown Germany, 2009).

In the United States, Canada, New Zealand and Australia, a graduated driver’s licence programme is used. Although the exact details vary by country and state, first-time drivers usually undergo a three-stage learning process; a learning phase where drivers have to undergo a minimum number of supervised practical driving lessons on the road, an intermediate phase where they can drive unaccompanied but only in low-risk situations (e.g. not at night or with teenage passengers) and a full unrestricted driving licence (Shope, 2007; Williams, 2017). Additionally, in the United States, first-time drivers learn how to drive in an automatic car without gears (Longford, 2005).

**1.4 Aim and Objectives**

As drivers are required to perform some manual driving tasks when operating Level 2 AVs on the road and either have to (Levels 2 and 3 AVs) or can (Level 4 AVs) take over control of the vehicle when the limitations are reached or a system failure occurs, drivers of AVs will need to undergo both manual and AV driver training when learning how to drive AVs on the road (see section 1.2). Therefore, to develop driver training requirements for AVs, it is necessary to understand current driver training for manual vehicles (encompassing non-automated gear and automatic cars i.e. Level 0), to ensure that these basic skills and competencies are captured. As such, the aim of this review is to assess the existing training for drivers of manual vehicles in order to uncover the themes and interconnections between these themes that are present in the training literature. Then existing research on driver training for AVs will be reviewed in order to investigate the presence of these themes within this literature, the key challenges associated with each theme and how current driver training for AVs has overcome these challenges. The intention is that this will help to identify a set of training requirements for drivers of AVs, so that a training programme can be developed to work towards realising the benefits associated with AVs (mentioned above) and eliminating some of the challenges.

1. **Method: Understanding Driver Training Requirements for Automated Vehicles**

**2.1 Search methods and source selection**

Two separate searches were conducted in October 2019: one for manual vehicle driver training (section 2.1.1) and one for AV driver training (section 2.1.2).

*2.1.1 Manual Vehicle Driver Training Articles*

Key terms (see Table 1) were entered into Web of Science and Scopus. Table 1 illustrates the down selection process that resulted in 420 articles. Subsequently, review articles and articles related to Eco-driving (e.g. Jeffreys, Graves, & Roth, 2018; Rutty, Matthews, Andrey, & Del Matto, 2013; Sullman, Dorn, & Niemi, 2015) were removed, as these went beyond the scope of the review. In total, 68 articles were reviewed.

Table 1

*Syntax used during the literature search for manual vehicle driver training*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Syntax | Search Tool | Number of articles before filter | Filters Applied | Action | Number of articles after filter |
| Intitle: “train” OR "training" AND “vehicle\*” OR "car\*" OR “driver” OR “driving” NOT “pilot study” NOT “pilot trial” *AND*LANGUAGE:(English) | Web of Science | 488 | Articles related to the rail industry, the training of the transport rather than the driver, pilot studies and articles where full texts could not be found. | Titles of top 1000 most cited papers were reviewed | 265 |
|  | Scopus | 15,883 |  | Titles of top 1000 most relevant papers were reviewed | 155 |

*2.1.2 Automated Vehicle Driver Training Articles*

Key terms were initially entered into Web of Science and Scopus. Table 2 shows the syntax that was used to find sources for this part of the review. Due to the limited number of articles returned, the same search was then conducted in Google Scholar. Although this article is focusing on Levels 2, 3 and 4 automation, due to the limited number of driver training articles for AVs (as indicated by the limited number of search results), articles which made reference to Level 1 automation were kept in this analysis in order to gain insights into the driver training strategies that can be used for Levels 2, 3 and 4 automation.

Across the three databases, 10 unique articles were found. Many articles were filtered out because they focussed on the training of the vehicle (mostly using neural networks) rather than the driver (e.g. Kim, Cha, Ryu, & Jo, 2019; Rezgui, Oest O'Leary, Bisaillon, & Chaari Fourati, 2019; Yang, Wang, Liu, Deng, & Hedrick, 2017). This highlights a gap in the literature in relation to driver training for AVs.

Each of these articles were read and within these articles, a further 16 papers were identified as relevant. In total 26 papers (21 journal articles and 5 conference papers) were reviewed. All papers referred to either Level 1, 2 or 3 automation (defined in section 1.1), therefore no insights in relation to driver training for Level 4 AVs could be gained. As a result, the research used in this literature review will only focus on Level 1, 2 and 3 AVs. In the future when more research on Level 4 AVs is conducted, some of the findings from this review could be applied to Level 4 AVs.

Table 2

*Syntax used during the literature search for AV driver training*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Syntax | Search Tool | Number of articles before filter | Filters Applied | Action | Number of articles after filter |
| Intitle: “train” OR “training” AND “driverless” OR “autonomous car\*” OR “autonomous vehicle\*” OR “automated car\*” OR “automated vehicle\*” OR “automation” OR “high automation” OR “conditional\* automation” OR “partial\* automation” OR “conditional\* automated” OR “partial\* automated” *AND*LANGUAGE:(English) | Web of Science | 134 | Articles which did not relate to automation in transport, articles which referred to the training of the transport rather than the driver and articles where the full text could not be found | All titles reviewed | 2 |
|  | Scopus | 36 |  |  | 3 |
|  | Google Scholar | 28 |  |  | 1 |
| Intopic: training AND autonomous vehicle\* OR autonomous car\* OR driverless vehicle\* OR driverless car\* OR semi-autonomous vehicle\* OR semi-autonomous car\*  AND LANGUAGE:(English) | Web of Science | 236 |  |  | 2 |
| Intopic: training AND partially auto\* vehicle\*  AND LANGUAGE:(English) | Web of Science | 37 |  |  | 2 |
| Intopic: training AND connected auto\* vehicle\*  AND LANGUAGE:(English) | Web of Science | 117 |  |  | 0 |
| Intopic: training AND high\* auto\* vehicle\*  AND LANGUAGE:(English) | Web of Science | 1,318 |  |  | 0 |

**2.2 Theme Elicitation: Identification of Themes in Manual Vehicle Driver Training**

The grounded theory approach is the process of searching, analysing, conceptualising and interpreting themes in data, using inductive reasoning, in order to develop a theory (Braun & Clarke, 2006; Charmaz, 2001). The grounded theory approach to theme elicitation has been successfully used in past literature reviews in order to identify core concepts/themes which exist in a body of literature (e.g. Foster, Plant, & Stanton, 2019; Parnell, Stanton, & Plant, 2016; Rafferty, Stanton, & Walker, 2010). This approach was used to identify the key themes that exist in manual vehicle driver training. To do this, each paper was read, and an iterative and open approach was used to generate themes (searching for repeated patterns in the data), following the guidelines from Braun and Clarke (2006). This produced a total of eight themes; workload, speed of processing, attitudes and personality, situation awareness, attention and memory, procedural skills, hazard and risk perception and mental models (described in Section 3). Appendix A summarises the 68 manual vehicle driver training papers and the themes that were identified within each one.

**2.3 Theme Interconnections within the Manual Vehicle Driver Training Literature**

The eight key themes that were identified in the manual vehicle driver training literature were explored in depth in order to determine how they are interconnected with each other. The number of papers which made interconnections between the eight themes is displayed in Table 3. These were based upon the training programmes that were implemented, the measurable effects that the training programmes had on drivers and the associations that the authors made throughout their articles. For example, if a paper mentioned that X causes Y, then a “from” interconnection between X and Y was recorded. The mean number of papers which cited an interconnection was 4.46 papers (Mdn= 2, Mode= 0). For brevity, only the interconnections which were cited by more than 4.46 papers are explained in section 3.1, as these were most prevalent in the literature.

**2.4 Deductive Thematic Analysis of the Automated Vehicle Driver Training Literature**

After the eight key themes were generated from the manual vehicle driver training literature, the 26 AV driver training papers were analysed using deductive reasoning in order to identify the presence of these themes within the papers. An additional key theme of trust was identified, as this theme was mentioned in 21 of the 26 AV driver training papers (trust was not mentioned in the manual vehicle driver training literature). Appendix A summarises the 26 AV driver training papers and the themes that were identified within each one.

Additionally, the nine themes were explored in depth in order to determine how they are interconnected with each other in the AV driver training literature. The number of papers which made interconnections between the nine themes is displayed in Table 4. These were based upon the training programmes that were implemented, the measurable effects that the training programmes had on drivers and the associations that the authors made throughout their articles. The mean number of papers which cited an interconnection was 3.68 papers (Mdn= 2, Mode= 0), therefore only the interconnections which were cited by more than 3.68 papers are explained in section 3.2, as these were most prevalent in the literature. This allowed comparisons to be made between the manual and AV driver training literature.

Table 3

*The interconnections between the eight key themes in the manual vehicle driver training literature.*

| From |  |  |  | To |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Hazard and Risk Perception | Attention and Memory | Procedural Skills | Situation Awareness | Mental Models | Personality and Attitudes | Speed of Processing | Workload |
| Hazard and Risk Perception |  | 17\* | 25\* | 2 | 5\* | 6\* | 5\* | 1 |
| Attention and Memory | 34\* |  | 21\* | 4 | 1 | 2 | 3 | 0 |
| Procedural Skills | 5\* | 8\* |  | 2 | 1 | 12\* | 2 | 3 |
| Situation Awareness | 12\* | 5\* | 6\* |  | 2 | 4 | 0 | 0 |
| Mental Models | 13\* | 5\* | 7\* | 3 |  | 0 | 0 | 1 |
| Personality and Attitudes | 2 | 2 | 8\* | 1 | 2 |  | 0 | 0 |
| Speed of Processing | 2 | 2 | 10\* | 0 | 0 | 0 |  | 0 |
| Workload | 1 | 3 | 0 | 0 | 0 | 0 | 0 |  |

\* These interconnections have been cited by more than 4.46 papers and are discussed further in Section 3.1.

Table 4

*The interconnections between the nine key themes in the AV driver training literature.*

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| From |  |  |  |  | To |  |  |  |  |
| Hazard and Risk Perception | Attention and Memory | Procedural Skills | Situation Awareness | Mental Models | Personality and Attitudes | Speed of Processing | Workload | Trust |
| Hazard and Risk Perception |  | 0 | 15\* | 1 | 10\* | 9\* | 0 | 2 | 6\* |
| Attention and Memory | 0 |  | 4\* | 3 | 1 | 0 | 1 | 2 | 0 |
| Procedural Skills | 7\* | 4\* |  | 2 | 16\* | 10\* | 8\* | 6\* | 11\* |
| Situation Awareness | 0 | 0 | 8\* |  | 3 | 2 | 1 | 1 | 2 |
| Mental Models | 8\* | 4\* | 23\* | 6\* |  | 11\* | 8\* | 3 | 18\* |
| Personality and Attitudes | 0 | 3 | 7\* | 0 | 1 |  | 3 | 1 | 2 |
| Speed of Processing | 0 | 0 | 0 | 0 | 0 | 0 |  | 0 | 0 |
| Workload | 0 | 3 | 3 | 2 | 1 | 2 | 0 |  | 0 |
| Trust | 1 | 4\* | 8\* | 1 | 2 | 2 | 2 | 1 |  |

\* These interconnections have been cited by more than 3.68 papers and are discussed further in Section 3.2.

1. **Results**

**3.1 Manual Vehicle Driver Training: The Eight Themes in Manual Vehicle Driver Training**

For each theme, a definition and an explanation of how they are measured and trained in the manual vehicle driver training literature is given. Additionally, the key interconnections identified in Table 3 are explained.

*3.1.1 Theme 1: Workload*

Mental workload is a measurable quantity of the information processing demands that are placed on an individual during a task (Sanders & McCormick, 1993). It refers to the interaction between the task demands (the resources demanded by a task/situation) and an individual’s resources (the resources that an individual has to deal with the demands: Gopher & Donchin, 1986; Wilson & Sharples, 2015).

In driver training, drivers’ workload is measured in three main ways; using a workload questionnaire (e.g. Nasa-TLX) (van Leeuwen, Happee, & de Winter, 2015), by measuring drivers’ primary driving performance over time (e.g. Gamache, Lavallière, Tremblay, Simoneau, & Teasdale, 2011) or by measuring drivers’ performance on a non-driving related secondary task. This is because if drivers are asked to perform a secondary in-vehicle task whilst driving (e.g. Pradhan, et al., 2011), their performance on that task can indicate the demands imposed by the primary driving task (if they perform the secondary task well, less demands were imposed by the primary driving task, therefore their workload was low). Similarly, training increases drivers’ knowledge and understanding of the road environment and their vehicle and they gain more experience on the road, therefore over time, their procedural skills (controlling the car) will become automated and their cognitive skills (hazard anticipation) and reaction time to events will improve (Gamache, et al., 2011; van Leeuwen, et al., 2015; Wang, Zhang, & Salvendy, 2010). This frees up some of their resources that they would usually allocate to the driving task, reducing the workload that they experience. This suggests that to reduce drivers’ workload, driver training should make drivers continuously practice their driving skills so that these skills become automated and workload reduces.

*3.1.2 Theme 2: Speed of Processing*

Speed of processing is the speed at which an individual can perceive, process and respond to information that is presented to them (Ball, Edwards, & Ross, 2007; Salthouse, 1985). Speed of processing is important because driving requires drivers to process and manipulate lots of cognitive, physical and sensory information in a complex and changing environment (Ross, et al., 2016).

Drivers’ speed of processing can be trained (improved) and measured in many ways. Firstly, drivers can practice three tasks which are designed to improve their ability to detect, identify, discriminate and localise different targets (e.g. car) on a computer screen (Ball, et al., 2007). In this case, the speed at which drivers perform these tasks is used to indicate their speed of processing. Alternatively, hazard perception training can improve drivers’ speed of processing. In some forms of hazard perception training, drivers watch video-clips/photographs of hazardous scenarios and perform a response (e.g a key press) when they spot a hazard (Meir, Borowsky, & Oron-Gilad, 2014; Shimazaki, Ito, Fujii, & Ishida, 2017). In this case, drivers’ reaction time is used to measure their speed of processing and this is because drivers need to be able to perceive and process the relevant information in the environment in order to respond/react to the hazard. Studies show that this hazard perception training reduces the time it takes drivers to look at driving hazards (Kahana-Levy, Shavitzky-Golkina, Borowsky, & Vakil, 2019; Shimazaki, et al., 2017), increases drivers’ ability to perceive/spot hazards on the road (Crundall, Howard, & Young, 2017; Isler, Starkey, & Williamson, 2009; Meir, et al., 2014) and reduces drivers’ reaction time when responding to hazards (Isler, et al., 2009). This suggests that the hazard perception training is speeding up drivers’ ability to perceive, process and respond to hazards, all of which are components of a driver’s speed of processing (the “from” link in Table 3 from hazard and risk perception to speed of processing).

Additionally, Table 3 suggests that speed of processing training is important because it influences drivers’ procedural skills. Older drivers (with speed of processing decline) and brain-damaged patients who underwent the three-task speed of processing training mentioned above, had a faster speed of processing and were better and safer at driving compared to a no-training control group (no speed of processing decline) (Klonoff, et al., 2010). Additionally these drivers made fewer dangerous manoeuvres after undergoing training compared to before training (Eramudugolla, Kiely, Chopra, & Anstey, 2017; Roenker, Cissell, Ball, Wadley, & Edwards, 2003). Therefore, in driver training for AVs, drivers’ speed of processing needs to be trained. This will improve their procedural skills which will reduce their liklihood of an accident.

*3.1.3 Theme 3: Attitudes and Personality*

Attitudes are a relatively enduring set of beliefs, feelings and intentions towards an entity (object, person, system, technology) (Eagly & Chaiken, 1993). Personality is the “*dynamic organization within the individual of those psychophysical systems that determine his characteristics, behaviour and thought*" (Allport, 1961, p. 28). In driver training, drivers’ attitudes and personality are measured using self-report questionnaires (e.g. Montag’s Driving Internality and Driving Externality scale (Huang & Ford, 2012)) and by measuring drivers’ behaviour. This is because attitudes and personality can affect drivers’ procedural skills (Boccara, Delhomme, Vidal-Gomel, & Rogalski, 2011a) (the “from” link in Table 3 from attitudes and personality to procedural skills). Drivers who overestimate their driving abilities and/or have poor attitudes towards driving, speeding and road violations, violate more rules (e.g. speed limits), commit more driving mistakes and have more collisions on the road (Boccara, Delhomme, Vidal-Gomel, & Rogalski, 2011b; Tronsmoen, 2010). Similarly, drivers who have an internal locus of control (believe that they are in control of their driving behaviour and events in the driving environment), are safer on the road compared to those who have an external locus of control (believe that external factors (e.g. other people) and factors beyond their control (e.g. luck/chance) are responsible for their driving behaviour and events/outcomes that occur) (Huang & Ford, 2012).

However, Table 3 suggests that drivers’ attitudes and personality are also affected by their procedural skills and hazard and risk perception. As drivers’ procedural skills (e.g. controlling the car) improve through training, their confidence and positive self-assessments of their driving skills increase (Boccara, et al., 2011a; Boccara, et al., 2011b). However drivers tend to overestimate their driving and hazard perception abilities, which increases their risk-taking behaviour (e.g. speeding) and their beliefs about handling dangerous situations on the road (Boccara, et al., 2011b). Because of this, driver training programmes have been introduced to show drivers how good their driving skills actually are in order to improve their perceptions of their driving ability and limitations, reduce their risk-taking behaviour and improve their driving and hazard perception skills (Biassoni, Balzarotti, & Ciceri, 2015; Ivancic IV & Hesketh, 2000). Research suggests that hazard/risk perception training (Isler, Starkey, & Sheppard, 2011; McKenna, Horswill, & Alexander, 2006), watching or experiencing risky situations in a driving simulator (Ivancic IV & Hesketh, 2000) and making drivers complete self-evaluations of their driving abilities (Isler, et al., 2011) made drivers more aware of hazards on the road. This reduced their confidence in their driving abilities (Isler, et al., 2011; Ivancic IV & Hesketh, 2000), made them have safer attitudes towards risky driving (e.g close following) (Isler, et al., 2011; Lenné, Liu, Salmon, Holden, & Moss, 2011) and decreased their risk-taking behaviour (McKenna, et al., 2006). Therefore training programmes should make drivers aware of their driving abilities and limitations and hazards/risks in the environment. This will reduce their confidence in their driving abilities and their risk-taking behaviour.

With regards to personality, learning how to detect (hazard perception training), approach and negotiate hazards (skill-based training of procedural skills) increased drivers’ internal locus of control and reduced their external locus of control (Huang & Ford, 2012; Stanton, Walker, Young, Kazi, & Salmon, 2007b). Having an internal locus of control is important because this makes drivers more proactive in trying to improve their driving skills (Stanton, et al., 2007b), therefore this suggests that if drivers have an internal locus of control, the AV driver training will be more effective.

*3.1.4 Theme 4: Situation Awareness*

Situation awareness is defined by Endsley (1995, p. 36) as “*the perception of elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future*”. Situation awareness can be distributed in a system (Stanton, et al., 2006; Stanton, 2016). This theory suggests that humans and non-humans (e.g. technology) can both have situation awareness; however situation awareness is affected by the agent’s experience, memory and training, therefore each agent’s situation awareness may be different. Situation awareness can also be shared, so if one agent’s situation awareness degrades, another agent can compensate for this.

One method that has been used to train drivers’ situation awareness is commentary training. This has two variations. Firstly, drivers are asked to provide a verbal commentary about what they are doing, what they can see (Level 1 Situation Awareness), what they are thinking, their understanding of the situation (Level 2 Situation Awareness), what might happen next (Level 3 Situation Awareness) and what actions they will take to avoid hazardous situations whilst they or an expert is driving or whilst watching a video of themselves or an expert driving (Crundall, Andrews, van Loon, & Chapman, 2010; Isler, et al., 2009; Young, Crundall, & Chapman, 2017). The second method involves drivers listening to an expert or a peer providing a verbal commentary in one of the four conditions (Crundall, et al., 2010; Isler, et al., 2011). To test the effectiveness of this method in improving drivers’ situation awareness, drivers’ procedural skills, attention and/or hazard perception are compared before and after training. This is because research has shown that commentary training improves drivers’ procedural skills (e.g speed, acceleration, braking, road position, steering, headway and gear changes), hazard and risk perception (e.g hazard anticipation, assessement and detection and speed when looking at, recognising, identifying and reacting towards hazards) and attention (e.g frequency and speed in attending towards/fixating on future hazards) (Crundall, et al., 2010; Muttart, Dinakar, Fisher, Garrison, & Samuel, 2019; Petzoldt, Weiß, Franke, Krems, & Bannert, 2013; Rosenbloom, Shahar, Elharar, & Danino, 2008; Stanton, et al., 2007b; Walker, Stanton, Kazi, Salmon, & Jenkins, 2009; Young, et al., 2017).

This suggests that in driver training for AVs, drivers’ situation awareness needs to be trained as this influences their procedural skills, hazard and risk perception and their attention (the “from” links in Table 3 from situation awareness to procedural skills, attention and hazard and risk perception). Additionally, distributed situation awareness becomes important as the AV will be capable of developing situation awareness and this may be different from the driver’s (Stanton, Salmon, Walker, Salas, & Hancock, 2017).

*3.1.5 Theme 5: Attention and Memory*

Memory is defined as *“the ability to remember information, experiences, and people*” (Cambridge Dictionary, 2020). Attention is defined as “*the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought*” (James, 1980, p. 403). In driver training, drivers’ attention is measured in two main ways; secondary task performance and visual behaviour. This is because people tend to look at the objects/information sources which they are attending to. This is known as overt attention (de Haan, Morgan & Rorden, 2008). Additionally, drivers’ performance on the secondary task can indicate how much attention was allocated to that task. If their performance was high, lots of attention was allocated to the secondary task. However if their performance was low, not enough attention was allocated to that task (Rudin-Brown & Parker, 2004).

In driver training, drivers’ attention and memory can be trained via mental model training and hazard perception training. In some forms of hazard perception training, drivers are given top-down schematic views of hidden and visible hazardous scenarios and an explanation of the risks (Pradhan, Pollatsek, Knodler, & Fisher, 2009). This helps them develop an accurate mental model for the road environment, so if they encounter a similar situation in the future, they know what they should attend to in the scene if the risks/hazards were to materialise. Additionally, as some of the hazards are hidden from view, the training encourages drivers to visualise the location of hazards. This helps them process the information deeply, ensuring that it reaches their long-term memory (the “from” link in Table 3 from mental models to attention and memory).

Similarly, in most forms of hazard perception training, drivers learn what they should attend to in the environment in order to detect hazards/risks. The learning process can take different forms (e.g viewing images of hazardous scenes and moving circles onto the hazardous/risky areas, experiencing the consequences of not attending to hazards (crashes), or watching hazardous video-clips and providing commentary on the hazards), however the underlying objective (teaching drivers to attend to risky/hazardous areas) is the same (Isler, et al., 2009; Pollatsek, Narayanaan, Pradhan, & Fisher, 2006; Vlakveld, et al., 2011). This training improves drivers’ understanding of where their attention should be allocated when driving (Fisher, Narayanaan, Pradhan, & Pollatsek, 2004; Fisher, Pollatsek, & Pradhan, 2006; Pradhan, Fisher, Pollatsek, Knodler, & Langone, 2006a). Additionally, the training improves drivers’ attention as drivers are more likely to attend to/look at the risky/hazardous areas of the driving scene after training. These two things improve their hazard/risk perception as this makes drivers more able to detect, recognise, assess and predict hidden and visible hazards in the driving scene (Pradhan, et al., 2009; Pradhan, Fisher, & Pollatsek, 2006b; Regan, Triggs, & Godley, 2000). As a result, drivers are more likely to attend to these areas when they encounter similar situations in the future (Fisher, et al., 2004; Pollatsek, et al., 2006; Vlakveld, et al., 2011). This suggests that there is a close bidirectional relationship between hazard and risk perception and attention (Table 3), therefore in driver training for AVs, drivers need to be taught about what they should attend to in the environment in order to detect hazards and risks.

The manual driver training literature also suggests that drivers’ situation awareness can affect their attention and memory, procedural skills training can improve drivers’ attention and memory and attention and memory training can improve drivers’ procedural skills. These interconnections are explained elsewhere (3.1.4 (situation awareness) and 3.1.6 (procedural skills)).

*3.1.6 Theme 6: Procedural Skills*

Procedural Skills are the skills that drivers need to control and handle their vehicle on the road (Ebnali, Hulme, Ebnali-Heidari, & Mazloumi, 2019a). This includes braking, accelerating and steering. In driver training, many different procedural skills are measured. These include accelerator and/or brake pressure (Crundall, et al., 2010), speed (Regan, et al., 2000), headway (Stanton, et al., 2007b) and lateral positioning (Cox, et al., 2017). In driver training, procedural skills are taught in two main ways. Firstly drivers are given a written or verbal description about how to perform these skills and then they practice these skills in a simulator or on the road until they become automated (Sportillo, Paljic, & Ojeda, 2019).

Secondly, attention and hazard and risk perception training can train (improve) drivers’ procedural skills. In some training programmes, drivers are taught about what areas of the road environment they should attend to in order to detect hazards/risks. This improves their attention and hazard perception (see section above) and these two things improve their procedural skills when dealing with those hazards on the road. For example, drivers are more likely to press their brakes when reaching intersections, they move further across the roadway when overtaking vehicles (Dorn & Barker, 2005; Fisher, et al., 2002; Wang, et al., 2010), they reduce their pressure on the accelerator and increase their pressure on the brake when approaching hazards (Crundall, et al., 2010), they show better directional control (Bédard, et al., 2008; Isler, et al., 2011) and they have fewer collisions on the road (Crundall, et al., 2010).

Additionally, research suggests that procedural skills training can affect drivers’ attention and hazard and risk perception. If drivers undergo training which improves their procedural skills on the road, the attentional demands that the driving task imposes on the driver reduces (Gamache, et al., 2011). This is because over time, the procedural skills will become automated. As a result, drivers will attend to more areas of the road scene and their gaze tunnelling towards the road centre will reduce (van Leeuwen, et al., 2015). This suggests that there is a bidirectional link between attention and memory and procedural skills (see Table 3).

Drivers’ procedural skills also influence their hazard and risk perception. In training, if drivers are exposed to risky/hazardous situations that can occur on the road and they learn how to recognise, avoid and handle them (e.g. skidding in puddles), their risk perception towards driving (Rosenbloom, et al., 2008) and the risky situations that can occur on the road (e.g. talking on a mobile phone whilst driving) (Biassoni, et al., 2015) increases and they make more secondary glances towards hazardous situations (Romoser & Fisher, 2009). Additionally in police driver training, drivers are taught speed, steering and road positioning techniques in order to increase their awareness of risks and hazards on the road e.g. repeatedly pulling out from behind parked vehicles in order to see the road ahead (Dorn & Barker, 2005). Therefore, there is also a bidirectional link between hazard and risk perception and procedural skills (see Table 3). This suggests that in driver training for AVs, drivers need to be told about what they should attend to in the environment. This will improve their attention, hazard and risk perception and their procedural skills when dealing with hazardous situations.

The manual driver training literature also suggests that drivers’ situation awareness can be measured using their procedural skills, drivers’ attitudes and personality, mental models and speed of processing can affect their procedural skills and procedural skills training can improve drivers’ attitudes and personality. All these interactions are explained elsewhere (3.1.2 (speed of processing), 3.1.3 (attitudes and personality), 3.1.4 (situation awareness) and 3.1.8 (mental models)).

*3.1.7 Theme 7: Hazard and Risk Perception*

Hazard perception is the situation awareness of hazardous situations in the road environment (Isler, et al., 2009). A hazard/risk is defined as “*anything which causes the driver to change the position or speed of their vehicle*” (Stanton, et al., 2007b). This includes other road users (e.g. pedestrians, cyclists, other vehicles), the road layout (e.g. blind bends, hedges), environmental conditions (e.g. weather, light) or a combination of these three factors.

In driver training, drivers’ hazard perception ability is measured in three main ways; by measuring drivers' reaction time to hazards, by measuring their performance (e.g. number of hazards detected) and/or by measuring their visual behaviour (e.g number or duration of fixations on hazards). This is because if the drivers’ perception of hazards improve, they will identify more hazards in the driving scene (e.g. click on more hazards in video-clips), look towards more hazards and react faster towards them (e.g. click on hazards in the video-clips quicker) (e.g Isler, et al., 2009; Pradhan, et al., 2006a).

Many methods have been used to train drivers’ hazard perception. The two most common methods are road commentary production (section 3.1.4) which improves drivers’ situation awareness of the road environment and attention training which teaches drivers what they should attend to in the environment in order to detect hazards/risks (section 3.1.5). This is because research has shown that if drivers’ attention and/or situation awareness is trained, their hazard perception improves (see sections 3.1.4 and 3.1.5) (Fisher, et al., 2002; Isler, et al., 2009; McKenna, et al., 2006). Therefore, this is evidence for the “from” links in Table 3 from situation awareness and attention and memory to hazard and risk perception.

Additionally, mental model training can improve drivers’ hazard and risk perception. In some forms of risk perception training, drivers are told about the risks/hazards that can occur on the road (e.g. slippery/wet roads), where they should look to perceive the risks/hazards, how the safety equipment in the car (e.g. seatbelts) and their behaviour (e.g. speed) can affect the likelihood of these risks/hazards occurring and what they should do to avoid these situations (Meir, et al., 2014; Taylor, et al., 2011; Yamani, Biçaksiz, Palmer, Hatfield, & Samuel, 2018). This information helps them develop their mental model (knowledge and understanding) of the road environment and the hazards and risks that can occur, both of which increase their awareness and perception of hazards/risks on the road (i.e. drivers are more likely to look towards hazards after training). Additionally, this increased perception of risk/hazards further strengthens drivers’ mental model of the road environment, the rules of the road and where hazards may occur (Bédard, et al., 2008; Biassoni, et al., 2015; Pradhan, et al., 2006b), therefore the relationship between mental models and hazard and risk perception is bidirectional (Table 3). Therefore, in driver training for AVs, drivers need to learn about the risks and hazards that can occur and what they should look at in the environment in order to detect them. This will improve their attention, hazard and risk perception, situation awareness and mental models for the road environment.

The manual driver training literature also suggests that drivers’ procedural skills can affect their hazard perception ability and hazard perception training can improve drivers’ procedural skills, attitudes and personality and speed of processing. All these interactions are explained elsewhere (3.1.2 (speed of processing), 3.1.3 (attitudes and personality) and 3.1.6 (procedural skills)).

*3.1.8 Theme 8: Mental Models*

Mental Models are a person’s model, internal representation, knowledge and understanding of the physical world, the behaviour of a system or the automation (Saffarian, de Winter, & Happee, 2012; Stanton & Young, 2005). This model helps them use and understand the world/system and predict what will occur next. In driver training, drivers’ mental models are measured in two main ways; using questionnaires to test drivers’ knowledge (Bédard, et al., 2008) and by evaluating their driving behaviour. This is because research suggests that mental models are strongly linked to drivers’ driving behaviour (Table 3, see below).

As mental models are developed through experience and training (Johnson-Laird, 1989), one method that has been used to train (improve) drivers’ mental models of the road environment and/or their vehicle is the combination of written instructions/taught classroom-based activities and on-road driving practice (IAM RoadSmart, 2016; Stanton, et al., 2007b). Using this method, drivers have been taught about and/or experienced the rules of the road, the vehicle technology, how different conditions/medications may effect driving (Bédard, et al., 2008), the risks associated with traffic accidents (e.g passengers (Lenné, et al., 2011)), how to approach and negotiate hazards efficiently and safely (Huang & Ford, 2012; IAM RoadSmart, 2016), and where they should look when changing lanes (Lavallière, Simoneau, Tremblay, Laurendeau, & Teasdale, 2012).

Research suggests that the combination of on-road practice and classroom-based activities is effective in developing the drivers’ mental models and procedural skills. After training, drivers showed better, increased and more interconnected knowledge (Stanton, et al., 2007b; Walker, et al., 2009), they had better knowledge of safe driving practices (Bédard, et al., 2008) and traffic (Söderstrom, Pettersson, & Leppert, 2006), they were less likely to commit road violations (e.g straddling lanes, incorrect lane use) (Bédard, et al., 2008; Lenné, et al., 2011) and they showed better close-down behaviours and procedural skills generally (e.g braking, speed, headway and gear changes (Huang & Ford, 2012; Lavallière, et al., 2012; Stanton, et al., 2007b)) and when negotiating hazards (e.g reduced speed sooner (Lenné, et al., 2011)). This is because the on-road driving practice reinforced the information that the drivers learnt/read and this developed their procedural skills and mental models further. This suggests that mental model training can improve drivers’ procedural skills (Table 3), therefore in driver training for AVs, theoretical and practical training should be used.

The manual driver training literature also suggests that mental model training can improve drivers’ attention and memory and hazard and risk perception, both of which further develop their mental model of the road environment and/or their vehicle. All these interactions are explained elsewhere (3.1.5 (attention and memory) and 3.1.7 (hazard and risk perception)).

* 1. **Identifying a Set of Training Requirements for Drivers of Automated Vehicles**

The eight themes identified in the manual vehicle driver training literature were applied to the literature available on driver training for AVs (26 papers), in order to develop a set of training requirements for drivers of AVs. This resulted in four challenges with AVs and these challenges and the ways in which driver training has or has not overcome these challenges are discussed. Figure 1 summarises this analysis: the key challenges are displayed in the white boxes, the driver training that was undertaken to overcome these challenges are displayed in the light grey boxes and the key themes (highlighted in **bold** throughout) that improved as a result of this training are displayed in the dark grey boxes. The following section will describe the links between challenges, training and key themes as depicted in Figure 1. The key interactions between themes (from Table 4) will also be described.

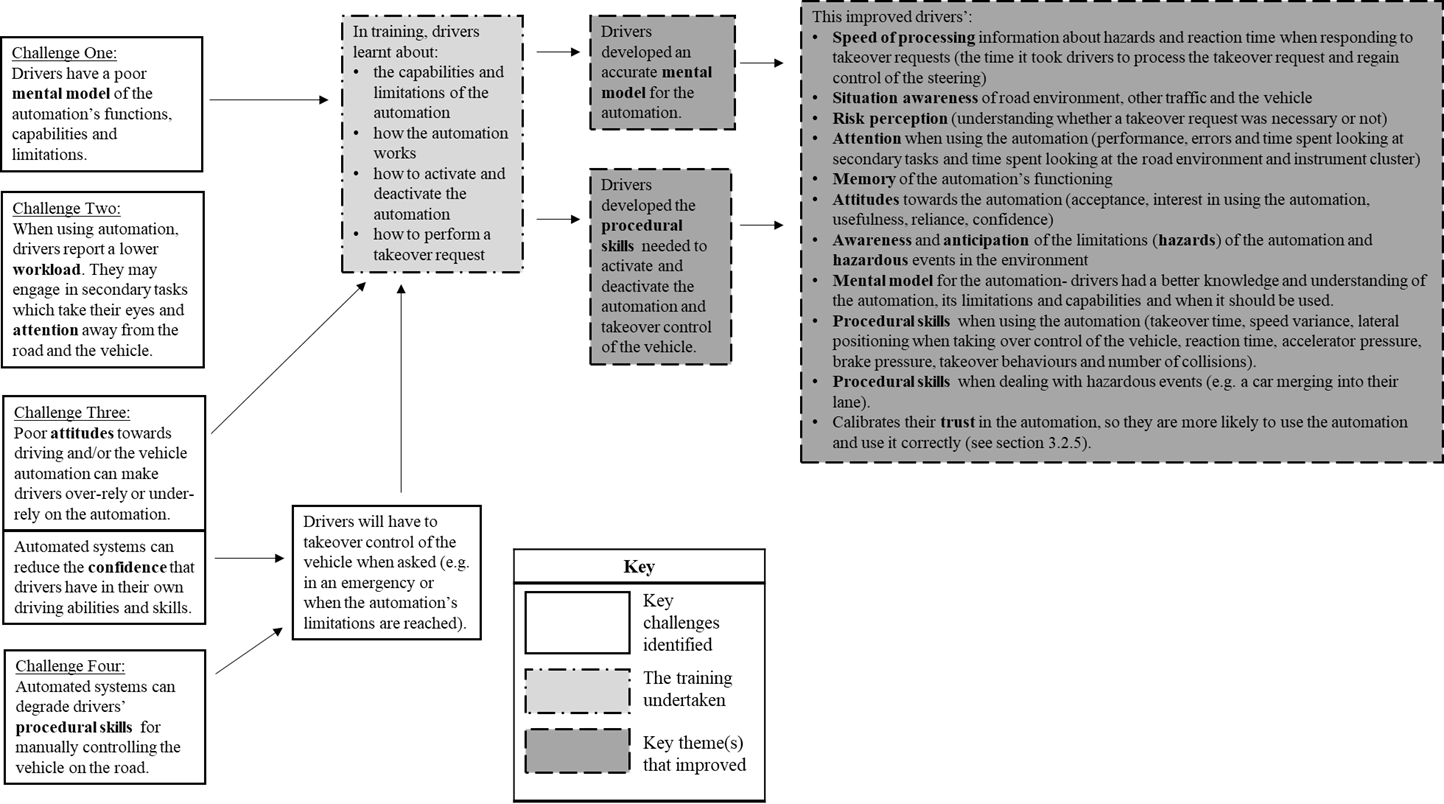


Figure 1- A summary of the relationship between the challenges of AVs, the training undertaken and the impact on key themes.

*3.2.1 Challenge One: Poor Mental Model of the Automation*

It is well cited in the AV driver training literature (and other automation domains including aviation (Trösterer, et al., 2016)) that drivers have a poor mental model of the automation’s functions, capabilities and limitations (first challenge box in Figure 1) and this can be detrimental when they use the automation (Ebnali, Kian, Ebnali-Heidari, & Mazloumi, 2019b; Revell, et al., 2020; Saffarian, et al., 2012). As mental models give drivers a set of expectations which they use to interpret events and actions in the environment (Endsley, 2017), a poor mental model impairs their situation awareness of the automation. They may have unrealistic expectations about the automation (Ebnali, et al., 2019b; Endsley, 2017) and they will not know when the automation should be used or when they need to regain control of the vehicle (Boelhouwer, van den Beukel, van der Voort, & Martens, 2019). This can negatively affect drivers’ attitudes and procedural skills. For example, if they believe that the automation is not fallible, they may over-trust and over-rely on the automation and not take over control of the vehicle when needed. However if they believe it is unreliable, they may under-rely on the automation and not use it when it could be used (Barg-Walkow & Rogers, 2016; Cahour & Forzy, 2009; Korber, Baseler, & Bengler, 2018). Therefore, in driver training for AVs, appropriate mental models for the automation need to be developed. This is because drivers’ mental models influence their procedural skills, attitudes and situation awareness (see the “from” links in Table 4).

There is a consensus in the literature that experience and context both have a considerable influence on mental model development (Bainbridge, 1992; Johnson-Laird, 1983; Moray, 1990; Revell & Stanton, 2012), therefore this link has been exploited in AV driver training programmes in order to improve drivers’ mental model of the automation. In the majority of the AV driver training programmes investigated, drivers were given a written or verbal description about the capabilities and limitations of the automation, what the automation does, how and when to activate and deactivate the automation and how to perform a takeover request (e.g. Korber, et al., 2018). They were then allowed to practice using the automation (activating and deactivating the automation, experiencing the capabilities and limitations of the automation and performing takeover requests) in a simulator (Hergeth, Lorenz, & Krems, 2017; Payre, Cestac, Dang, Vienne, & Delhomme, 2017; Sportillo, Paljic, Ojeda, Fuchs, & Roussarie, 2018a; Sportillo, Paljic, & Ojeda, 2018b) (the training box in Figure 1). This improved their mental model (knowledge) for the automation (Cahour & Forzy, 2009; Forster, Hergeth, Naujoks, Krems, & Keinath, 2019; Koustanai, Cavallo, Delhomme, & Mas, 2012), as drivers had a better knowledge of the functionality of the automation after training (Beggiato, Pereira, Petzoldt & Krems, 2015) and the latter elements also taught them the procedural skills they needed to operate (activating and deactivating the automation) and takeover control of the vehicle (Korber, et al., 2018; Koustanai, et al., 2012) (the bidirectional link between mental models and procedural skills in Table 4 and the two smaller theme boxes in Figure 1).

As a result, drivers’ risk perception (understanding whether a takeover request is necessary or not) (Ebnali, et al., 2019a) and situation awareness of the automation, other traffic and the road environment improved (Ebnali, et al., 2019b; Forster, et al., 2019) (second and third bullet points in the last theme box in Figure 1). This is because drivers were more likely to use the automation. As the automation controlled some (Level 2) or all (Level 3) of the dynamic driving tasks, this freed up some of the resources that drivers would usually allocate to the driving task so more resources could be allocated to scanning, perceiving and understanding elements in the environment, increasing their situation awareness (Endsley, 2017). Additionally, this increased situation awareness further improved drivers’ mental model for the automation (drivers had a better understanding of the limitations and capabilities of the automation and when it should be used (Forster, et al., 2019; Koustanai, Mas, Cavallo, & Delhomme, 2010) and their procedural skills when using the automation (takeover time, reaction time, takeover behaviours and number of collisions) (Ebnali, et al., 2019b; Forster, et al., 2019; Koustanai, et al., 2012). Therefore this supports the “from” link from situation awareness to procedural skills and the bidirectional link between situation awareness and mental models in Table 4.

*3.2.2 Challenge Two: How to Ensure Optimum Workload*

When drivers use automation, they report a lower workload and reduced demands on their attentional resources (de Winter, Happee, Martens, & Stanton, 2014; Endsley, 2017; Saffarian, et al., 2012; Stanton & Young, 2005). The automation is controlling some (Level 2) or all (Level 3) of the dynamic driving tasks, therefore drivers may allocate more of their attentional resources to the non-automated aspects of driving, the road environment (weather, road signs, road layout, infrastructure, other traffic, hazards) and the interfaces in the vehicle (Funke, Matthews, Warm, & Emo, 2007). As a result, their ability to respond to hazardous events, such as a takeover request or a pedestian or object on the road, may improve (Koustanai, et al., 2012; Rudin-Brown & Parker, 2004). Therefore in hazardous situations, the drivers’ attention affects their procedural skills, supporting the “from” link from attention and memory to procedural skills in Table 4.

However there are problems associated with this lower workload (second challenge box in Figure 1). As mentioned in section 1.2, drivers of Level 2 AVs are required to monitor the automation whilst it is in operation. However, as they are not actively involved in the driving task, they may get bored and fatigued and as a result, perform this task poorly or not at all (Molloy & Parasuraman, 1996; Parasuraman, et al., 1993). In contrast, in Level 3 AVs (defined in section 1.1) drivers are not required to monitor the automation, therefore they can perform non-driving related secondary tasks whilst the vehicle is driving autonomously. This is problematic because secondary tasks take drivers’ eyes (and therefore attention, see section 3.1.5) away from the road and the vehicle. This could impair their ability to respond to hazardous events; they may not takeover control of the vehicle when needed (Endsley, 2017) and they take longer and are less successful (making them more likely to have collisions) when trying to takeover control of the vehicle (Funke, et al., 2007; Korber, et al., 2018). This suggests that the type of driving automation used (see section 1.1 for the different types) and what drivers do when automation is being used can affect their procedural skills when dealing with hazards on the road. Therefore due to these different monitoring challenges, different training requirements will be needed for drivers of Levels 2 and 3 AVs. In training programmes for drivers of Level 2 AVs, drivers need to be told that they should monitor the automation whilst it is in operation. With regards to Level 3 AVs, even though drivers are not required to monitor the automation, due to the issues mentioned above, drivers should still be told to regularly check the automation so that they can successfully takeover control of the vehicle when required.

When the training programmes mentioned in section 3.2.1 were analysed, it was found that they did not tell drivers what tasks they should perform whilst the vehicle was driving autonomously, therefore this challenge was not captured in the training programmes (in Figure 1, there are no links between this challenge and the training or theme boxes). Despite this, the combination of mental model and procedural skills training (see section 3.2.1 above) did improve drivers’ reaction time to takeover requests (the time it took drivers to process the takeover request and regain control of the steering) (Ebnali, et al., 2019a; Hergeth, et al., 2017; Sportillo, et al., 2018a; Sportillo, et al., 2018b; Sportillo, et al., 2019), therefore their speed of processing improved (i.e the “from” links in Table 4 from mental models and procedural skills to speed of processing). Additionally, the training programmes did improve drivers’ memory of the automation’s functioning, drivers’ performance and errors on non-driving related secondary tasks and the time drivers’ spent looking at the non-driving related secondary tasks, the road environment and the instrument cluster in the vehicle (Cahour & Forzy, 2009; Korber, et al., 2018; Koustanai, et al., 2012), therefore their memory and attention when using the driving automation also improved (supporting the “from” links in Table 4 from mental models and procedural skills to attention and memory). This suggests that the consequences of this challenge (impaired attention and reaction time (speed of processing)) were captured in the training programmes (first and fourth bullet points in the last theme box in Figure 1).

*3.2.3 Challenge Three: The Effect of Personality and Attitudes*

Drivers who have a sensation seeking personality and/or an external locus of control take longer to react to hazardous events (e.g. automation failure) compared to those who are low in sensation seeking and/or those who have an internal locus of control (Rudin-Brown & Parker, 2004). Additionally, drivers who have an internal locus of control may be reluctant to handover control of the vehicle to the automation as they will still believe that they are responsible for the outcomes that occur. However, as drivers who have an external locus of control believe that external factors (e.g. other people or the automation) and factors beyond their control (e.g. luck/chance) are responsible for their driving behaviour and events/outcomes that occur, they may be more willing to handover control of the vehicle to the automation (Rudin-Brown & Parker, 2004). This suggests that drivers’ personality can affect their procedural skills (the “from” link in Table 4 from attitudes and personality to procedural skills), therefore in driver training for AVs, the drivers’ personality may influence the effectiveness of the training.

Similar effects can be seen with drivers’ attitudes. Driving automation can have a negative effect on drivers’ attitudes (third challenge box in Figure 1); they can reduce the confidence that drivers have in their own driving abilities/skills, therefore they may over-rely on the automation and use it in situations where it should not be used (Koustanai, et al., 2010; Koustanai, et al., 2012). Similarly, if drivers have poor attitudes towards driving, this can negatively effect their procedural skills when using the automation. For example, drivers who dislike driving, worry and/or get distressed when driving, deviate more within their lane when automation is used (Funke, et al., 2007). However, if drivers accept the automation, they are more likely to use, comply, rely and depend on the automation (Barg-Walkow & Rogers, 2016; Endsley, 2017; Saffarian, et al., 2012) and they show better procedural skills when using it; they take over control of the automation faster and have fewer collisions on the road, compared to those who do not accept the automation (Ebnali, et al., 2019b). This suggests that drivers’ attitudes can affect their procedural skills (the “from” link in Table 4 from attitudes and personality to procedural skills), therefore in driver training for AVs, positive attitudes towards the automation need to be developed.

When the training programmes mentioned in section 3.2.1 were analysed, it was found that the combination of mental model and procedural skills training did improve drivers’ attitudes towards the automation (the “from” links in Table 4 from mental models and procedural skills to attitudes and personality and the sixth bullet point in the last theme box in Figure 1). They increased drivers’ interest in driving an AV, their acceptance, usefulness and confidence towards the automation, their compliance, their opinions towards the pleasantness and security of the automation and their (reduced) willingness to engage in secondary tasks (Barg-Walkow & Rogers, 2016; Beggiato & Krems, 2013; Boelhouwer, et al., 2019; Cahour & Forzy, 2009; Sportillo, et al., 2018b). However the training programmes did not increase drivers’ confidence in their manual driving abilities/skills, so drivers may still over-rely on the automation after undergoing this training. Therefore, this challenge was only partly captured in the training programmes.

*3.2.4 Challenge Four: Procedural and Hazard Perception Skill Degradation*

As AVs control some (Level 2) or all (Level 3) of the dynamic driving tasks, this can degrade drivers’ manual driving skills over time (Saffarian, et al., 2012) (last challenge box in Figure 1). This is problematic because with Level 2 and Level 3 AVs (defined in section 1.1), drivers have to takeover control of the vehicle when asked, therefore they still need to know how to brake, accelerate and steer the vehicle safely on the road (Beggiato, Pereira, Petzoldt, & Krems, 2015; Payre, Cestac, & Delhomme, 2016). Additionally if they have to takeover control of the vehicle in a limited amount of time, this can increase the workload that they experience (Funke, et al., 2007; Stanton & Young, 2005) (the “from” link in Table 4 from procedural skills to workload). This increases the stress that they experience, increasing their workload further (Funke, et al., 2007). This suggests that training programmes for drivers of AVs need to reduce the workload that drivers experience.

Additionally the level of driving automation used will influence how much attention drivers allocate to the driving task. The more aspects of the driving task that are controlled by the human (i.e the more procedural skills that drivers carry out) (Levels 0-2 Automation, see section 1.1), the more attentive they will be towards the driving task (Endsley, 2017). This is because they are more involved in the driving task. However, if the driving automation controls all dynamic driving tasks (Level 3 automation and beyond), the driver becomes less involved in the driving task. This frees up some of the resources that they would usually allocate to controlling and handling the vehicle, therefore more of their attention can be directed to the road environment increasing their hazard and risk perception (Endsley, 2017)(the “from” links in Table 4 from procedural skills to attention and memory and hazard and risk perception). Therefore in driver training for AVs, drivers’ procedural skills for activating and deactivating the automation (e.g. pressing buttons and/or the pressing the brake or accelerator (Beggiato, et al., 2015)) and manually controlling the vehicle need to be trained.

When the training programmes mentioned in section 3.2.1 were analysed, it was found that they taught drivers the procedural skills needed to activate and deactivate the automation and takeover control of the vehicle (the training box in Figure 1). As a result, their automation procedural skills including takeover time, speed variance, standard deviation of lateral position, accelerator pressure, brake pressure, response time and behaviours towards hazardous events (e.g. a car merging into their lane) and number of collisions on the road improved (Ebnali, et al., 2019a; Ebnali, et al., 2019b; Koustanai, et al., 2010; Payre, et al., 2016; Payre, et al., 2017; Sportillo, et al., 2018a; Sportillo, et al., 2019) (evidence for the “from” links in Table 4 from mental models to procedural skills). However the training programmes did not teach drivers how to manually control their vehicle on the road (brake, accelerate and steer the vehicle), therefore this challenge was only partly captured in the training programmes (see Figure 1). Once drivers have taken over control of their vehicle (performed the takeover procedure), they will still need to manually control their vehicle on the road, therefore these manual procedural skills will still need to be taught (or refreshed for experienced drivers) in future training programmes for drivers of AVs.

Additionally, these training programmes did not reduce the workload that drivers experienced when they were compared to a no-training control group (Ebnali, et al., 2019b). This could be because in the training programmes investigated, drivers were only exposed to the driving automation on one occasion, therefore there was not enough time for their AV procedural skills (activating and deactivating the automation and performing takeover requests) to become automated (which in-turn would have reduced the workload that they experienced (van Leeuwen, et al., 2015)). In driver training for manual vehicles, drivers practice the procedural skills needed to manually control their vehicle on the road (e.g. steering, accelerating, braking, use of gears) on multiple occasions before they take their practical driving test. This ensures that these procedural skills become automated, reducing the workload that they experience. Therefore this suggests that in driver training for AVs, drivers should be made to practice the procedural skills needed to manually control their vehicle on the road, perform takeover requests and activate and deactivate the automation on many occasions so that these skills become automated and their workload reduces. Additionally, this will increase the drivers’ confidence in their manual and automated driving skills, helping to overcome the challenge of reduced confidence mentioned in section 3.2.3.

Finally, as the limitations of the automation are risky/hazardous situations for the driver and other road users (if the driver does not take over control of the vehicle in time, they could crash, get injured or die), the training programmes (mentioned in section 3.2.1) improved drivers’ hazard perception (the seventh bullet point in the last theme box in Figure 1 and the “from” links in Table 4 from mental models and procedural skills to hazard and risk perception). This is because drivers became more aware of the limitations of the automation and they became better at anticipating hazardous events in the environment (Beggiato & Krems, 2013; Cahour & Forzy, 2009; Ebnali, et al., 2019a; Sportillo, et al., 2019). As a result, their procedural skills in these situations improved (the “from” link in Table 4 from hazard and risk perception to procedural skills); these drivers moved less within their lane when trying to takeover control of the vehicle (Ebnali, et al., 2019a; Ebnali, et al., 2019b), they took over control of the vehicle quicker (Ebnali, et al., 2019a; Hergeth, et al., 2017; Sportillo, et al., 2019), they released the accelerator and applied the brakes faster when alarms sounded (Koustanai, et al., 2012) and they had fewer collisions on the road (takeovers were more successful) (Ebnali, et al., 2019b). Additionally, drivers were able to encorporate these limitations into their mental model of the automation (Beggiato & Krems, 2013), which further increased their understanding and knowledge of the automation, its limitations and when it should be used (Cahour & Forzy, 2009; Forster, et al., 2019; Koustanai, et al., 2012) (the “from” link in Table 4 from hazard and risk perception to mental models).

However, as drivers may still have to manually control the vehicle on the road (see above), they will still need to be taught about what they should attend to in the environment in order to detect and perceive (and therefore avoid) the more traditional hazards on the road (e.g pedestrians, bends). This was neglected in the AV driver training programmes that were mentioned in section 3.2.1 (see Figure 1), as the focus was on the limitations of the automation (i.e. the hazards associated with the automation), which could explain why there was more evidence for an interconnection between situation awareness and hazard and risk perception and attention and hazard and risk perception in the manual vehicle driver training literature (see Table 3 and Table 4). As the limitations of the automation (i.e. the situations where the driver may have to takeover control of the vehicle) are usually indicated by an alarm, drivers could use their hearing rather than their sight to perceive the danger, therefore their attention was not a useful measure to determine whether the driver had perceived the hazard or not. Instead researchers measured drivers’ reaction time when responding to the takeover request (the quicker they perceive the limitation, the faster they will respond to the takeover request). However as the drivers’ ability to detect and perceive hazards on the road is still important when driving an AV (see above), the traditional hazard perception training of improving drivers’ attention (i.e what they look at in the driving scene (e.g Pollatsek, et al., 2006)) and/or situation awareness of the driving scene (via commentary training (e.g Isler, et al., 2009)) should be implemented in future training programmes for drivers of AVs.

*3.2.5 The Introduction of Trust as a Key Theme in Automated Vehicle Driver Training*

Trust was mentioned in 21 of the 26 AV driver training papers (77.8%), therefore trust became the ninth “key” theme in AV driver training. Trust is an attitude that the user has about an entity (system, person, object or technology) which affects their expectations and interactions with that entity (Cahour & Forzy, 2009).

Developing trust in the automation is important because research suggests that the driver’s trust influences their attention and procedural skills (the “from” links in Table 4 from trust to attention and memory and procedural skills). If the driver’s trust is calibrated, they will perform more appropriate behaviours (e.g braking rather than steering or accelerating) and have fewer collisions on the road (i.e will be more successful) when taking over control of the vehicle (Ebnali, et al., 2019b; Korber, et al., 2018; Payre, et al., 2016). However problems occur when their trust is too high or too low. If they do not trust the automation, they will be reluctant to handover control of the vehicle to the automation (Cahour & Forzy, 2009) and they may not use it, even in situations where the automation is safe to use (Boelhouwer, et al., 2019; Lee & See, 2004). However if their trust is too high, they will over-rely on the automation, use the automation in situations which exceed the automation’s capabilities (Lee & See, 2004; Korber, et al., 2018) and not takeover control of the automation when needed (Barg-Walkow & Rogers, 2016; Boelhouwer, et al., 2019; Rudin-Brown & Parker, 2004).

With regards to their attention, although the driver has to monitor the automation in a Level 2 AV (defined in section 1.1) and takeover control of Level 2 and Level 3 AVs when asked, if they over-trust the automation, they may not do these tasks (Korber, et al., 2018; Rudin-Brown & Parker, 2004; Saffarian, et al., 2012). They may allocate less attention to the road environment and the automation and in a Level 3 AV allocate more attention to secondary non-driving related activities e.g. mobile phone (Endsley, 2017; Korber, et al., 2018; Rudin-Brown & Parker, 2004). This can lead to disastrous consequences; drivers may not be able to takeover control of the AV in time, leading to a crash, injury and/or death, as described at the start of this review. Therefore in driver training, appropriate levels of trust in the automation needs to be developed.

One way this can be done is by improving drivers’ mental models, hazard and risk perception and procedural skills. Research suggests that if drivers are told about and experience the automation’s capabilities and limitations in training (i.e. the training mentioned in section 3.2), they will develop an accurate mental model for the automation and they will know what risks/hazards may occur and how and when to take back control of the vehicle when required (Cahour & Forzy, 2009; Koustanai, et al., 2012). This calibrates their trust in the automation (Beggiato & Krems, 2013; Ebnali, et al., 2019b; Hergeth, et al., 2017; Sportillo, et al., 2019) (the final bullet point in the last theme box in Figure 1) which in-turn influences if, how and when they use it (their procedural skills) in the future (Barg-Walkow & Rogers, 2016; Koustanai, et al., 2010; Rudin-Brown & Parker, 2004). Therefore this provides evidence for the “from” links in Table 4 from mental models, procedural skills and hazard and risk perception to trust.

However, for training programmes to be effective in calibrating drivers’ trust they need to convey accurate information about the reliability of the automation. The reliability of the automation is likely to be context specific as it will depend upon the ambient environmental and road conditions, the complexity of the road and surroundings, as well as the behaviour of other road users and the presence of vulnerable road users. In some situations, the automation may be very reliable and in others not so much. To do this, the research literature suggests that two things need to occur. Firstly, training materials need to provide drivers with accurate information about the capabilities and limitations of the automation. If drivers are not told about the automation’s limitations, they may not develop an appropriate mental model for the automation. They may believe that the automation is more reliable than it actually is, making them over-trust and over-rely on the automation (Beggiato & Krems, 2013) and they may use it in situations which exceed the automation’s capabilities and functions (Barg-Walkow & Rogers, 2016; Cahour & Forzy, 2009; Korber, et al., 2018). This could impair their driving performance (Ebnali, et al., 2019b) as they are less likely to monitor the automation (Cahour & Forzy, 2009; Saffarian, et al., 2012), the driving environment and the instrument cluster in a Level 3 AV (Korber, et al., 2018) (as they are more likely to engage in non-driving related secondary tasks (Endsley, 2017)), and they are less likely (and less successful at) to take over control of the vehicle when needed (Cahour & Forzy, 2009), all of which increase their likelihood of a collision. However, drivers may not be able to understand the complexity associated with too many limitations either. If drivers are informed about too many limitations (and their interactions), their mental model for the automation may also be inaccurate. They may believe that the automation is unreliable, reducing their trust in the automation. As a result, they may under-rely on the automation and not use it when it can/should be used (Barg-Walkow & Rogers, 2016). This suggests that training materials need to provide drivers with accurate information about the capabilities and limitations of the automation.

Secondly, drivers also need to experience the limitations of the automation in training. The development of the mental model is not enough on its own to calibrate drivers’ trust in the automation (Cahour & Forzy, 2009; Koustanai, et al., 2010). If drivers are only informed about the automation’s capabilities and limitations, their trust in the automation remains unchanged. This is because non-experienced limitations can disappear from the drivers’ mental model of the automation (Beggiato, et al., 2015; Beggiato & Krems, 2013). However if drivers are informed about and experience the automation’s limitations and capabilities, the limitations of the automation will remain active in the drivers’ mental models, and as a result, their trust in the automation may better match the actual automation’s reliability (Beggiato, et al., 2015; Beggiato & Krems, 2013; Koustanai, et al., 2010). Therefore, in driver training, drivers need to experience and be told accurate information about the capabilities and limitations of the automation. This will help them develop a more appropriate mental model for the automation, which in-turn will calibrate their trust in the automation (the “from” link in Table 4 from mental models to trust). Having an appropriate level of trust is important because this may improve drivers’ attention and procedural skills when using the automation (the “from” links in Table 4 from trust to procedural skills and attention and memory).

These effects correspond to Muir’s (1994) model of trust. The model suggests that if the outcomes of the automation are predictable, drivers are more likely to depend on and have faith in the automation. Therefore by providing drivers with accurate information about the limitations and capabilities of the automation and allowing them to experience these properties and how to deal with them first hand, the training makes the automation predictable whilst also developing the driver’s mental model of the automation and their procedural skills for dealing with the limitations (takeover behaviours). As the information is accurate, the driver’s mental model will correspond with/match their actual experiences with the automation, making them trust and more likely to use and depend on the automation. Therefore this suggests that training materials need to teach drivers about the capabilities and limitations of the automation and how and when they need to take over control of the vehicle, as this will help develop their trust in the automation.

**4.** **Summary, Implications and Conclusions**

AVs are expected to bring a huge number of benefits to society, however in order for them to be realised, driver training is required to teach drivers how to use them appropriately and safely on the road. As drivers of AVs are either required (Levels 2 and 3 AVs) or can (Level 4 AVs) takeover control of the vehicle when the limitations are reached or a system failure occurs, there needs to be an understanding of current driver training for manual vehicles. Through a comprehensive and systematic literature review, this paper identified eight themes which exist in current manual vehicle driver training. These were workload, speed of processing, attitudes and personality, situation awareness, attention and memory, procedural skills, hazard and risk perception and mental models. These were applied to the limited literature available on AV driver training, and a ninth theme of trust emerged. The matrices (Table 3 and Table 4) show that at all themes are interconnected with each other, therefore a multifaceted approach (covering all nine themes) to driver training is required. By taking into account the challenges associated with AVs, the current training for drivers of AVs, the gaps that were identified in this training (missing from Figure 1) and the manual vehicle driver training literature (which filled in these gaps), a set of training requirements for drivers of AVs has been identified. Table 5 displays these training requirements. The key challenges are displayed in the first column, the driver training requirements are displayed in the second column and the key themes (highlighted in **bold** throughout) that will improve as a result of these requirements are displayed in the third column. In summary, drivers need to understand the capabilities and limitations of the automation, how the automation works, what their job is whilst automation is being engaged, how to activate and deactivate the automation and how to perform a takeover request. In the majority of the AV driver training programmes that were analysed, drivers were given theoretical and/or practical training to meet these requirements. Additionally, as drivers may have to manually takeover control of the vehicle when the automation’s limitations are reached or a system failure occurs, they will still need to learn (and refresh) the procedural skills needed to control and handle the vehicle on the road (e.g. navigation, hazard detection and vehicle control) and what they should attend to in the environment in order to detect hazards on the road. These two training requirements were not covered in the AV driver training programmes that were analysed in this article, therefore when designing and developing training programmes for drivers of AVs in the future, as these skills are manual driving skills, trainers should use the ways in which these requirements are trained and measured in manual vehicle driver training (approaches identified in section 3.1) to ensure these requirements/themes are covered. For example, future training programmes could include commentary training or attention training to improve drivers’ situation awareness of the road environment, attention and hazard and risk perception. Similarly, to improve drivers’ skills and confidence in manually controlling the vehicle on the road, trainers could use a combination of theoretical and practical skill-based training over repeated sessions (e.g. one hour a week). The training solution described here is the most appropriate and effective (ideal) way to train drivers. However if this training is voluntary, drivers may not be willing to undergo such an extensive training programme due to the time and resources required. Therefore, for this training solution to be implemented effectively, mandatory driver training will need to be enforced. Future research is required to validate the themes and interconnections beyond the qualitative approach that was used in this article. This article focussed on Levels 1, 2 and 3 automation as the literature on driver training for AVs only focussed on these three types of driving automation. However Level 4 AVs are being built and tested therefore driver training will be required to teach drivers how to use Level 4 automation safely and appropriately on the road. As such, additional research will be needed to identify the training requirements for drivers of Level 4 AVs. In this paper the challenges and training requirements for drivers of Levels 2 and 3 automation have been combined, however as the driver’s and automation’s roles differ for each level of automation, future work should split these challenges and requirements for each level of automation, in order to gain a better understanding of the differences between the levels and therefore the different training solutions that should be taken. Future work will be found in applying this framework to conduct a Training Needs Analysis for drivers of AVs. This will help develop a comprehensive training programme for drivers of AVs so that all the themes identified (issues/challenges associated with AVs) can be addressed.

Table 5

*The training requirements for drivers of AVs.*

|  |  |  |
| --- | --- | --- |
| Key Challenge | AV Driver Training Requirement | Outcome (Expected Theme(s) Improvement) |
| When using automation, drivers report a lower **workload**.They may engage in secondary tasks which take their eyes and **attention** away from the road and the vehicle. This could impair their ability to respond to hazardous events and takeover control of the vehicle. | Drivers need to be told that they should **monitor** the automation whilst it is in operation. (Level 1 and 2 automation only)**.\***  Drivers need to be told about what they should **monitor** in the vehicle to check that the automation is operating correctly and how often these checks should be performed (Level 3 automation)**.\*** | This will help to improve drivers’:   * **Mental model** for the automation- drivers will have a better knowledge and understanding of the automation, its limitations and capabilities and when it should be used. * **Procedural skills** for activating and deactivating the automation and taking over control of the vehicle * **Procedural skills** when using the automation (takeover time, speed variance, lateral positioning when taking over control of the vehicle, reaction time, accelerator pressure, brake pressure, takeover behaviours and number of collisions). * **Procedural skills** when dealing with hazardous events (e.g. a car merging into their lane). * **Speed of processing** information about hazards and reaction time when responding to takeover requests (the time it takes drivers to process the takeover request and regain control of the steering). * **Situation awareness** of the road environment, other traffic, and the vehicle. * **Risk perception** (understanding whether a takeover request is necessary or not). * **Attention** when using the automation (performance, errors and time spent looking at secondary tasks and time spent looking at the road environment and instrument cluster). * **Memory** of the automation’s functioning. * **Attitudes** towards the automation (acceptance, interest in using the automation, usefulness, reliance, confidence). * **Awareness** and **anticipation** of the limitations (**hazards**) of the automation and **hazardous** eventsin the environment * Calibrates their **trust** in the automation, so they are more likely to use the automation and use it correctly (see section 3.2.5 above). |
| Drivers have a poor **mental model** of the automation’s functions, capabilities and limitations. | Drivers need to learn about:   * the capabilities and limitations of the automation * how the automation works * how to activate and deactivate the automation * how to perform a takeover request |
| Poor **attitudes** towards driving and/or the vehicle automation can make drivers over-rely or under-rely on the automation. |
| Driving automation can:   * reduce the **confidence** that drivers have in their own driving abilities and skills. * degrade drivers’ **procedural skills** for manually controlling the vehicle on the road.   However, drivers will have to takeover control of the vehicle when asked (e.g. in an emergency or when the automation’s limitations are reached). | * Drivers need to learn about the capabilities and limitations of the automation and how the automation works. * Drivers need to be taught the **procedural skills** needed to activate and deactivate the automation and perform a takeover request * Drivers need to be taught the **procedural skills** needed to control and handle the vehicle on the road (e.g. braking, steering) in both normal and emergency (hazardous) situations.**\*** * Drivers need to continuously practice these manual and AV **procedural skills**.\* * These manual and AV **procedural skills** should be refreshed and tested on a regular basis**\*** * Drivers need to be taught about what they should **attend** to in the environment in order to **detect** and **perceive** (and therefore **avoid**) hazards on the road. Therefore, they need to undergo the traditional **hazard perception** training of improving drivers’ **attention** (i.e. what they look at in the driving scene) and/or **situation awareness** of the driving scene.**\*** | * This will improve drivers’ **mental model** for the automation- drivers will have a better knowledge and understanding of the automation, its limitations and capabilities and when it should be used. * Drivers will have the **procedural skills** needed to activate and deactivate the automation and takeover control of the vehicle. * Drivers will have the **procedural skills** needed to manually control the vehicle on the road. * This will increase drivers’ **confidence** in their manual and AV driving skills. * These skills will become automated which in-turn will reduce the **workload** that they experience.   Drivers will have:   * A greater **situation awareness** of the road environment * **Attend** to more **hazards**/**risks** in the environment * See these **hazards** earlier   As a result, this will help to improve drivers’:   * **Hazard perception** of hazards in the road environment. * **Reaction time** towards the hazards. * **Procedural skills** when dealing with the hazards on the road. |

**\*** This was neglected in the AV driver training programmes that were analysed in section 3.2

**5. Appendix A**

*The manual vehicle driver training papers (68 papers) and the AV driver training papers (26 papers) that were used in this literature review.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Author(s) | Date | Title | Publication | Vehicle Mode | Theme(s) Identified |
| Ball, K., Edwards, J. D. and Ross, L.A | 2007 | The impact of speed of processing training on cognitive and everyday functions. | Journal: *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences* | Manual Vehicles | Procedural Skills; Speed of Processing |
| Barg-Walkow, L. H. and Rogers, W. A. | 2016 | The Effect of Incorrect Reliability Information on Expectations, Perceptions, and Use of Automation. | Journal: *Human Factors* | Automated Vehicles | Attitudes and Personality; Hazard and Risk Perception; Mental Models; Procedural Skills; Situation Awareness; Trust |
| Bédard, M., Porter, M. M., Marshall, S., Isherwood, I., Riendeau, J., Weaver, B., Tuokko, H., Molnar, F. and Miller-Polgar, J. | 2008 | The Combination of Two Training Approaches to Improve Older Adults' Driving Safety. | Journal: *Traffic Injury Prevention* | Manual Vehicles | Hazard and Risk Perception; Mental Models; Situation Awareness; Procedural Skills |
| Beggiato, M. and Krems, J. F. | 2013 | The evolution of mental model, trust and acceptance of adaptive cruise control in relation to initial information | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour* | Automated Vehicles | Attitudes and Personality; Hazard and Risk Perception; Mental Models; Procedural Skills; Trust; Workload |
| Beggiato, M., Pereira, M., Petzoldt, T. and Krems, J. | 2015 | Learning and development of trust, acceptance and the mental model of ACC. A longitudinal on-road study. | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour* | Automated Vehicles | Attitudes and Personality; Mental Models; Hazard and Risk Perception; Procedural Skills; Trust |
| Biassoni, F., Balzarotti, S. and Ciceri, M. R. | 2015 | The Contribution of Safe Driving Training in Educating Drivers to Risk Perception. | Journal: *Procedia Manufacturing* | Manual Vehicles | Attitudes and Personality; Hazard and Risk Perception; Mental Models; Procedural Skills |
| Boccara, V., Delhomme, P., Vidal-Gomel, C. and Rogalski, J. | 2011a | Development of student drivers' self-assessment accuracy during French driver training: Self-assessments compared to instructors' assessments in three risky driving situations. | Journal: *Accident Analysis and Prevention* | Manual Vehicles | Attention and Memory; Attitudes and Personality; Procedural Skills |
| Boccara, V., Delhomme, P., Vidal-Gomel, C. and Rogalski, J. | 2011b | Time course of driving-skill self-assessments during French driver training. | Journal: *Accident Analysis and Prevention* | Manual Vehicles | Attitudes and Personality; Hazard and Risk Perception; Procedural Skills |
| Boelhouwer, A., van den Beukel, A. P., van der Voort, M. C. and Martens, M. H. | 2019 | Should I take over? Does system knowledge help drivers in making take-over decisions while driving a partially automated car? | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour* | Automated Vehicles | Attitudes and Personality; Mental Models; Hazard and Risk Perception; Procedural Skills; Situation Awareness; Trust; Workload |
| Brooks, J., Kellett, J., Seeanner, J., Jenkins, C., Buchanan, C., Kinsman, A., Desmond, K. and Pierce, S. | 2016 | Training the Motor Aspects of Pre-driving Skills of Young Adults With and Without Autism Spectrum Disorder. | Journal: *Journal of Autism and Developmental Disorders* | Manual Vehicles | Attention and Memory; Attitudes and Personality; Hazard and Risk Perception; Procedural Skills; Speed of Processing |
| Bruce, C. R., Unsworth, C. A., Dillon, M. P., Tay, R., Falkmer, T., Bird, P. and Carey, L. M. | 2017 | Hazard perception skills of young drivers with Attention Deficit Hyperactivity Disorder (ADHD) can be improved with computer based driver training: An exploratory randomised controlled trial. | Journal: *Accident Analysis and Prevention* | Manual Vehicles | Attention and Memory; Hazard and Risk Perception; Mental Models; Procedural Skills; Situation Awareness |
| Cahour, B. and Forzy, J.-F. | 2009 | Does projection into use improve trust and exploration? An example with a cruise control system. | Journal: *Safety Science* | Automated Vehicles | Attitudes and Personality; Hazard and Risk Perception; Mental Models; Procedural Skills; Situation Awareness; Trust |
| Casner, S. M. and Hutchins, E. L. | 2019 | What Do We Tell the Drivers? Toward Minimum Driver Training Standards for Partially Automated Cars. | Journal: *Journal of Cognitive Engineering and Decision Making* | Automated Vehicles | Attention and Memory; Attitudes and Personality; Mental Models; Hazard and Risk Perception; Procedural Skills; Situation Awareness; Speed of Processing; Trust |
| Cassavaugh, N. D. and Kramer, A. F. | 2009 | Transfer of computer-based training to simulated driving in older adults. | Journal: *Applied Ergonomics* | Manual Vehicles | Attention and Memory; Procedural Skills; Situation Awareness |
| Casutt, G., Theill, N., Martin, M., Keller, M. and Jancke, L. | 2014 | The Drive-Wise Project: Driving Simulator Training increases real driving performance in healthy older drivers. | Journal: *Frontiers In Aging Neuroscience* | Manual Vehicles | Attention and Memory; Procedural Skills; Speed of Processing |
| Chapman, P., Underwood, G. and Roberts, K. | 2002 | Visual search patterns in trained and untrained novice drivers. | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour* | Manual Vehicles | Attention and Memory; Hazard and Risk Perception; Mental Models; Procedural Skills; Situation Awareness |
| Cox, D. J., Brown, T., Ross, V., Moncrief, M., Schmitt, R., Gaffney, G. and Reeve, R. | 2017 | Can Youth with Autism Spectrum Disorder Use Virtual Reality Driving Simulation Training to Evaluate and Improve Driving Performance? An Exploratory Study. | Journal: *Journal of Autism and Developmental Disorders* | Manual Vehicles | Attention and Memory; Hazard and Risk Perception; Procedural Skills |
| Crundall, D., Andrews, B., van Loon, E. and Chapman, P. | 2010 | Commentary training improves responsiveness to hazards in a driving simulator. | Journal: *Accident Analysis And Prevention* | Manual Vehicles | Hazard and Risk Perception; Procedural Skills; Situation Awareness |
| Crundall, D., Howard, A. and Young, A. | 2017 | Perceptual training to increase drivers’ ability to spot motorcycles at T-junctions. | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour* | Manual Vehicles | Attention and Memory; Hazard and Risk Perception; Procedural Skills; Speed of Processing; Workload |
| Cuenen, A., Jongen, E. M. M., Brijs, T., Brijs, K., Houben, K. and Wets, G. | 2016 | Effect of a working memory training on aspects of cognitive ability and driving ability of older drivers: Merits of an adaptive training over a non-adaptive training. | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour.* | Manual Vehicles | Attention and Memory; Procedural Skills |
| Cuenen, A., Jongen, E. M. M., Brijs, T., Brijs, K., Van Vlierden, K. and Wets, G. | 2019 | The effect of a simulator based training on specific measures of driving ability in older drivers. | Journal: *Transportation Research Part F: Traffic Psychology and Behaviour.* | Manual Vehicles | Attention and Memory; Mental Models; Procedural Skills; Speed of Processing |
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**Funding**

This research was funded by IAM RoadSmart and the Engineering and Physical Sciences Research Council.

**CRediT authorship contribution statement**

**Siobhan E. Merriman:** Conceptualisation, Methodology, Investigation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing, Visualization. **Katherine L Plant**: Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition. **Kirsten M A Revell:** Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition. **Neville A Stanton:** Conceptualisation, Writing - Review & Editing, Funding acquisition.

**Acknowledgments**

The authors would like to thank two anonymous reviewers for their helpful comments on earlier drafts of this paper.

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