Smart light-emitting textiles

as affective interfaces for the autonomous vehicle interior

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Date: 04/09/2023 Signature: Andreea G Mandrescu

ABSTRACT

This thesis investigates the use of dynamic smart textiles that emit light in different colours and intensities for car interiors, aimed to enhance vehicle users' emotional states and their relationship with the immediate environment.

Autonomous vehicle developments represent a paradigm shift for today's automotive industry. With no distinction between passenger and driver, a vehicle's interior can transform from a driving to a living space, with a focus on user/passengers' experiences. Technological advances in Human-Machine Interfaces (HMI) and 'affective interfaces' mean that smart reactive systems can now sense and respond to human psychological states, creating dynamic user experiences. Affective interfaces are currently being tested to improve safety and enhance ambiences, which is most relevant at SAE Level 5 automation, which is in the focus of this study.

This research builds on previous studies by testing users' psychological associations and preferences for lighting variations in a simulated autonomous vehicle interior. Further, it attempts to understand how users respond to coloured lighting variations, in simulated driving scenarios: (a) a motorway journey, (b) on busy inner-city streets. The simulated driving scenarios are hypothesized to cause, boredom, in scenario (a) and stress in scenario (b). Qualitative interviews were conducted where test participants were shown driving simulations with a combination of red/orange and blue/purple light-emitting smart textiles. Specifically designed questions examined whether these coloured light transitions could suitably address individual users' emotional states and strains hypothesised in these scenarios.

The outcomes of this proof-of-concept study of the CHAMEOLit simulation, will lead to the creation of a prototype model of the smart textile. Autonomous vehicles are not yet fully developed and it is accepted that testing methods are limited to simulated driving scenarios. Nevertheless, data collected from the qualitative research testing the first version of the prototype, and refined in the second version of the prototype, retains the potential to advance the development of smart textile systems for affective interfaces in future cars and further industry research is recommended. With safe driving foremost and centred on individual, human design, such tangible interfaces can recreate the emotional intelligence of autonomous cars, in dynamic ambiences.

Keywords: autonomous vehicles; smart textiles; affective interfaces; affective ambience; colour lighting.

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List of Accompanying Materials

Appendix I	Participant Information and Consent Form - PDF
Appendix II	NDA RCA – External Participants - PDF
Appendix III	Questionnaire for user participants - PDF
Appendix iv	Matrix - Excell Spread sheet
Appendix v	Ethics Approval Email – JPG & Outlook Form

Body of Practice

CHAMEOLit system – creation of CHAMEOLit system (series and final prototype)

CHAMEOLit - 14 video simulations series – MP4 video

CHAMEOLit - video simulation prototype – MP4 video

Definitions

ACC	Adaptive cruise control
ADAS	Advance driver assistive systems
ADS	Automated driving system
CMF	Colour, material and finish
DDT	Dynamic driving task
ECG	Electrocardiogram
HMI	Human-machine interfaces

ICMS	In-cabin monitoring system
LED	Light-emitting diode
ODD	Operation design domain
POF	Polymeric optical fiber
SAE	Society of Automotive Engineers
UI	User interface
UX	User experience

Chapter 1: Introduction

Developments in autonomous vehicles represent a paradigm shift for the automotive industry. With no distinction between passenger and driver, the interior of the vehicle will transform from a driving into a living space focusing on passengers' experiences. Technological advances leading to full autonomy are based on integrating ADAS and ADS systems that make vehicles automated (Lipson and Kurman, 2016). HMI and, specifically, 'affective interfaces' mean that smart reactive systems in cars can now sense and respond to human psychological and emotional states and strains (Ho and Spence, 2013). This thesis will focus on HMI in SAE Level 5 autonomous cars by testing a smart textile system, which has the potential to become an affective interface and to create an adaptable interior.

Affective Interfaces

Affective interfaces will either provide: relaxation (through sound and light), enhance the productivity/work mode or suggest social activities to connect with friends/family. Affective interfaces can be integrated into smart systems to react to data collected in the car interior via sensors and cameras including physiological changes of the passengers such as heart rate, ECG, eye movements or facial expressions. The smart system interpret the data and the smart 'affective interfaces' respond to users' emotional states with emotional intelligence in a pre-programmed manner. Typically, in the automotive industry, these studies have focused on the driver's emotions as they are meaningful for a safe drive (Eyben et al., 2010).

Much of the published literature relating to the psychology and behaviours of car users focuses on: (a) the emotional (mainly negative) states of the driver and, (b) ways of improving safety when analysing these 'disruptive' emotional states. Thus, the main emotional states that can negatively influence the driver, and by extension the safety of a journey, are road rage, fatigue, stress, confusion, nervousness, and sadness (Eyben et al., 2010). However, in autonomous cars all vehicle users will be passengers. Arguably, some, if not all negative states, can also be present in passengers in the same or similar driving scenarios (e.g., traffic jams, dangerous driving from external drivers can cause stress and anxiety, long monotonous journeys can cause boredom, fatigue or sleepiness). Therefore, this research is interested in testing smart light-emitting textiles as affective interfaces, that can alleviate potential negative states and strains for passengers in fully-autonomous vehicles, with a specific focus on two types of journeys: (a) motorway journeys, (b) busy city streets.

Smart materials

These affective interfaces could be achieved through high-performance ‘smart textiles’, which can be pre-programmed to sense, react and reversibly change their shape, form or colour when responding to electrical, magnetic or other stimuli. Passive textiles, currently used in production, could be transformed into dynamic adaptive surfaces. One type of smart textile is a light-emitting textile with optical fibres connected to a power source that can be pre-programmed to deliver coloured lighting with various intensities. The specific focus of the study will be to investigate whether smart light-emitting textiles could be used as affective interfaces.

Ambient Lighting

Human emotions and emotional states can be influenced by colour and light. One way of addressing emotional states of passengers is through light that can be pre-programmed for specific driving scenarios that cause discomfort. For example, in a study about improving mood with affective ambiences within homes, Kuijsters et.al. (2015) concluded that it is possible to change the mood with lighting ambiences with a clear, positive meaning. Similarly, in automotive studies, Hassib et. al. (2019) investigated the application of ambient (colour) lighting as an ‘emotional feedback modality’ in affective interfaces that could adapt and respond to the driver’s needs. The study showed that blue lighting was perceived as calming, and orange as alerting, close to red, and desirable when a driver’s attention was needed.

Research and Design Process

This thesis builds on the studies mentioned above, which are further discussed in the literature review, by testing users’ responses for blue/purple or red/orange lighting variations within an autonomous vehicle. It attempts to understand how users respond to these coloured lighting variations in two driving scenarios simulations: (a) motorway journey, (b) busy city streets. For this purpose, I used semi-structured interviews for qualitative research with user participants. After seeing the smart light-emitting textiles changing colours in these scenarios, participants were asked to determine if the colour lighting influenced their emotional states or strains caused by these types of driving journeys.

By analysing participants' responses, a simulation of an improved version ‘CHAMEOLit’ was created for proof of concept. CHAMEOLit is the name of the smart light-emitting textiles system used for the semi-structured qualitative interviews. The qualitative feedback provided information on the value of the smart textile system, and therefore the scope for developing it further. In order to address the aim of this study, all improvement comments and suggestions were reviewed and a prototype for future testing was created.

As autonomous vehicles are not fully developed yet, the testing methodology is limited to simulated driving scenarios and the outcome of the study will need to be interpreted accordingly. The data collected and the prototype has the potential to advance the development of smart illuminated textile systems for affective interfaces. These affective interfaces can make the emotional intelligence of autonomous cars tangible in dynamic ambiences centred on individual, human design. According to Sokolova and Fernandez-Caballero, '[t]he principal ambition of affective computing consists in trying to "humanize" computers by making them emotionally coherent to the human who interacts with them by enabling them 'to recognize, express, "have" emotion, and finally be able to demonstrate emotional intelligence' (2015, p.277).

Affective interfaces offers a great opportunity for the exploration of new materials for vehicle interiors. This study aims to show the value of smart textiles systems for the passengers of the future autonomous vehicles. CMF (colour, material and finish) design is a 'professional discipline which focuses on designing and specifying colours, materials and finishes to support both functional and emotional attributes of product' (Becerra, 2016, p.12). In the automotive industry, and as part of the author's personal experience, a CMF designer works closely with many departments, like engineering, UX/UI or production departments to create design strategies. An important aspect of CMF design is the ability to understand various trends and create visions and future opportunities for a particular brand in the next 3 to 7 years ahead of the product release. This research hopes to make the case that CMF design should incorporate smart textiles and push the use of current in-vehicle textiles to the next level, to adapt and respond to stimuli and engage with the future passenger's needs.

Chapter 2: Literature Review

The literature review is based on three main fields that are relevant for the current study alongside my personal professional experience within the particular industry. Those areas of research are: autonomous vehicle/future of driving; smart material systems/smart light-emitting textiles; user psychology/affective interfaces and ambiences (Fig. 1).

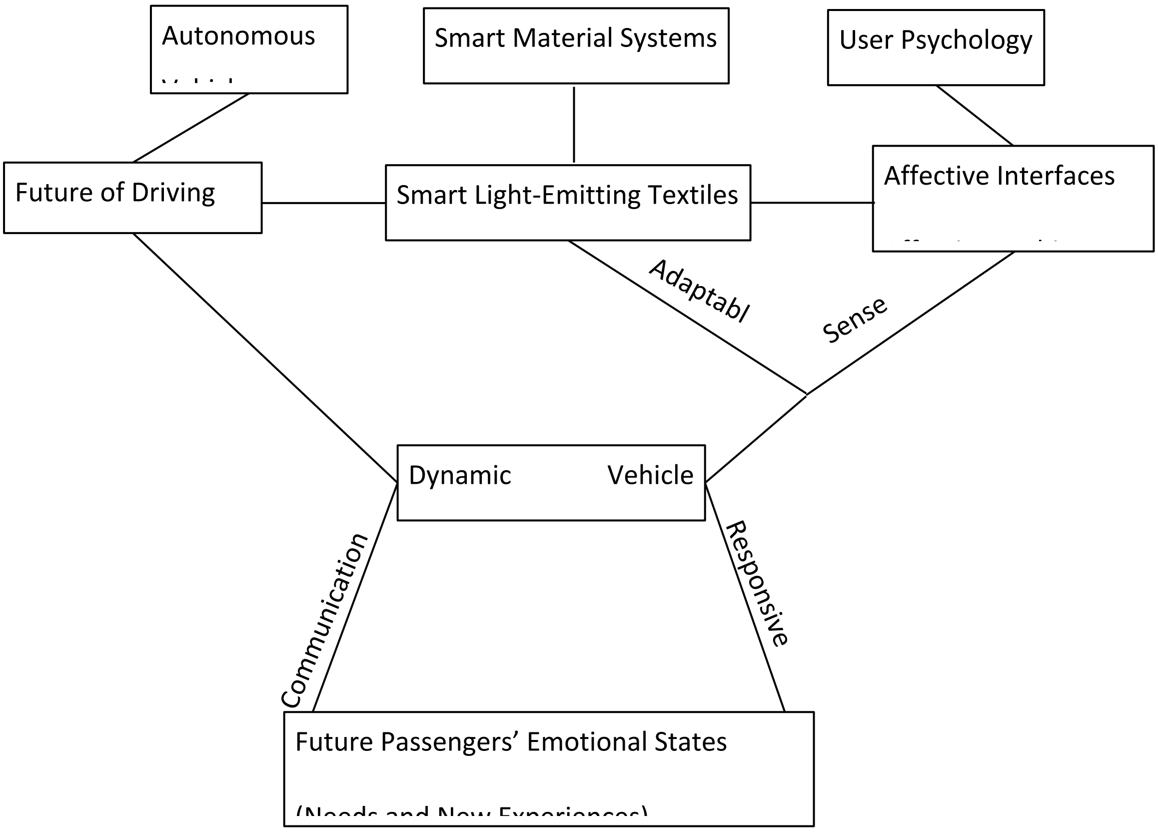

Figure 1: Research mapping. Source: Andreea G. Mandrescu (2022).

2.1 Future of Driving

This chapter introduces the levels of automation, the advancement of driving systems and in-vehicle systems, and the implications for vehicle users.

2.1.1 Levels of Automation

For a better understanding of automated vehicles, the Society of Automotive Engineers (SAE) defines six levels of automated driving from Level 0 (no automation) to Level 5 (fully automated driving).

Figure 2 shows what the levels mean for drivers, vehicles and how they operate on the road (SAE International, 2021b, p.4):

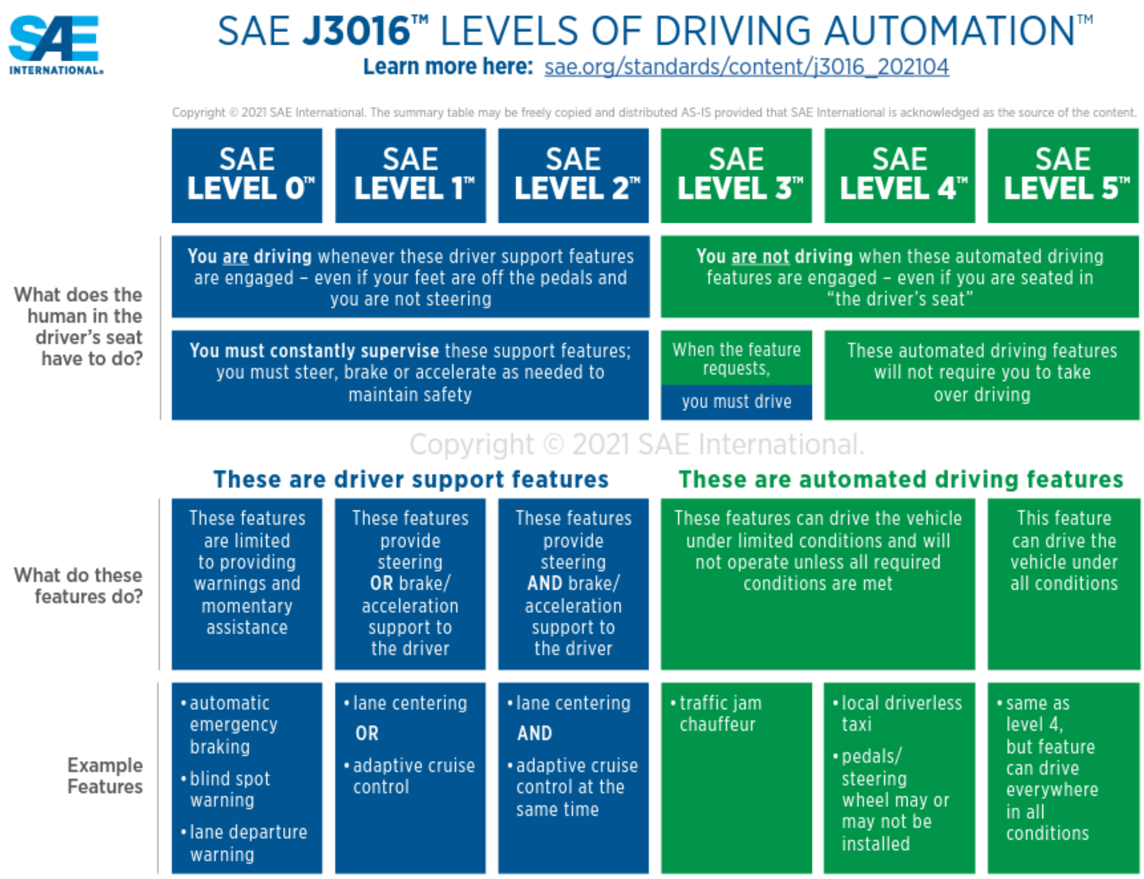

Figure 2: Visual chart. Source: (SAE International, 2021b).

The levels are described as following:

Level 0 - 'No Driving Automation' - 'the driver performs the entire DDT'.

Level 1 - 'Driver Assistance' - 'the driver performs the remainder of the DDT which is not performed by the driving automation system'. When the systems is on, it performs 'either the longitudinal or the lateral vehicle motion control subtask'.

Level 2 - 'Partial Driving Automation' – now the automation system 'performs the lateral and the longitudinal *vehicle* motion control subtasks'. (for example, Tesla's Autopilot system).

Level 3 - 'Conditional Driving Automation' - when ADS is engaged, the driver has to take over the driving, if necessary. At this level, ADS, when engaged, performs all DDT within ODD [the operation design domain]'.

Level 4 - 'High Driving Automation' - the driver becomes a passenger. Level 4 automated driving system is capable of automatically performing DDT, the main difference between level 3 and 4.

Level 5 - 'Full Driving Automation' - 'A *vehicle* with an ADS [Level 5], once programmed with a destination, is capable of operating the vehicle throughout complete *trips* on the public roadways, regardless of the starting and end points or intervening road, traffic, and weather conditions' (SAE International, 2021a, pp.28–32).

2.1.2 Examples

According to Becker (2020), the first production vehicle SAE Level 2 was released by Daimler in 2013, followed by Tesla with the Autopilot system. In 2017, Audi revealed that Audi A8 will be the first vehicle to be manufactured with SAE Level 3 driving capabilities (Traffic Jam Pilot system) with a later statement from the company that the system would be terminated in 2021 (Becker, 2020). A recent example is Mercedes that has reached SAE Level 3 with the Drive Pilot system which will be an option in 2024 S-Class and EQS Sedan models to be released end of 2023 in Germany. Currently it is the only Level 3 automation system deployed in a production car (Boora, 2023). The company is already testing this system for SAE Level 4 with Automated Valet Parking in controlled car parks. SAE Level 5, fully autonomous vehicles, are being tested but none are currently in production. In 2010, Google has tested fully driverless cars using artificial-intelligence software that can sense anything near the car and mimic the decisions made by the human driver (Markoff, 2010). Volkswagen has recently tested on-road self-driving prototypes with passengers on board to collect data for studying from driving scenarios to refine the technology (Ryan, 2023).

2.1.3 Implications For The Vehicle User

The examples above are only a few to show the progress in systems innovation and how they increasingly affect the driver's involvement in the act of driving. As the system evolves, from ADAS to ADS, the driver's role changes to a passenger in SAE Level 5. The implementation of these systems will facilitate a safer and more comfortable drive (Schmidt et al., 2010). Furthermore, Mercedes-Benz states that it is the 'ultimate luxury experience' to allow 'customers to win back precious time' when the system is active, 'through relaxation or productivity' with appealing examples of how this time can be spent, either communication with others via in-vehicle applications, or relaxing and enjoying other means of entertainment (Mercedes-Benz Group, 2022).

2.1.4 In-Vehicle Advanced Systems

Technological advances include also in-vehicle advanced systems, developed to monitor and assist the user for a safe and comfortable drive like drivers' monitoring system and driver drowsiness detection, both part of in-car safety technology. These systems, and the occupant monitoring system, are sub-systems of an in-cabin monitoring system (ICMS) (Infineon Technologies AG, 2023). In order to detect drivers' attention or the level of drowsiness, monitoring technologies have been deployed like angle sensors to detect steering wheel corrections (Honda Sensing®), or driver eye and face recognition or physiological measurements (heart rate variability) in combination with journey conditions (CORE for Tech™). The feedback varies from graphic to audio messages that alert the driver. Beyond monitoring, advanced infotainment system - as proposed in 2021 S-Class Mercedes - named "My MBUX" includes voice-activating systems, face and eye-tracking cameras which automatically detect and inform in-vehicle features to adjust angles. The infotainment and comfort settings can be also used when sitting in the rear cabin (Davies, 2020). This fact is important for this study that investigates smart material textiles, which can be pre-programmed to deliver colour changes using the current sensing features available in many vehicles.

2.1.5 Future Of Driving: From Safety To Quality Time

Research into future driving scenarios forecast the next generation of driving as 'experiences' around 'perceived safety, understanding, driving comfort [and] driving enjoyment' (Hartwich et al., 2020). McGill et al. (2020) believe that it becomes pertinent to research 'how the technology can best assist passengers in making the most of their time' during their journeys and 'how best to satisfy passengers' needs'. In automated driving, both passenger and driver are 'considered merely as agents … whose action goals and intentions are derived without individual differences' between them (Drewitz et al., 2020, p.28).

Without the need of a human driver, surveys and various workshops were conducted to predict how time will be spent in these future vehicles. The main predicted themes were 'quality time, productive time, and down time (or time for regeneration)' (Oehl et al., 2020). Two examples coming out of Renault and Volvo are concept cars for SAE Level 5 automation. The first by Renault is EZ-GO, shown at the Geneva Motor Show in 2018, which depicted a smart taxi that could provide shared rides for multiple passengers. This 'city-bound pod' allows 'walk-in access for up to six passengers, who can spend their journey working, chatting, reading, or even snoozing' (Briscoe, 2018). The second example from Volvo was the 360c fully-autonomous concept car that would provide an alternative to short-haul flights for working commutes. The car could serve as 'a mobile bedroom, replacing red-eye flights with a smoother, calmer, quicker, and more environmentally friendly travel option' (Savov, 2018). Or it could become a 'mobile office' to create a more productive and connective work commute. These fully-autonomous concept cars are looking at ways that time and space can be used purposefully, but they do not show innovative use of materials. In 2022, Volkswagen VW GEN.Travel has been developed with some of these features in mind, with a modular interior that can tailor the environment to encourage sleep with responsive light, sound and scent systems (Volkswagen Group, 2022). This latest concept is part of the trend direction which predicts that 'the industry is becoming more realistic and has settled on a core set of themes: wellness, productivity and accessibility' with a preference towards comfort (Interior Motives, 2023, p.10). The direction also foresees that the journey in autonomous vehicle is expected to become 'more of a multi-sensory experience' and different departments will work jointly like UX (user experience) and CMF to develop 'sound, lighting and even sent design' (Interior Motives, 2023, p.10). Smart material systems and smart materials offer unique opportunities for autonomous vehicle systems to create individual experiences.

2.2 Smart Material Systems

Smart material systems are important because they are being deployed across different industries from architecture to consumer goods. For example, active mass dampers that stop buildings from collapsing during earthquakes, and colour changing kettles using thermochromics. Even in orthodontic treatments, shape metal alloy Nitinol is being used in archwires to correct teeth misalignments. As a result, the application of smart materials has led to new smart products in various industries (Tao, 2001, pp.3–4).

2.2.1 Smart Systems, Smart Material Systems and Smart Materials

According to Akhras, 'smart materials and smart structures – and by extension smart systems – consist of systems with sensors and actuators that either embed in or attached to the system to form an integral part of it' (Akhras, 2000, p.25). Smart systems do not necessary incorporate smart materials to be considered 'smart'. However, smart materials are vital in smart material systems. For example, in automotive ACC (adaptive cruise control) 'intelligent automation technology' allows the user to select a driving speed and following distance, but it is not a smart material system as it does not incorporate a smart material (Parliamentary Office of Science and Technology, 2008; Verberne et al., 2012, p.801). Similarly, the in-vehicle systems, which collect data from sensors and cameras, are programmed to send a feedback reaction, a graphic signal or voice or haptic response, but do not include a 'smart material' that can change colour or shape for that purpose.

The 'smartness' element in a material, according to Ferrara & Bengisu, is 'determined by the relationship between its properties, its state, and the energy applied directly to the material' (2014, p.5). 'Smartness' can also be described in relation to material properties, such as 'self-adaptability, self-sensing, memory and multiple functionalities' (Kamila, 2013, p.876). These materials can 'sense and react to environmental conditions or stimuli 'from mechanical, thermal, chemical, electrical, magnetic or other sources ' and by their response to stimuli, they can be categorised 'into passive smart, active smart and very smart materials' (Tao, 2001, pp.2–3). Accordingly, '[p]assive smart materials can only sense the environmental conditions or stimuli; active smart materials will sense and react to the conditions or stimuli; very smart materials can sense, react and adapt themselves accordingly' (Tao, 2001, p.3). Beyond this, there is a 'higher level of intelligence' that can be realised from smart materials and structures that can react or be activated 'to perform a function in a manual or pre-programmed manner' (Tao, 2001, p.3). Due to their smart capabilities, they 'are often considered to be a logical extension of the trajectory in materials development toward more selective and specialised performance' (Addington and Schodeck, 2005, p.3).

2. 2.2 Smart Materials Classification

Smart materials can be divided into passive or active smart according to their characteristics and how they react to external stimuli (Fig. 3), or according to the input and output (Fig. 4). Optical fibres, used for their light-emitting qualities in the CHAMEOLit system, is a passive smart material. Figure 5 also shows an important group of materials, chromogenic materials, which reversibly change their colour due to external stimuli, such as light, temperature, chemicals, pressure, or electricity. These materials can also potentially be used for colour changes attributes, however, further research and testing is needed for deployment in vehicle interiors. Optical fibres, however, are technologically ready to be deployed in-vehicle.

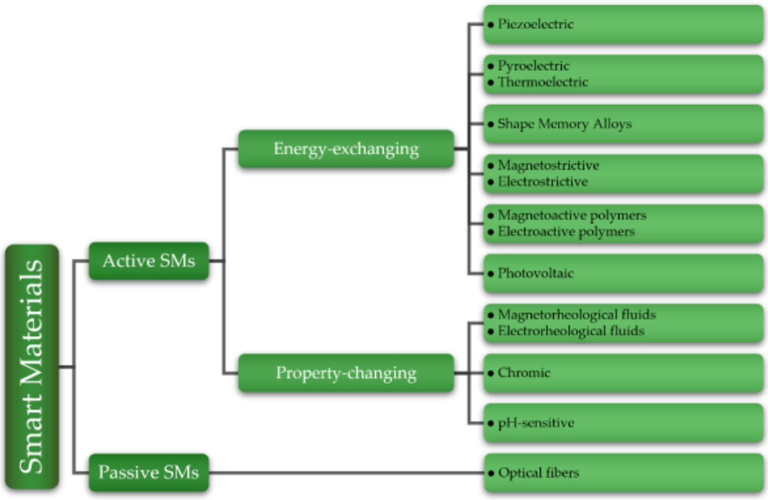

Figure 3: Smart Materials Classification: examples of active and passive SMs. Source: (Bocchetta et al., 2023, p.3).

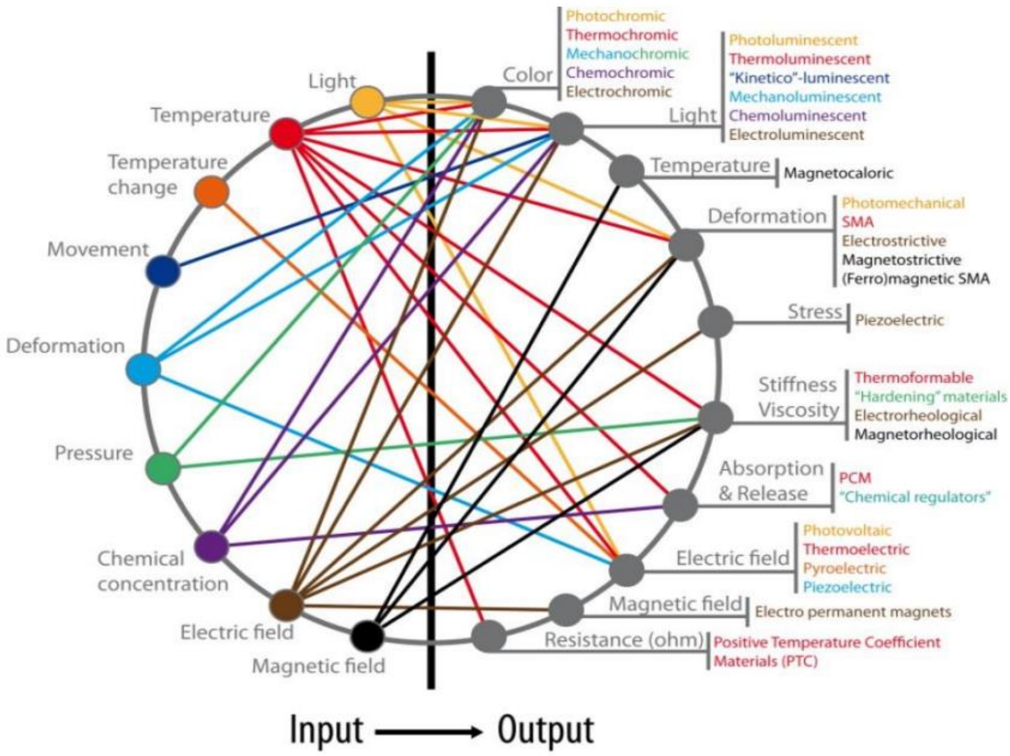

Figure 4: One possible classification of smart materials. Source: (Lefebvre et al., 2014, p.371).

2.2.3 Smart Textiles

'Smart textiles are the textile version of smart materials' (Pailes-Friedman, 2016, p.19) and are a successful outcome of combining 'traditional textiles […] with material science, structural mechanics, sensors, actuator technology, advanced processing technology, communication, artificial intelligence, biology, etc.' (Tao, 2001, p.3). They can sense changes in the environment and react to various stimuli (variations in heat, stress/pressure, chemicals, electric and magnetic fields) in predetermined ways. They can be smart with or without the integration of electric input and engineered from the molecular level up to fibres, yarns and fabrics. Different smart materials, such as shape memory, chromic and conductive materials, optic fibres etc. and sensors, devices and wires, can be applied in textiles.

The evolution and development of these textiles flourished in the past 20 years to answer new demands in medicine, performance sports and protective wear. In architecture, they are 'integrated with optical fibre sensors…to monitor the health of major bridges and buildings' or can measure 'temperature, strain/stress, gas, biological species and smell' (Tao, 2001, p.4). E-textiles, can be made conductive through conductive yarn, fibre, thread, ink, film or coating and other smart textiles can contain chromic materials and can reversibly change their colour upon different changes in the environment and stimuli like pressure/stress, electric or magnetic fields. Not only colour, but also the light can be manipulated, by incorporating LEDs, OLED lights or fibre optic lighting systems or using photoluminescent inks. CHAMEOLit would be classed as a smart textile system that is intended to deliver pre-programmed colour changing through optical fibres. Optical fibres are transparent and flexible, made from silica glass or plastic. This study focuses on polymeric optical fibre (POF) defined as 'a circular optical waveguide' with PMMA (polymethyl methacrylate) (Tao, 2001, p.141).

2.2.4 Smart Light-Emitting Textiles: In Automotive

In the context of automotives, optical fibres have already been integrated in the interior textiles with applications like 'lighting textiles' by Munda company. Munda POFs woven textiles are flexible and can illuminate and backlight textiles and non-textile surfaces. Their use in applications is functional or aesthetic rather than seeking an emotive response through colour changes. Another company with similar applications is EFI Lighting that uses Lightex® technology, which 'is a patented principle of weaving optical fibres and surfaces [in a] treatment to diffuse light' when connected with in-vehicle LED sources (EFI Lighting, 2020). Though innovative in applications, the illuminated textiles are used in a decorative manner rather than seeking an emotional response.

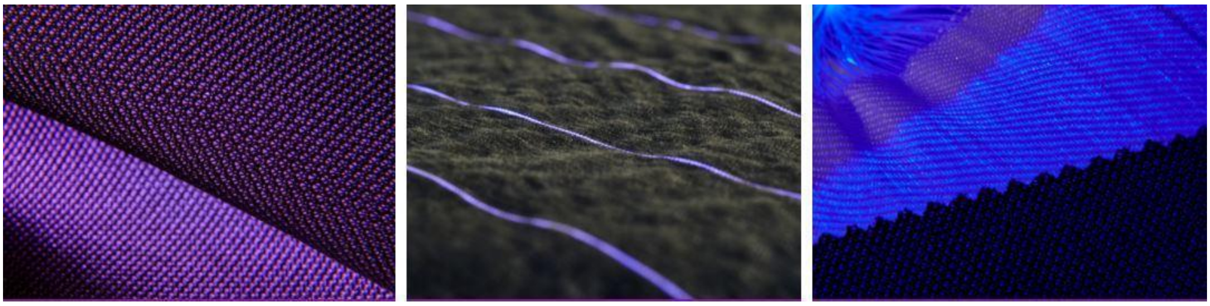

Figure 5: Textile lighting systems. Source: (Munda Textile Lichtsysteme GmbH, 2020).

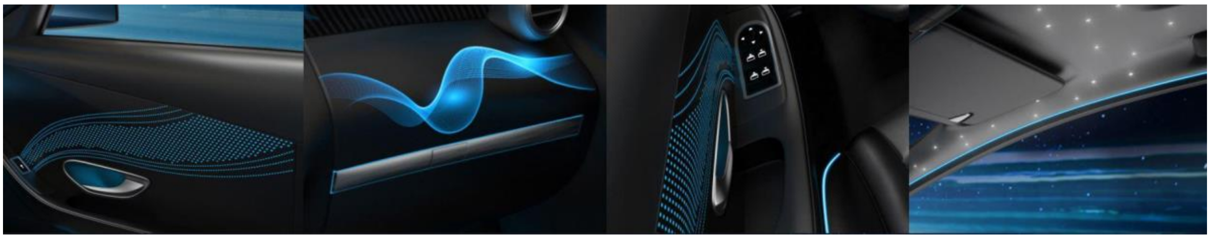

Figure 6: Textile lighting system. Source: (EFI Lighting, 2020).

2.2.5 Smart Light-Emitting Textiles: In Art And Design

More experimental implementations of POFs in non-automotive settings are also being researched. Chen et al. (2020) investigated the use of POFs directly into the loops of the textile structure using a hand flat knitting machine to create fully-knitted garments for fashion design. The research intended to apply optical fibres into a knitted structure, addressing a technical challenge. The effect created is aesthetic with potential functional applications rather than looking for an emotional response. Similarly to Chen et al. (2020), Ge and Tan (2021) researched a new Jacquard weaving technique for 3D stretchable textiles by combining double weave and elastic yarns. This was also to explore and overcome the technical challenges of creating a structure that enables movement through non-stretchable fibre optics. These examples are shown for the inspirational effect that they create.

Figure 7: Knitted POF raglan jumper, illuminated in a dim room. Source: (Chen et al., 2020).

Figure 8: Stretched state (left) and relaxed state (right) of POF sample. Source: (Ge and Tan, 2021).

Figure 9: The three-dimensional illuminance of POF sample attached to multicolour LEDs. Source: (Ge and Tan, 2021).

Barbara Jansen explores in depth the use of fibre optics in both woven and knitted textiles in her PhD, *Composing over time, temporal patterns in Textile Design* (2013). She experiments with subtle colour and light changes and colour transitions. She introduces the element of time and uniform colour transitions into her textile design, given the advancement of using optical fibres in structures. This has a strong connection to this research, which will also use time and colour transitions as part of these programmable smart textiles for autonomous vehicles.

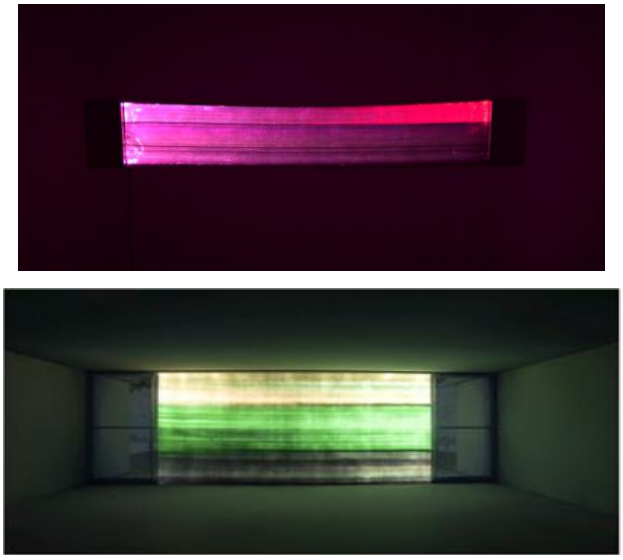

Figure 10: Expressions. Source: (Jansen, 2013).

Textile artist and designer, Sarah Taylor, explores the use of POFs in creating light-emitting paper strips and, together with Sara Robertson developed a beautiful ‘Digital Lace’. This art piece shows colour lighting transitions, also using thermochromics which reacted to heat. The textile piece is relevant for the study not only for the beautiful aesthetics that it creates, but also for the potential emotional response from the viewer through pre-programmed colour transitions.

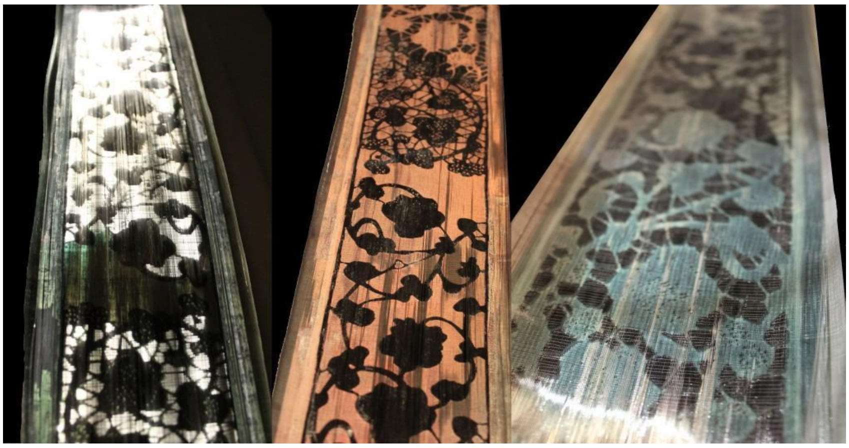

Figure 11: Digital lace. Source: (Robertson, 2014).

An award-winning textiles artist, Malin Bobeck Tadaa,, developed a unique method of integrating LEDs with sensors and electronics into fabrics and creating textile art. Her work engages with the audience which becomes part of the art-work by responding and interacting with it. Her work is inspiring, as it seeks to engage and create through interaction, an almost immersive experience which this study, seeks to achieve through the CHAMEOLit system using smart light-emitting textiles.

Figure 12: Tactile refuge. Source: (Tadaa, 2017).

The art textiles and installations, as well as the research studies above, have been inspirational for the dynamic capabilities of smart light-emitting textiles. The possibilities of dynamic changes through time in colour variations and intensities, as well as the interactive aspect in more complex systems, create experiences which, in autonomous vehicle interior, can be tailored to each journey and user.

The next section will elaborate on user psychology in relation to experience, emotional design and human-machine interfaces (HMI) in the vehicle interior. It will explain what affective computing, affective interfaces and affective ambiences are, and how light and colour have been used to influence people's perception of a space.

2.3 User Psychology

2.3.1 Interaction Design, Experience Design and Emotional Design

As explained, smart materials are transformative in nature and opens new design opportunities. According to Ferrara and Bengisu, they 'mark a turning point in the methods of design and material design'. However, the diversity of options is vast when 'temporal dimension is added to issues relating to shape, colour and texture'. Furthermore, the authors insist on the necessity of including the ‘temporal dimension, considering the variability of sensorial aspects in time and the temporal form of interaction between product and user’, which merges their design with interaction and experience design (2014, p.92).

Interaction design is ‘a user orientated design method’ which ‘aims to create a physical and emotional dialogue between a product and its user’ shown ‘in the dynamic interplay between form, function, and technology’ (Ferrara and Bengisu, 2014, p.91). Experience design ‘encompasses the design of interaction through the involvement of all senses’ as it looks at the whole ‘experience and the satisfaction of the user during the use of the product or system, with the aim to optimising them’ (Ferrara and Bengisu, 2014, p.91). Experience design methodology is interested in the ‘quality of experience of a specific user during the interaction with a specific product, and studies sensations, emotions, joy, simplicity, and ease of action’ (Battarbee and Koskinen 2007 cited by Ferrara and Bengisu, 2014, p.92).

Because experience design examines the emotional aspect of an interaction, it shows that emotions are an important factor in the process; as ‘part of the human experience while interacting with the world’, emotions influence how the world is being perceived (Bengisu and Ferrara, 2018, p.85). Since design can influence emotions, ‘emotional design’ become an important approach in order ‘to stimulate [them] through aesthetic and psychological characteristics of the object (Norman 2005 cited by Bengisu and Ferrara, 2018, p.85).

In this area, there are three theorists of note: Leonel Tiger, Don Norman, and P. W. Jordan. Jordan’s work on product design culminated in a framework of four different types of pleasure that someone can experience in relation to a product. In Designing Pleasurable Products (2000), he identified these levels as: Physio-pleasure, Socio-pleasure, Psycho-pleasure and Idea-pleasure. Physio-pleasure refers to enjoyment through the body and its senses: touch, sound and smell; socio-pleasure is derived from relationships (with friends, relatives) and aspects of relationships like status or a sense of belonging (Han and Bowerman, 2015, p.70). Psycho-pleasure is an emotional or cognitive reaction and is an appreciation of ‘stress relief, stimulation, usability and achievement [or] doing a difficult task well’ (Han and Bowerman, 2015, p.70). Lastly, idea-pleasure is related to ‘principles, tastes and aspirations’, meaning enjoyment of the values represented by a product, like green, environmental aspects. Primarily, the CHAMEOLit system would appeal to someone’s physio-pleasure, because of their sensing of coloured light changes, and psycho-pleasure, because of its intended therapeutic effect of coloured light transitions to change the users’ mood and in-vehicle ambience. It could also be argued that it may draw on socio-pleasure, through the affective interfaces ability to establish an HMI relationship.

For Norman, there are three levels of design: Visceral, Behavioural and Reflective, as defined in *Emotional Design: Why We Love (or Hate) Everyday Things* (2007). Visceral design is related to the users' perception of a product's design, and how it makes the user feel, for instance, the strategic use of colour to elicit particular moods. The behavioural level is the experience of using the product (or its usability), like a product's function, performance and effectiveness. The reflective level is about users' thoughts and feelings regarding the product before, during and after use, and can encourage users to share those experiences with others. In combination, all three of the levels make up 'product experience' (Komninos, 2020). Since this research is engaged in testing a prototype of a smart textile for an affective interface, it is important to include questions for the users that touch on all aspects of the product experience. Using Norman's framework, questions have been designed to ask about the visceral, behavioural and reflective experience of the smart textile system in video simulations.

Further, in the automotive context, experience and emotional design will be at the core of autonomous vehicles as shown previously. 'The significance of the experiential dimensions' through exploration of this new space 'might change capacities for working and relaxing; the experience of co-presence whilst on the move; how travel planning and coordination are experienced; and the sensory pleasures and pains of being on the move' (Bissell et al., 2020). According to Sokolova and Fernandez-Caballero, light and colour are 'omnipresent environmental factors' that are essential because they affect and influence human emotions; therefore, the application of coloured light is an appropriate development for creating affective interfaces in cars (2015, pp.275–276). Smart light-emitting textiles have the potential to induce and create new passenger experiences because they are dynamically responsive to the individual and can draw on light intensity and colour transitions to communicate.

2.3.2 Emotions and Affective Interfaces

In an automotive context, the communication between systems and driver/passenger is conducted via Human Machine Interfaces (HMI). However, when it comes to understanding human emotions, the system does not yet have a clear 'language' of communication to understand the driver's emotions and condition (Davoli et al., 2020). In addressing this issue, many studies have investigated various design solutions, incorporating one or a mix of visual, auditory and haptic elements for intuitive HMI (Carsten and Martens, 2019). Mehrotra et al. (2022) defined HMI as 'combined modalities' of visual, auditory and haptic interfaces, the most common being a combination of audio-visual-haptic interfaces (which makes up 58% of all HMI). The majority of R&D into HMI is at Level 3 automation, however, because it is purely passenger-focused design this particular research is positioned at Level 5 automation, where there are less available studies.

2.3.3 Future of HMI

With the vision of a fully autonomous vehicle, an intuitive HMI will make the communication between the future vehicle and the passenger more clear. As the passenger will experience a new state of interaction, having his/her needs known and answered by automated systems is 'crucial for successful, goal-oriented interaction with the environment' (Drewitz et al., 2020, p.17). 'Automated vehicles should therefore know whether their users are uncertain, stressed or nervous and react accordingly' as 'these systems must focus on the human being and be able to take into account the different nature of different human states, resulting needs and resulting intentions' (Drewitz et al., 2020, p.17).

2.3.4 New Interfaces and Tracking Passenger Emotions

In future automated vehicles, new dynamic interfaces can enhance experience through technology, to either provide relaxation (through sound and light), enhance productivity/work modes (cancelling noise) or suggest social activities to connect with friends/family (Oehl et al., 2020). From this perspective, 'human beings must be viewed as a self-changing systems (physiology and circadian rhythms, changing action motives)' (Drewitz et al., 2020, p.28). Seeing human passengers as systems that have 'changing states and basic needs' means that they 'can be influenced by situational conditions as well as the cognitions and emotions triggered by them' (Drewitz et al., 2020, p.28). There is a gap in the literature around car passengers' emotional states while driving, because most studies looked at drivers' emotions as a main factor for safety in vehicles. In a Level 5 automated vehicle, all users are passengers and the affective interfaces become part of a designed experience with a mood or atmosphere.

2.3.5 Affective Interfaces and Emotions

As part of the on-going research for intuitive HMI, affective interfaces are in development as a new type of interface between humans and machines. The term affect, within 'affective interfaces', can be described as 'several relevant constructs that are distinct, but frequently treated as interchangeable, including emotions, feelings, and moods' (Jeon, 2015). 'Emotions …occur and diminish quickly, and thus are relatively intense and clear (anger and fear)' and 'moods are less intense, more diffuse, and more enduring and thus unclear to the person experiencing them (just like feeling good or bad)' (Bodenhausen, Sheppard and Kramer 1994 and Forgas cited in Jeon, 2015). Regarding car interfaces, research is interested in the potential relationship of emotions to communication between passengers and machines, particularly relating to safety or trust.

As early as 1997, Rosalind Picard was theorising the importance of human emotions in computing systems. She believes that 'emotions are important in basic rational and intelligent behaviour, that contribute to a richer quality of interaction… in an intelligent way' (Picard, 1997, p.2). Emotions are transient and changing, including within a fixed environment like a car where time and speed contribute to the journey, so we can speak of 'emotional states' that are 'multi-variate'. Picard says that an 'emotional state refers to [a person's] internal dynamics when [they] have an emotion'. She further adds that emotional states are 'multi-variate - including aspects of both [a person's] mental state and physical state,' which 'changes with time and with a variety of other activating and conditioning factors' (Picard, 1997, p.24). Emotion detection and recognition plays an important part in creating an emotional intelligent feedback response to the user, namely the passenger in the car interior. Picard, Vyzas and Healey identified the emotions in 'all modes of communication - word choice, tone of voice, facial expression, gestural behaviours, posture, skin temperature and clamminess, respiration, muscle tension, and more' (Picard et al., 2001, p.1176). Therefore, given this definition, a system can be taught to recognise emotions, to some degree.

2.3.6 Affective Computing and Affective interfaces

The study of human emotion and computing is called 'affective computing' and was established by Picard. The word affect 'refers to feeling, emotions, mood, attitude, preferences and personality traits' (Sokolova and Fernández-Caballero, 2015, p.277). Affective interfaces and systems are part of the affective computing, which is linked to human emotions because it is computing that 'relates to, arises from, or deliberately influences emotions' (Picard, 1997, p.3). The system in which the 'human affect plays a role in the interaction between the human and its technology has been called the 'affective loop' (Sokolova and Fernández-Caballero, 2015, p.277). According to Picard, '[t]he affective loop usually consists of a five step process […]: user affect detection, user affect interpretation, system affective state synthesis, synthetic affective state expression, and user affect influence' (cited in Sokolova and Fernández-Caballero, 2015, p.277). Affective interfaces are part of it, because they are created to ‘sense, interpret, and respond to human emotions’ and ‘enhance the quality of the interaction’ (Calvo and D’Mello, 2010, p.18).

The principle of the affective system is to understand human emotional states (Braun and Serres, 2017; Hassib et al., 2019). Affective abilities and emotional intelligence will enable computers and computing to ‘respond intelligently’ to human emotions and to regulate the emotions of others, and potentially their own (Picard, 1997, p.3). According to Picard, Vyzas and Healey, emotional intelligence ‘consists of the ability to recognize, express, and have emotions, coupled with the ability to regulate these emotions, harness them for constructive purposes, and skillfully handle the emotions of others’ (2001, p.1175). While ‘affect-sensitive interfaces are being developed in a number of domains, including gaming, mental health, and learning technologies’ including vehicles, advancements in this area could bring major benefits for autonomous vehicles, because it creates a dynamic, adaptive interior that works for and with the passenger (Calvo and D’Mello, 2010, p.18).

2.3.7 Colour and Colour Lighting Impact Emotions

The dynamic effect of ambient light and colour lighting has been explored for its potential effect in improving negative emotions and moods in non-automotive research and studies. Light and colour influence a person’s mood both biologically (circadian rhythm) and as such the mood’, and psychologically, through associations, and thereby could influence affective states (Kuijsters et al., 2015). Furthermore, Ferrara & Bengisu cited Itten’s experiment from 1961 that ‘empirically demonstrated that when stationed in two different environments at the same temperature, but of a different colour, the personal sensitivity to cold can change… [in] a red/orange room people started to feel cold only when the temperature fallen down to 11-12 degrees C while they felt already cold at 15 degrees C in a blue-green room’ (2018, p.82).

These results showed that that colour has an effect on blood circulation ‘blue-green slows it down while red/orange colors stimulate it’ (Ferrara and Bengisu, 2014, p.82). This explains the use of warm colours in a ‘ski resort when they enter the building from the freezing cold outside' and cool colours used in healthcare places due to their calming effect (Ferrara and Bengisu, 2014, p.82). In their study to create a ‘colour emotion model’, Valdez and Mehrabian show that ‘[b]righter colours appeared to be more pleasant, less arousing and less dominant than darker colours… [s]aturated colours appear to be more arousing and more dominant than less saturated colours,’ while ‘hues appeared weak on emotions, a consistent support for a relationship for hue on pleasure was found’. According to this study, '[t]he most pleasant colours were blue, blue-green, green, purple-blue, red-purple and purple whereas red-yellow, green-yellow and yellow are the least pleasant (Valdez and Mehrabian 1994 in Bronckers, 2009, p.8).

Another study on the effect of colour in an office environment by Kwallek, Soon and Lewis (2007) found 'warm colours like red, made the environment more arousing compared to cool colours… [w]ith cool colours on the other hand, like green and blue, the environment was perceived as relaxed'. Their experiment used painted walls to change atmosphere, however, Bronckers (2009) tested how the atmosphere of an environment is perceived with the colour lighting using LED lights (Fig. 13).

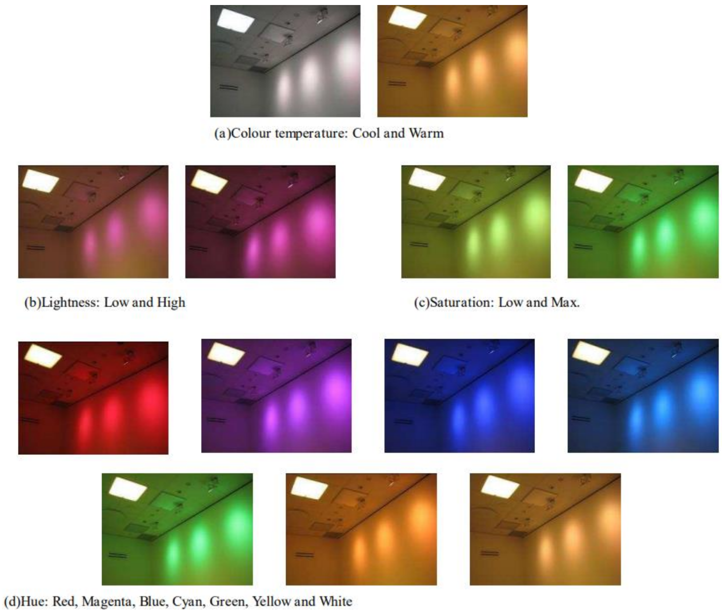

Figure 13: Photo examples of the independent factors: (a) CT of white light, (b) lightness, (c) saturation and (d) hue. Source: (Bronckers, 2009).

The experiment was conducted with forty participants and overall, the findings were: [f]or coziness the results of hue revealed that red compared to magenta, blue, cyan, green and white was perceived as the most cosy' and [b]lue and white appeared to be the least cozy' (Bronckers, 2009, p.37). These results on 'hue on the perceived atmosphere suggest that people are capable of matching colour to atmosphere' (Bronckers, 2009, p.37). This study was done on selected single hues for investigating the atmosphere that they create, however, 'in reality environments are often defined by colour combinations' (Bronckers, 2009, p.37).

In a similar direction to this research, a study by Kuijsters et al. (2015) tested users' individual responses to colour hues in light ambiences in interior design. The researchers conducted a study for improving the mood of elderly people through 'affective ambiences'. Kuijsters et al. defined this as situation whereby 'it is possible to use lighting to create ambiences whose affective connotation (also referred as atmosphere, cosy or activating) can be clearly recognised by people. A 'cosy ambience' was created using functional lighting at a lower illuminance with added orange coloured lighting and 'activating ambience' using functional lighting at a higher illuminance […] with added cyan coloured accent lighting. Respondents were exposed to mood induction lighting (sadness or anxiety) for 2, 4, 6, 8 or 10 minutes, with waiting periods in between of 2 minutes. During the tests their skin conductance response, heart rate and heart rate variability were monitored.

However, Kuijsters et al. (2015) mentioned that it is unknown whether the exposure of a person to an affective ambience actually changes a person's mood towards an intended affective state through coloured ambiences. Kuijsters et al. noted that previous research showed 'that the affective evaluation of colours was mainly based on saturation and lightness and less on hue' and that the 'saturation rather than the hue determined the arousing effect of a colour' (Mikelides 2006 cited in 2015). They concluded that it is possible to change the mood with lighting ambiences and with a clear affective connotation. Thus, higher arousal has been achieved with an activating ambience through shortwave, cyan-coloured accent lighting. The cosy ambience was reported to achieve higher pleasure and less anxiety through orange-coloured accent lighting. However, further investigations are still needed with longer exposure times on participants with true negative moods.

2.3.8 Circadian Rhythm Lighting: Pros & Cons

The Global Wellness Trends Report (2020) also showed a major shift in wellness and based on circadian health optimisation, with solutions that can reset circadian rhythms through various light applications. The shift in interest has been triggered by airline travel and the 'always-on work culture' that has disrupted circadian rhythms (Global Wellness Summit, 2020). There are various applications that work as interventions to change people's mood based on circadian rhythms. Light therapy is delivered through an app that calculates when the user needs light doses, which can help with jet lag. In addition, there are blue-light glasses to block light emitted from screens and devices or lighting systems for hotel rooms and homes that follow a circadian rhythm of cool morning tones and warm evening tones (Global Wellness Summit, 2020).

Like the wellness technology trends, this research is using light as an intervention, however, it is looking at colour lighting and colour associations in specific driving scenarios. Circadian rhythm is a twenty-four hour loop that differentiates between day and night, but specific driving scenarios could happen at any time. For example, long drives at night might need warm colours for alertness or cool colours for sleep, (depending on the passengers' needs), not the time on the clock. Equally, previous studies have used colour choices based on wave-lengths from circadian rhythms, not by research on people's preferences or associations for coloured lighting. This research will not use circadian rhythms, because the lighting smart system should react to the situation of stress or drowsiness, not the time of day.

2.3.9 Dynamic Interfaces in Cars Using Ambient Lighting

Affective interfaces and systems in the automotive industry have been investigated in industry and academia to regulate emotions, as emotions can impact performance and safety on the road (Braun et al., 2019). Eyben et al. (2010) state that much of the research investigated emotional states of the driver for safety reasons and found that the main emotional states that can influence the driving safety are road rage, fatigue, stress, confusion, nervousness, and sadness. Different affective systems and interfaces have been employed in cars to regulate these emotions, such as adaptive music, ambient lighting, emphatic speech interventions, reappraisal, relaxation techniques, state-/bio-feedback or temperature control (Braun et al., 2019, p.5; Löcken et al., 2015, p.505).

2.3.10 Emotions in Driving Scenarios

In the autonomous car, it is understood that the focus becomes increasingly centred around the passenger. In this sense, an affective interface should be designed with the principles of emotional and experience design, with the intention of creating an affective effect. While definitive data on the moods of passengers in driverless cars is not to hand, because they are not available on the road or in extensive testing, emotions of drivers can be reviewed, to determine the most common feelings associated with driving scenarios. In this way, design for an affective interface that attempts to communicate an 'intervention' to alleviate negative emotions or strains can be considered.

Two of the commonly identified emotional states in vehicles on road have been selected for the CHAMEOLit system testing: Boredom and Stress. According to the APA Dictionary of Psychology, boredom is defined as: 'a state of weariness or ennui resulting from a lack of engagement with stimuli in the environment… generally considered to be one of the least desirable conditions of daily life' and stress is defined as the physiological or psychological response to internal or external stressors. Stress involves changes affecting nearly every system of the body, influencing how people feel and behave'.

Because many studies on emotions in driving scenarios are focused on aspects of safety, they often use examples of risky behaviour for correction. Which is why this research will extend those experiments into an intervention with coloured lighting through a smart light-emitting textile, to alleviate or change such emotional states and strains.

2.3.11 Ambient Lighting in Car Interior

The following four studies use lighting in responsive ways to communicate with the drivers in simulation studies for vehicles that are not fully automated. In these applications of ambient lighting systems, the focus is on supporting the driver for more intuitive and faster decisions in certain driving scenarios. Löcken et. al. (2015) tested LED lighting in doors and the dashboard to illuminate different patterns to support drivers to make faster decisions about changing lanes (Fig. 14). This use of light is a practical signal to the driver that uses brightness to convey proximity, and not an emotional response from the driver. Similarly, in Figure 15, a purple LED stripe next to the wing mirror informs the driver of the distance to a closing car through its location and brightness (Löcken et al., 2015, p.204). They are responsive systems but not *affective* smart material interfaces.

Figure 14: Light display integrated into a driving simulator. Source: (Löcken et al., 2015, p.505).

Figure 15: Driving simulator in the middle of a trail during the experiment. Source: (Löcken et al., 2015, p.204).

Similarly, the ambient lighting system investigated by Matviienko et al. (2016) called NaviLight (Fig. 16) illuminates on the left or right of the steering wheel or dashboard to encourage the driver to steer in that direction. Another design is the ChaseLight system (Fig. 17) by Meschtscherjakov et al. (2015) that provides a visual tool to understand vehicle speed. LED lights flash along the A pillars to indicate speed relative to the speed limit on the road.

Figure 16: NaviLight. Source: (Matviienko et al., 2016).

Figure 17: ChaseLight. Source: (Meschtscherjakov et al., 2015).

Like Löcken et al. (2015), the NaviLight and Chaselight both use ambient lighting as safety signals to the driver by sensing the road and others, but not the emotions of the users. A more complex experiment with ambient lighting systems in vehicles is by Hassib et al. (2019), who tested different colour lighting to tackle negative emotions that affect or distress drivers. They tested simulations with no light, a blue light and an orange light, while collecting data from the driver. Data was collected from wearable physiological sensors to detect emotional valence (if an emotion is more positive or negative) and arousal valence (the emotion intensity) and short interviews were carried out for self-reported experiences. The orange light was intended to be calming, but the hue of the colour within the simulation was closer to red and was perceived as alarming.

Figure 18: A driver in the simulator study wearing the EEG and heart rate sensors. Source: (Hassib et al., 2019).

The difference between ambient lighting, affective interfaces and affective ambience is that ambient lighting highlights car interior features for information or aesthetics; however, affective interfaces react to passengers' emotional states while driving and can create an affective ambience. Therefore, the conclusion is that colour lighting has not yet been investigated to alleviate particular emotional states of passengers in driving scenarios, or with autonomous vehicles. Moreover, though sporadically used in the vehicle, the use of smart light-emitting materials and textiles have not been implemented for affective interfaces.

2.3.13 Ambient Lighting for Mood Atmosphere in Car Interiors

In the automotive sector, ambient lighting is being investigated for driver-focused needs but their potential within affective interfaces, especially for passengers, are unexplored. The ambient lighting sector has current and in-research applications with a market that was reported at US$ 3.1 billion in 2015 and expected to grow to US$ 4.68 billion by 2022 (Credence Research, 2016). Current applications enhance the design of the interior or particular areas that make the journey more comfortable for the driver (Credence Research, 2016). These applications are facilitated by LED advanced technology, because they have multiple colour options for car designers and are easy to integrate in vehicle interiors (Ogbac, 2020). Depending on the brand, ambient lighting varies from subtle to bright, simple to complex (lighting a place in two colours simultaneously or changing colours through the journey) (See Fig. 20 Ogbac, 2020). Examples of complex systems are the Rolls Royce headliner (Fig. 19), which mimics the effect of a starlit sky with 1300 hand woven fibre optic cables and 2020 Mercedes Benz A-class system (Fig. 20) that has 64 colours of ambient lighting with pre-coded colour selection and multicolour animated transitions.

Figure 19: Rolls Royce Wraith starlight headliner. Source: (Ogbac, 2020).

Figure 20: 2020 Mercedes Benz A Class interior ambient lighting 05. Source: (Ogbac, 2020).

2.3.14 Justification of Coloured Lighting Choices

This section justifies the reasons why the CHAMEOLit lighting system was visualised using blue and red gradients of coloured lighting in the reactive textile design. The LED lighting in CHAMEOLit can be pre-programmed for any hue of colour and a range of intensities. Because this study could not be conducted in-person in a video simulation, the luminescence and intensity of light cannot be tested via screened examples in online interviews. This meant that the contrast of colour in the ambient lighting system was the most feasible test for assessing perceived changes in user participants' mood in stressful or boring driving scenarios. On researching ambient lighting for interiors, there is a significant body of literature testing blue and red coloured lighting and its effects both physiologically, or through self-reported methods only (Adler, 2017; Ou et al., 2012; Bakker et al., 2013; Braun et al., 2019). Blue and red hues are often chosen to test in contrast in interior design studies because they represent opposites of cool versus warm colours. Cool colours like blue have short wavelengths that the majority of studies cite as calming people down, whereas warm colours have long wavelengths like red can stimulate or arouse the senses (Jacob and Suess 1975 in Dijkstra, 2009; Kaya and Epps, 2004; Yildirim et al., 2011; Mahnke 1996 in Tofle et al., 2004; Adams and Osgood 1973 in Van Hagen et al., 2009; Bakker et al., 2013). However, some physiological studies and brain research contradicts this assertion. For example, Yoto et al., (2007) and Figueiro & Rea (2010) found blue to stimulating over red, and other studies have shown no relationship between colour effects and wavelengths (Fehrman and Fehrman 2004 in Elliot and Moller, 2007; Mikkelides 1990 in O'Connor, 2011) nor between colour and mood (Ainsworth et. al. 1993 in Kaya and Epps, 2004). There are significant differences in how coloured lighting was tested, for instance, Figueiro & Rea (2010) exposed users to light at night, for up to an hour, at different levels of luminescence, which could provoke stimulation for blue light, similarly to red light. Because there is a lack of consensus in the stimulating or relaxing effect of blue or red ambient lighting in the literature, the focus of this qualitative study fell on testing user preferences between these two common colour pairings in ambient in-vehicle lighting.

Since this study could not perform physiological tests or in-person testing with controlled lighting luminescence, the main insight from the interviews came from the users' self-reported associations with the two colour gradients. Unlike many studies reviewed here, this study presented users with ambient lighting in context within the video simulation, which included other factors, such as, light that enters the car from the environment, and animated transitions between the colour gradients of blue-purple and red-orange with brightness increasing and decreasing. Taking self-reported data to open-ended questions on colour associations evokes both individual and cultural meanings. As primary colours both blue and red have been researched from multiple perspectives, with some scholars claiming universal values for these hues, and others claiming only specific cultural meanings. Blue is often reported as universally appealing as symbolising 'infinity and serenity in relation to the sky and the sea', including 'coolness, truth, tranquility [and] conservatism' but also 'introversion, sadness [and] depression' (Gunes and Olgunturk, 2020, pp.15–16). Whereas red is claimed to universally signify passionate emotions with implications of 'heat, intensity, and force' or connotations of love, passion, royalty, war, blood or fire (Gunes and Olgunturk, 2020, pp.15–16). In contrast to this, colour is understood to transmit emotion, cognitive and learned meanings particular to a society, time or place, which become intuitively associated by individuals (Gunes and Olgunturk, 2020, p.15). Nonetheless, Gunes & Olgunturk (2020), like O'Connor (2011), assert that two distinct bodies of associations exist universally for these colours. This study chose to use blue and red coloured lightings because of evidence throughout the literature review that these contrasting colours had consistently reported different associations and effects on participants. Moreover, throughout the studies reviewed here the colour blue is repeatedly tested for its anticipated calming influence, and red for its alerting or activating effect, therefore, these colours were tested in the context of autonomous vehicles simulations in this study.

Chapter 3: Key Insights and Opportunities

Having reviewed the literature, there is a clear fusion of domains with a trend for all vehicles becoming increasingly advanced. From the driver/passenger perspective, smart material systems and the smart materials are emerging in parallel that create design opportunities to re-envision the interior design for new driverless experiences. Advances in car technology show that studies can now consider more fluid communication between users and vehicles, first, as HMI and in more complex examples, as affective interfaces and ambience. When looking at experience and emotional design, colour and light intensity are useful communication tools, and smart materials form new textiles to deliver this in novel ways. Research recognises that the use of colour and lighting for psychological responses in design in vehicle interiors creates ambience. However, studies do not test the impact of coloured lighting on an individual level and especially, within targeted driving scenarios that can affect the vehicle user.

Moreover, colour and space are emotionally significant to people, which is why 'affective ambiences' are now created in home interiors, and to a large extent in vehicle interiors. Like this study, vehicle designers are hoping to alleviate negative emotional states. However, they draw inspiration from wavelengths for lighting and from circadian lighting, with the aim to relax people to sleep in the evening and encourage alertness in the morning. However, circadian lighting follows a consistent pattern (without deviations), in lighting sequences which regulate human circadian rhythms. Depending on geographical positioning, daylight and night hours can significantly increase and decrease over a year and over the course of twenty-four hours, in a consistent rhythm that gradually changes. Using circadian lighting in a driving environment, it would be used for alertness in the morning and slowly turning warmer in tones with sunset lighting, so as not to disrupt the circadian biological rhythm of the vehicle user.

However, this type of lighting is not adaptive to other needs or purposes, or moods or emotional states that the vehicle user might experience throughout a journey. For example, the vehicle user experience can be directly impacted by the journey type: a monotonous drive, which may be calming, not engaging or boring, or city drives that could stress. Further, the mood they were in before taking the journey, or any other moods that they might experience throughout and unrelated to the journey, are influential. Therefore, opportunities exist to develop affective lighting ambience that might support circadian lighting, especially when and if it is needed for jetlag or early morning journeys. Furthermore, it can adapt to other needs and moods, such as invigorating lighting for a dull monotonous journey or calming lighting in a stressful one. This qualitative study will investigate using the CHAMEOLit system to answer the following questions:

- Can smart light-emitting textiles adaptive colours influence a user's emotional states, in a driving scenario?
- Can colour changing in a vehicle environment benefit passenger emotional states?
- Fundamentally, can the system change a person's mood by changing the colour of their environment?

In order to test these questions, two different emotional states that are found common in driving scenarios will be investigated: boredom and stress. As previously defined, boredom is an emotional or psychological state that is experienced by a person due to lack of metal stimulation or engagement. A lack of stimulation can be simulated when a passenger is in a long highway journey which is uneventful and monotonous, with the same window view for many hours. The second is stress, which is an emotional strain or tension. This study has hypothesised that a stressful driving scenario would be driving through a busy city environment, with twists and turns in the road and busy traffic, from other modes of transportation and pedestrians.

I chose to test two colour groups which transition from one colour to another: orange/red (warm) and blue/purple (cool). The choices were taken from previous research findings on colour and colour lighting that deemed red, 'lively', 'cosy' and 'more aroused' and blue, 'more relaxing' and 'calming' (Kuijsters et al., 2015; Löcken et al., 2015; Hassib et al., 2019; Bronckers, 2009). I added orange (which transitions to red and back) and purple (which transitions to blue), in order to test more colours and to show their transitions, which in a real journey would be adaptive to the changes in moods and needs of a vehicle user.

The location for the CHAMEOLit was also based on literature review evaluations and in-production applications of A-pillars, dashboard and headliner used in the 2020 Mercedes Benz A-class, Rolls Royce Wraith Starlight headliner and in Meschtscherjakov et al., (2015), Matviienko et al. (2016) and Hassib et al. (2019). These examples vary in applications and research: from creating ambient lighting as a feedback modality to influence the driver's attention, to signalling lane and speed changes, to creating an ambience in the vehicle and highlighting interior features. As design prototypes, I am not exploring the smart light-emitting textiles systems for the choice of materials, or the patterns or technologies they are made of (woven, knitted or lighting through perforated or transparent, or any other material type). This is a separate area to test and individually analyse the aspects of each choice. Instead, the thesis focuses purely on colour applications and colour lighting transitions that could be programmed into an affective interface. They would be used to respond to emotional detection and physiological sensors and would incorporate AI to adapt to a particular vehicle user's emotional states or strains, moods or needs. Thus, with base data and prototype thinking, this opens possibilities to build complex, smart textile systems that in a real life environment, would need to be tested.

Chapter 4: Design and Research Methodology

4.1 Introduction

In order to create a smart textile system for a car interior, it was necessary for user testing to be carried out. In the automotive, CMF designers will create images/visualisations of material placements in car interiors to show various concepts. Similarly, the UX (user experience) team would show their designs as visualisations and videos for probing their concepts. In some cases, the presentation would be done using a rendered image or a video that can be viewed live or remotely. The design concepts can also be presented using VR/AR technology in parallel to life-size models. When these ideas reach a certain level of design maturity, they are shown in more detailed and robust videos to conduct workshops with customers by testing their opinion or introducing new concepts in the market. In automotive related studies, researchers will use the same methods for testing practical and conceptual design ideas. For that purpose, static driving simulators are also used to probe hypotheses and design prototypes or in-vehicle features. For those tests, the research is carried out using qualitative and/or quantitative research (Meschtscherjakov et al., 2015; Matviienko et al., 2016; Hassib et al., 2019; Löcken et al., 2015).

4.2 Creation of Video Series

To probe the smart textiles systems, the researcher created a series of short videos to simulate the illuminations in the vehicle interior for semi-structured interviews with user participants. The structure of the user testing variables closely follows the examples discussed previously in the literature review when testing lighting effects. However, it is limited to using in-vehicle illumination simulations in video format, presented via PC/tablet screens due to limited resources for a university thesis. Testing was based on using driving scenarios simulations to show the concept of dynamic smart light-emitting textiles system which I have called CHAMEOLit. The system would react to the passenger or environment so as to be developed in an affective interface for an automotive interior. A detailed description of the system and simulations in video series for this qualitative research is captured in the body of practice. The coloured lighting groups used were two transitions: (1) red-orange-red, (2) blue-purple-blue. This section will explain the variables of light, colour groups, illumination placements and scenarios that are being tested in the video series.

4.3 Colour Choices in User Testing Materials

The findings from two research articles were the main source of inspiration for the current study methods of testing the coloured lighting. Hassib et al., (2019) used coloured ambient lighting in car interiors as a feedback modality to alert or calm the driver with three ambient lighting conditions: (1) no light, (2) blue light, (3) orange light in a static driving simulator, testing the system with twelve participants. Their findings, using physiological sensors and semi-structured interviews, were that ambient light improved driver performance for both blue and orange. Participants reported that blue light was relaxing and improved the ambience inside the car, but orange was alarming and undesirable, except for alerting at times (Hassib et al., 2019, p.15). In the second article, the purpose was to create affective ambiences through coloured light for interior design in homes. Kuijsters et al. recreated a room in a lab and studied how elderly people may react to coloured light intended to either relax or alert them. They created a 'cosy ambience' with lower luminescence and orange coloured accent lighting and 'activating ambience' with higher luminescence to which they added cyan coloured accent lighting (2015, pp.7–8). They tested the effectiveness of no ambience, activating ambience on alleviating sad moods, and the cosy ambience for alleviating anxious moods. Their findings were that there were improvements on mood using lighting ambiences, rather than no lighting ambience at all. Interestingly, the coloured lighting used in different scenarios and environments changed the way orange coloured lighting was perceived. In Hassib et al. (2019), orange was seen as undesirable due to the connotations that it has in driving. However, in the interior of the lab room, it was successful in creating a cosy relaxing ambience.

Unlike Hassib et al. (2019) and Kuijsters et al. (2015) who used physical location to test the effects of ambient and affective lighting, this research will use video simulations to explore the effects that these studies were also investigating. The testing used semi-structured interviews to learn more about users' self-reported emotional responses and experiences when viewing the colour lighting in these videos. Since the driver of the autonomous vehicle will be a passenger or user, extensive studies and research are being done to envisage vehicle interiors as a 'living' space and not a 'driving' space. This research offers a new direction by looking at light, colour and intensity for affective ambiences, which builds on previous research into the psychological effects of light in 'living spaces' like homes and vehicles.

4.4 Qualitative Interview Approach

For testing, a qualitative research method was chosen for a number of reasons, including the fact that all of the automotive studies reviewed in this thesis used qualitative interviews as some of their testing. The advantage of a quantitative survey for these video simulation would have been an easy integration of questions and videos on a survey platform, with absolute responses to specific questions on preferences of the colour lighting and locations in each of the driving scenarios. However, the disadvantage would have been a lack of detail on the reasoning behind participants' reactions and answers. Moreover, even open-ended text boxes would have not encouraged participants to express feelings or give more creative suggestions for future designs, without the natural conversational prompts from an interviewer. This research chose to conduct semi-structured qualitative interviews online because it allowed closed and open questions, with the flexibility for the interviewer to ask follow-up questions to fully explore ideas of the users' choices, including their thoughts and feelings, and any suggestions on improvements.

The disadvantage of this approach is that it was time-consuming; each interview took between 35 mins to 90 mins, depending on the interest and participation of the user. The data collection and analysis involved reviewing each recording and transcript of the interview, in order to make notes and categorise answers in a spreadsheet (Appendix IV). Another disadvantage of conducting this online (instead of in-person), was no control over the exact colour intensity and saturation via various users' screens. However, for the first test it was deemed sufficient, with later research to be done in person at a later date. The full running time for the video was 28 minutes alone. There were opportunities to ask questions while the videos were shown, which kept interest and cut down the total interview time. In the next section, I will describe how the thesis hypotheses were tested through the interview structure and question design.

4.5 Testing Hypothesis

The aim of this thesis is to discover whether smart light-emitting textiles can be pre-programmed with coloured light transitions that alleviate users' emotional states in fully autonomous vehicles. In order to test the effectiveness or influence of coloured light transitions, video simulations had to elicit a target emotional state. A common methodology used in vehicle design is the 'affect-induction methodology': it uses audiovisual materials to provide sensory stimuli that are intended to evoke particular emotional states, within which different designs are tested in automotive related research (Jeon, 2017, pp.456, 462). This research uses affect-induction methodology and chooses videos that depict two driving scenarios known to trigger either: (a) boredom because of its monotony or (b) stress-related experience driving through busy city streets. Even though the users are viewing video simulations in this study, the passive experience is intended to evoke the situation of a passenger in a fully autonomous vehicle.

Further, the two driving scenarios was created based on the hypothesis that these two journeys would affect passengers' moods or emotional states and strains. The first scenario was part of a journey on the motorway, while the second was a busy city journey. The premise was that with 15-20 minutes on a non-eventful motorway journey passengers might feel bored, potentially wanting an interaction or distraction, which is found common in these types of situations. With the second driving scenario, the assumption was that the passenger might experience a different state of mind (potentially nervousness, anxiety or lack of patience) while in a crowded environment and in a slow journey. Therefore, the premise of this research was that particular coloured lighting transitions can act as a positive intervention for implied negative emotional states and strains. The blue/purple scheme was assumed to calm and relax and red/orange to invigorate a bored user. Accordingly, red/orange was supposed to alleviate the boredom and invigorate the passenger in the motorway scenarios and blue/purple was supposed to relax and calm a stressed passenger in the busy city scenario. For a better understanding, Fig. 21 is a diagram representation of how the CHAMEOLit system is assumed to work as an intervention in the vehicle interior during the driving scenarios.

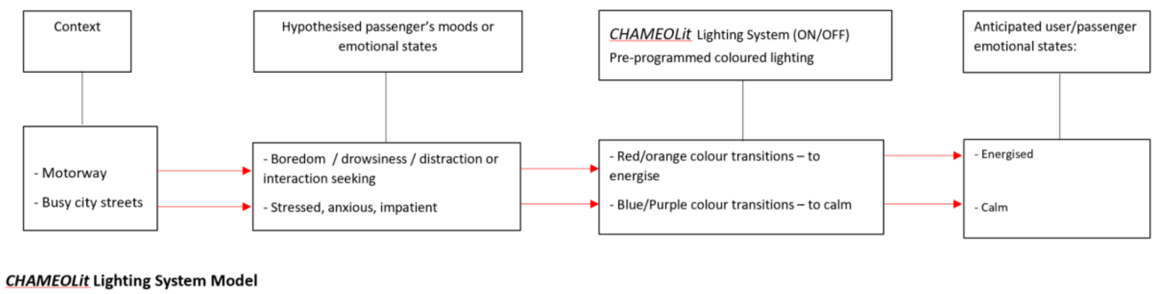

Figure 21: CHAMEOLit lighting system model used in creating the driving scenarios simulations for testing the smart light-emitting textile system. Source: Andreea G Mandrescu (2022).

4.6 Video Sequences

The semi-structured interview consisted of 14 short videos, each lasting two minutes and shown in sequence. The first sequence of seven videos 'Motorway Scenario' showed a journey in which the interviewee had to imagine that they had been on the road for 15-20 minutes and next sequence, of the seven showed 'Busy City Scenario'. The detailed information on how sequences were built to be shown to the user participants are captured in the body of practice document. Bellow, Table 1 shows the order of the video simulations starting with the motorway scenarios simulation, followed by busy city scenarios of the busy city streets and the placements of the colour transitions. Fig. 26 and 27, illustrates the exact locations of illuminations and the colour lighting effects (see body of practice: CHAMEOLit video simulation series).

Video No.	Context	Coloured Lighting	Position
1	Motorway Scenario (II Cropped)	System Off	N/A
2	Motorway Scenario (II – A)	Red/Orange	Dashboard
3	Motorway Scenario (II – A)	Red/Orange	A-Pillars
4	Motorway Scenario (II – A)	Red/Orange	Headliner
5	Motorway Scenario (II – B)	Blue/Purple	Dashboard
6	Motorway Scenario (II – B)	Blue/Purple	A-Pillars
7	Motorway Scenario (II – B)	Blue/Purple	Headliner
8	Busy City Scenario (I – Cropped)	System Off	N/A
9	Busy City Scenario (I – B)	Red/Orange	Dashboard
10	Busy City Scenario (I – B)	Red/Orange	A-Pillars
11	Busy City Scenario (I – B)	Red/Orange	Headliner
12	Busy City Scenario (I – A)	Blue/Purple	Dashboard

13	Busy City Scenario (I – A)	Blue/Purple	A-Pillars
14	Busy City Scenario (I – A)	Blue/Purple	Headliner

Table 1: CHAMEOLit lighting system video sequences.

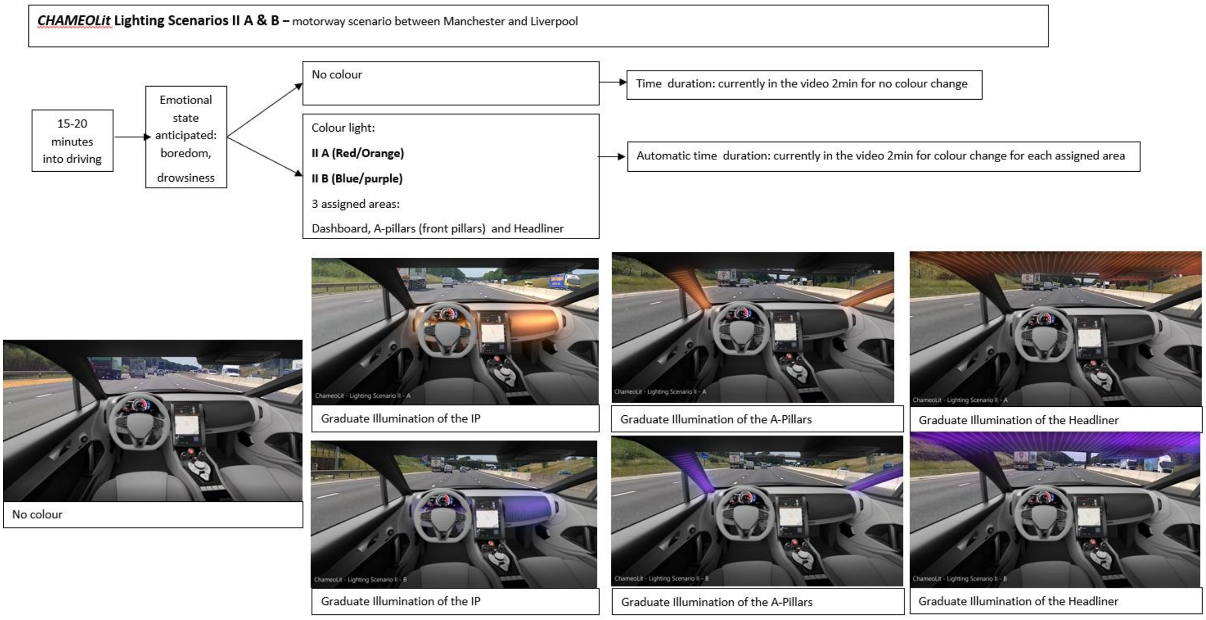

Figure 22: CHAMEOLit lighting system OFF/ON in motorway driving scenario. Source: Andreea G. Mandrescu (2022).

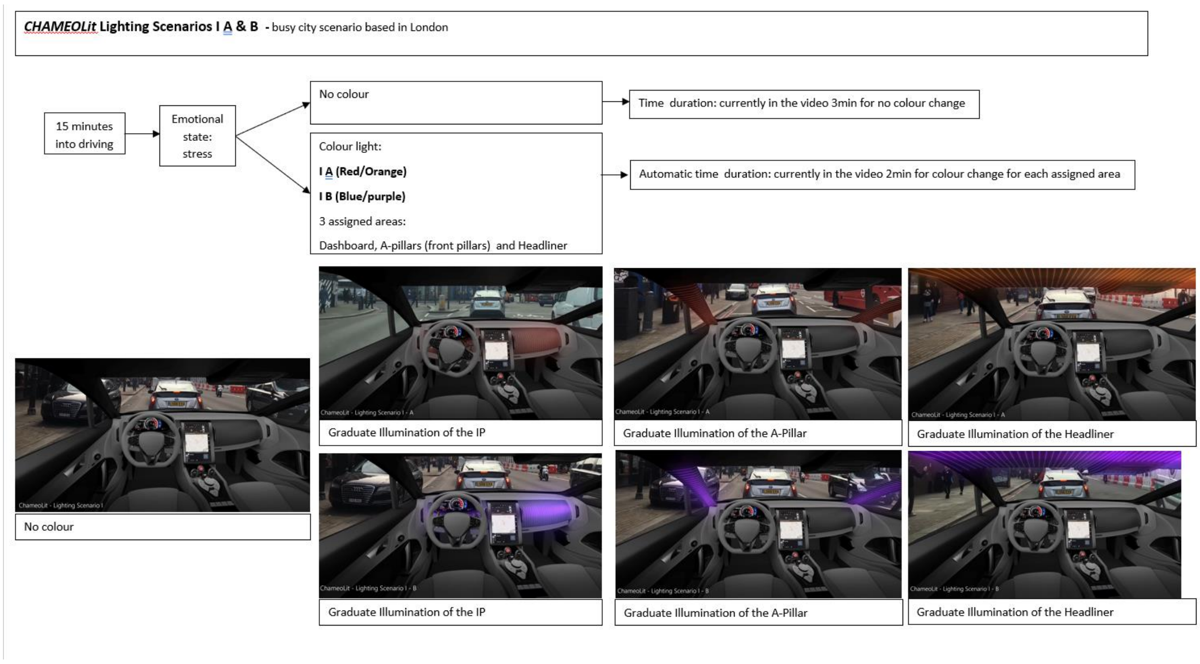

Figure 23: CHAMEOLit lighting system OFF/ON in 'busy city scenario'. Source: Andreea G. Mandrescu (2022).

4.7 Structure of Interview Questions

The questions the interviewee was asked were close- and open-ended. On viewing the videos, close-ended questions were asked for direct feedback on what was thought of the colours, placements, intensity, transition and preferences, compared to previous simulations. At the end of each video sequence, questions were open-ended and asked the interviewee for their preferences (overall) and thoughts on the lighting related to the driving scenarios (either the motorway, or later in the second sequence on the busy city street). The last section of open-ended questions was for reflections on the system's value and suggestions for different ways it can be applied, other expectations for a fully-automated car with a responsive interior smart material were also considered. The majority of the questions were geared towards testing the hypothesis of whether the scenarios caused boredom or stress (respectively), and to test if red/orange is lighting is seen as invigorating and in contrast, blue/ purple produced a calming effect. However, the most productive part of the interview was the final reflective session that established whether this type of system was of value to the participants, and how it could be optimised to improve passenger experience by improving mood, emotional states or strains. To view the full list of questions in sequence with the videos, please see Appendix III.

4.8 User Recruitment

This section will outline the procedures for recruiting participants for semi-structured qualitative interviews. The sample size for user participants was set at a minimum of 30 (the final number is 33) as is common for qualitative approaches. The literature review demonstrated that other similar studies (Hassib et al., 2019; van Huysduynen et al., 2017; Suk, 2013) have used a mixed adult population varying between 12 participants to 28 or 36 participants. Participants were found via advertising through a website known as *Call for Participants* and social media posts on the author's LinkedIn profile. This research project was approved by the Research Ethics Committee at the Royal College of Art, United Kingdom in March 2023, before recruitment began (Appendix V). To help encourage users to take part in this study, I offered a £10 voucher per person. The interviews lasted for approximately 45 minutes, and all took place via video call online using a free software, Zoom, with both the interviewer and interviewee on camera. The online interviews were recorded, with the interviewees' permission indicated in the Participation Information and Consent Form (Appendix I). The online interviews were transcribed by AI software as live closed captions, which were accessed with the saved video files after recording.

Although there was no need to be a legal driver to take part in the studies, this research replicated previous academic studies, which had surveyed a mixed adult population, only. Since the interviews relied on responding to visual aids, it was necessary to specify that all users were free of visual impairment, so as to be able to see the colours clearly and discuss the reference video in details, and importantly had no diagnosed colour blindness as the study was not intended to test participants with this condition at this time. There was little jargon or industry-specific language, but regardless, fluency in English was necessary to answer the semi-structured interview questions in detail. Because of the finer details in the video simulations, I asked for participants to access the video interviews on larger screens like computers or tablets. It was necessary to use Zoom to record and store the video data securely on the university cloud system and in private student accounts, because this software was offered as a synced, professional account to research students at the Royal College of Art.

The Participant Information and Consent Form explained to users the project, their participation and the anonymity and confidentiality (see Appendix I) and included screening questions, if diagnosed with colour blindness (in which case it was not applicable for this study) and if they had experience in the automotive industry. The second question was included in case the responses to the simulations given by professionals in the automotive industry were influenced by their professional knowledge. The second question did not eliminate the participant but was noted when looking for insight across the responses. In addition to this form, participants were asked to sign a non-disclosure agreement (Appendix II).

4.9 Recording and Data Storage

Confidentiality was maintained by keeping all the research data on an encrypted device and on a secure IT system. As mentioned above, the recordings of the online video interviews were automatically saved on the university's secure, cloud system, called the Panopto platform. From my password-protected student folder, which is only accessible with my credentials, the interview recordings were saved with fully closed captions that were auto-generated by AI software. The digital files are used for educational purposes only (for the above-described research project), and are to be erased once the research project is concluded. All responses were anonymised and each participant was assigned a number for the research discussion, e.g., 'participant 10 said they felt …'. This data retention policy was noted in the consent form.

4.10 Critique of the research design and data collection

Testing approach

It is important to acknowledge some of the potential weaknesses in the research design set out above, before beginning the data analysis. This research project is intended as a proof of concept, informed by current industry practices. In a commercial setting, this testing would have taken place in an in-person vehicle simulator or in a conference room with a large screen for a focus group to view. Increasingly VR headsets are also used. However, this project had to be adapted to the limited resources for university-based investigation. This excluded the use of an in-person vehicle simulator, VR headset and any physiological testing, which is used in similar studies covered in the literature review above.

The advantages of in-person testing as a focus group include: (a) test settings, especially for the colour and lighting variations, is identical for all user participants (b) any calibration of a single test screen is determined for all the testing (c) all users participate on the same time of day, experiencing the same light conditions in the test room. Physiological testing is possible in-person and can add additional quantitative data to a study. With regards to this qualitative research conducted online, the exact test conditions cannot be controlled. By doing video interviews each user participant will experience the coloured lighting and video simulation with minor differences depending on: (a) their device or screen size (b) lighting in their physical environment (c) screen calibration for colour or brightness. To counteract this, the research instructions for participants does specify either a tablet or computer to ensure a larger screen size. Compared to an in-person vehicle simulator this approach is less immersive, but this video simulation allows for an interplay of multiple lighting sources on the car interior from the video background. To improve participant interaction with the interviewer and the material, I will request for interviewer and interviewee to keep cameras on throughout the interview. Conducting individual interviews instead of a focus group reduces bias in group answers and allows for more personal reflections and associations. However, the varying times of day that the interviews were scheduled for, may impact interviewee alertness, as well as lighting in their physical space.

Design of experiment

The series of video simulations and the sequence of videos and questions is intended to expose the user participants to a controlled contrast of 'no lighting', 'blue lighting' and 'red lighting' and multiple driving scenarios and lighting positions. While this is thorough, it is also highly repetitive for the participant and brings the interview duration to 40 to 60 minutes. This could impact their attention span, but it is necessary to test all scenarios. The advantage of showing the driving scenario without lighting first, is to familiarise themselves with the situation before introducing the test components. On the negative side, editing the clips to 2 minutes each meant that participants will have to imagine they were 15 to 20 minutes into a journey, because showing a long continuous car journey would not repeat the same exterior events. Instead, the participants will see the same section of the journey with each lighting scenario. However, some studies may prepare participants with additional details to the scenario, for example, the purpose of the journey or preceding events to the journey. This study did not add more story elements to the scenario in order to focus on any self-reported changes to emotional states caused by the driving scenario.

Parameters of questions

Some of the disadvantages of the semi-structured qualitative interview approach in this study have been set out above in section 4.4 Qualitative interview approach and 4.7 Structure of interview questions. In summary, the scripted approach can be repetitive for the interviewee, but qualitative research was favoured over a quantitative approach to include open-ended questions that allow for more detailed and creative responses. Moreover, within an industry context, proof of concept testing with users would never be conducted only by quantitative research for new designs and applications. This is because the responses would be too limited in quality to warrant the cost and time of development for features that have not been fully explored through user experience. Therefore, qualitative methods, interview-based research and focus groups are the norm, and this and my experience as an industrial designer informed the design of this study.

Acknowledgement of conditions that affect parity

There were no demographic questions on age band, gender, nationality, country of residence, ethnic or cultural background or additional languages. This data will not be collected because the study is a proof of concept to establish if there is an interest in the general public for responsive light-emitting textiles in autonomous vehicles. This product development is not intended for particular group of consumers, the passenger-based driving experience in a fully-autonomous vehicle could be for any member of the public, including non-drivers. Again, this is why there is no screening question for driving experience.

Since this study does not collect data on age band, gender, nationality, country of residence, ethnic or cultural background or additional languages, it will not be possible to analyse the data by these characteristics. This means that there may be influences in the data collected, which cannot be attributed to specific groups of users. Therefore, generational differences, gender differences, cultural and linguistic associations cannot be explored within the data. Also, by not requiring participants to be UK residents, there is a risk that the driving conditions in the video simulations may be less familiar to some users and potentially distract their focus. Ultimately, the style of autonomous vehicle simulated without a steering wheel is not available commercially, which again tests the limits of every participants' imagination to immerse themselves in the conditions of this study.

Chapter 5: Data Analysis

This chapter presents an analysis of the results from the qualitative interviews, which coded the responses into thematic categories, and expressed the summary of the findings as a simple percentage of the total responses, but does not constitute quantitative testing or analysis. First, thematic analysis is conducted, using the Six Phases Approach suggested by Braun and Clarke (2006).

5.1 Six Phases Approach

Once the interviews had been completed, the next stage was to review material, making notes, and create a matrix for analysing the feedback on the smart light-emitting textile system depicted in the video simulations. This point marked the beginning of the qualitative thematic data analysis. Through the interviews, I wanted to test the hypothesis of particular coloured lights and journeys evoking specific moods; however, I was guided by the findings from the interviews and did not evaluate responses as incorrect by taking different feedback. In this way, thematic analysis was inductive, and I used the interview responses as a strong base for organising themes (Braun and Clarke, 2006, p.13). From a design and improvement perspective, this provided more ways to adapt the prototype and its features. All questions and answers were linked to the visual material and asked for self-reported feelings, and it did not look for deeper interpretation. Therefore, it was appropriate to use a semantic approach when analysing the interview data that takes a surface or explicit understanding of the responses (Braun and Clarke, 2006, p.14). As such, thematic analysis followed the six phases set out for qualitative data analysis.

Phase 1

I began this by listening carefully again to each recorded interview (alongside the captions) to ensure that all details and relevant information was correctly captured; here, I was looking for common meanings and patterns. In a spread sheet, I created a tab for each participant, with their answers on the right. Unfortunately, the transcript was not fully accurate, so I re-listened to the interviews and took short-form notes, with more detailed notations on their responses to the open-ended, reflective questions at the end of the interview.

Phase 2

When I reviewed the interviews and answers to the closed-ended questions, they were more diverse than anticipated. In Phase 2, the researcher is identifying initial codes, which are features in the responses that are interesting and relevant to the design process (Braun and Clarke, 2006, p.19). Before the interview, I had anticipated that the answers to the questions on the coloured lighting could be categorised as: ‘Preferred’, ‘Not preferred’ or ‘Neutral’. Broadly, this was the case for responses on the lighting placements. However, regarding responses to the lighting itself, these became more diverse and commented on aspects that were relevant to design feedback, though not asked explicitly in the semi-structured questions. The questions were focusing on placement and colour preferences, but the responses started to consider brightness and the transition of the colours. Moreover, there was a split in feedback on users’ emotions or moods related to the journey but also separately, the mood induced by the lighting. With this in mind, it was clear that I needed to create a more detailed matrix for the closed-ended questions. The open-ended ones were easily captured in long-form notes, which I revisited when I started building ideas for themes.

Phase 3

In the first attempt to code the responses, I organised the feedback into emerging themes (Braun and Clarke, 2006, p.19). By analysing the close- and open-ended answers, I highlighted repeated words that the participants used to describe their reflections and suggestions for how the system could be further developed. I took suggestions that the participants had for the coloured lighting and their improvements, and I categorised them into specific groups of design preferences and expectations. The second matrix created on the spreadsheet consisted of one tab to capture all the question responses for each participant, row by row (see Appendix IV). The focus of the matrix was to capture and compare closed-ended responses with a view to ascertain similarities,. The first column recorded the participant, experience in the automotive industry (see Appendix I), Video Number, Video Name, ‘CHAMEOLit system’ (Off, On: red/orange, On: blue/purple), and Placement (none/Dashboard/A-Pillars/Headliner. These columns were added for a quick filtering of answers). to identify themes,. Responses to the close-ended questions were split into seven columns, to fully incorporate participants’ feedback. These columns were: Placement Preference, Colour Preference, Colour Perception, Colour Brightness, Colour Transitions, Journey Mood and Lighting Mood. Most of these are easy to understand; however, Colour Perception refers to associations the participant may have had in reaction to the colours and this would be a subjective conception of colour, for instance, ‘optimistic’, ‘warmth’ and ‘calming. Colour Transitions was a preference for (or against) having a transition, and included preferences for speed or transition or other means of adapting the system.

The coding of the responses in a spreadsheet did not include any statistical calculation, it followed the system of qualitative coding to capture themes from the transcripts.

Phase 4

It was my intention through the interviews to discover users' moods associated with the journeys (the motorway and in busy city streets), and I was given specific feedback. But as the interviews progressed, it became clear that participants had strong associations with the moods created by lighting, and these moods did not necessarily match with the journey mood. They reported being bored on the journey, but did not want an 'energising' lighting mode. Many times was interpreted as an 'alerting lighting mode' due to red/orange associations to warning signs in transportation. Because my hypothesis was that the lighting would be seen as a desired intervention, I found it important to record these moods separately for comparison - journey versus lighting. Finally, the matrix included four other columns, which represented four themes drawn from my qualitative analysis of the interview data. These were: Emotional Ambience, Informative, Utilitarian and Aesthetic. As I built up thematic categories, I began to label relevant participant responses under these four themes. This point concluded Phase 4, which is when the researcher considers strong or weak aspects of the themes and works and to categorise then more carefully (Braun and Clarke, 2006, p.20).

Phase 5

Here, I identified codes within the participants' responses about the coloured lighting, their moods and immediate associations when watching the video scenarios. After analysing my notes on the interview data, I labelled each response to the close-ended questions against the four themes I had identified (Appendix IV). Through the process of comparing transcripts and themes, I simplified responses into codes such as: Not preferred, Neutral and Preferred, which were appropriate for questions on placement and colour preference. In addition, with the questions on colour perception, colour brightness, colour transition, journey mood and lighting mood, the respondents' subjective associations were usually a wide range of adjectives ('calming', 'exciting' and 'entertaining'). Where there were clear similarities, but different vocabulary used, synonymous words were counted in groups to analyse if responses agreed or differed from the hypothesis (see Data Analysis below). Early in the interview process, the first ideas for thematic coding were becoming noticeable. However, these themes illustrate a scale of distinct applications that range from affective, to purely utilitarian.

Theme 1: Emotional Ambience

This theme is most closely linked to the ultimate intention of the dynamic lighting system as an affective interface. The questions were framed to elicit emotional responses to the lighting system and journey, but it became clear that some respondents had strong mood associations. They used a wide range of adjectives to describe reactions to the environment outside and inside the car, using words like ‘calming’, ‘irritated’, ‘cocooning’ and ‘distracting’. Through the video simulations, these participants were able to tap into an emotional connotation. This included associating moods and feelings to the journey, the environment created by the lighting and to the colours of the lights themselves. The most important assumption was that the CHAMEOLit system would introduce an affective intervention to alleviate negative emotions within a journey. This category of Emotional Ambience refers to users who reported a change in their mood and feelings in the journey (due to the coloured lighting), positively or negatively. The majority of responses categorised in this theme showed a clear potential alleviation in the way that the participants would feel during the journey.

For instance, blue/purple was perceived as calming in the busy city scenario, which participants claimed to make them feel ‘nervous’, ‘alert’ or ‘anxious’. Users who valued the emotional ambience of the lighting system were most drawn to its placements in the headliner and dashboard, where they felt it had an all-encompassing impact. Their suggestions for the system were geared towards adding more light and interactive features to CHAMEOLit. They also suggested immersive experiences with lighting responding to music rhythms, which can be interpreted as seeking a richer responsive ambience that affect other senses then only visual cues from colour lighting for an emotional experience. However, there were ambiguous answers where participants would react to the lighting as ‘distracting’ or ‘alerting’. It was unclear if this was creating anxiety, or any feeling at all. It became obvious that not all participants found the CHAMEOLit system to be a simulation of an affective interface, and were only responding to its changes as a visual cue.

Theme 2: Informative

An ‘informative’ reading of the adaptive lighting system also emerged from the responses. When the responses frequently described red/orange lighting as ‘alerting’, it communicated that they were reading the lighting system in the same way that traditional signals in the transportation system are read. The lighting in the interior and exterior of the video simulation was interpreted by this group as direct feedback on the journey’s potential hazards, or the car’s performance. Comments that fell into this category included interpretations of red/orange lighting in the A-Pillar placement as a warning of cars outside coming in close to the vehicle. The dashboard lighting was understood as feedback on a possible malfunction inside the car, much like dials and indicators in today's driven cars. Categorising responses into this theme was clear because a language of signals was utilised, and this had a strong connotation between red/orange lighting as an alert of danger. Blue/purple lighting was questioned if it meant anything, or if it tried to communicate something regarding temperature like cooling, and to a lesser extent, calming.

Theme 3: Utilitarian

Beyond this theme of Informative, there were a group of users who responded to the CHAMEOLit system as a utilitarian feature, mainly relating to lighting placement and brightness. This was the smallest group of interviewees. The difference between Utilitarian and Informative was that the lighting system was only perceived as functional in the utilitarian theme. For example, the lighting was understood only as a means of illumination, and they evaluated its usefulness with reference to how easy it would be to read a book or a map. The CHAMEOLit system was found to be a low value interior feature and they did not rate its usefulness while it was daytime and outside the vehicle. Unlike the Informative theme, these responses did not seek to interpret any of the lighting as conveying information. Even as an adaptive system, the participants did not see any immediate uses for changes in coloured lighting or any ambient qualities. In the open-ended questions that clarified participants' opinions, this group were determined that light was only illuminance in darkness and did not have a design application.

Theme 4: Aesthetic

The Aesthetic theme related to responses that evaluated the lighting system's visual style and not in any way as an emotional intervention. Responses included words like 'artificial', 'harmonious', 'futuristic', 'spacious', 'like a disco/videogame' and 'attractive'. At times, it was difficult to differentiate aesthetic responses from the emotional ambience theme, because a positive evaluation of the lighting as 'luxurious' could also be interpreted to mean that it was in some way alleviating a mood, or feeling content, due to its effects in the vehicle's interior. Looking at the themes as a continuum, participants that valued aesthetic qualities of the CHAMEOLit system were more enthusiastic about the features and more open to interpreting applications than the utilitarian or informative groups. However, in their experience of the driverless simulation, they did not view its reactive system as an affective interface.

Suggestions for future applications included adding customisable colours and patterns, with perhaps more placements. In the open-ended questions with evaluations and applications for the lighting system, users would request coloured light transitions according to the seasons, or in contrast to the season in relation to warm and cool lighting and warm and cool day or the time of day or night. These suggestions were some of the most interesting because if the colours were to react to the exterior environment (a summer day or a winter day), with cool lighting and warm lighting, it would create an in-vehicle interior experience that would be pleasing and comforting to the passengers, and this might influence a sense of content and a positive mood. The users in this group were also concerned with the colours being ’harmonious’ or ‘complementary’, to the colours in the vehicle’s interior.

5.2 Qualitative Data Analysis: Testing the hypothesis per journey type

The insight that follows comes from summarising the qualitative research and does not represent a statistical analysis, and does not suggest that this data is objective. It is not presented as statistically significant because the user group was 33, which was an appropriate size for the qualitative research conducted.

Motorway scenarios

The first journey that the user participants viewed in the video simulations was the motorway. Hypothesis 1 for this driving scenario was to establish if the journey mood was boring. The first video in the motorway series introduced the participants to the journey without any lighting transition shown, in order to find out their experience of the driving scenario. The hypothesis was that the motorway journey would be monotonous, and the intention was that it would make users feel bored, as a consequence of constantly seeing the same scenery. When asked for thoughts about this and before seeing the CHAMEOLit system, 36% reported it was ‘relaxed’, followed by 24% who found it ‘boring’ and followed by 15%, who thought it was ‘comfortable’. The remaining remarks were a mix of comments such as, ‘travel sickness’, ‘sleepy’, ‘enjoyable’, ‘excited’ and ‘alert’. Essentially, if ‘comfortable’ and ‘relaxed’ were grouped, then at least half of the participants felt positive during the journey. At this stage, the mix of interview responses did not suggest that this journey is ‘boring’ (without any lighting intervention) for most respondents; however, only 6% reported an active feeling of alertness or excitement, as the majority reported a passive experience of the driving scenario.

Reponses to red/orange colour transition on motorways

This aimed to establish two points: if red/orange colour transition is considered energising and secondly, if it is a preferred colour lighting for this journey. The first lighting transitions shown to the participants on the motorway were red/orange. Because of the warm colour effect, the smart textiles system simulated in these colours was intended to make users on an uneventful motorway journey more invigorated. The users' preference regarding the red/orange lighting intervention on the motorway was mixed. Thirty-three percent of the responses Preferred this lighting, 24% felt Neutral and the majority did Not Prefer this colour transition. From colour perceptions of red/orange lighting on the motorway, only 5% reported it as providing an 'energising' mood. However, 23% of the responses found it 'alerting', 5% 'dangerous' and 3% 'warning'. With respect to warmth, the majority of the interviewees understood the red/orange colour as a literal temperature change (20%) or a warming ambience (a phenomenal reality rather than a physical reality - 15%), with a further 2% calling it 'cosy'. Counter to expectations that the orange lighting would invigorate, 5% found it 'pleasant', 3% 'relaxing' and 2% 'soothing'. The remaining responses were a mixture of moods and aesthetic valuations, such as: 3% 'attractive', 2% 'distracting' (as in too bright), 5% 'dull', 2% 'light show', 2% 'luxurious', 2% 'neutral', 5% 'optimistic' and 2% 'speed'.

As a consequence, almost a third of the participants considered the lighting a hazard signal, which was not the intended feeling of invigoration. It was not an affective response either, but a language of signs in the automotive environment with their associations and preferences for each placement. Also, a third of the interviewees who perceived the lighting as 'warmth', but without of energy, were not sensing an affective ambience. In fact, only 17% commented on the effects of the red/orange lighting, with the majority thinking of signals or temperature information, or even aesthetic qualities. With each video simulation, the participants saw the red/orange light in three positions, and responded that the dashboard and pillars were often perceived as 'warning', 'alerting' or 'dangerous' in orange. Participant 33 found all three positions to be 'energising'. The headliner was seen in a more ambient light, for instance, 'pleasant', 'warmth' (ambience), 'cosy', 'optimistic' and 'luxurious'. The headliner was rarely mentioned as a signal for 'alerting'.

In summary, the assumption that the red/orange lighting would be energising on the motorway was not reflected clearly across the interviews, and there were more responses related to alerting signals or warmth (phenomenal reality) indicators. Again, the feedback above represents a summary of the themes identified in the qualitative interviews, not statistically significant quantitative findings. In the interviews, it was also noticeable that the lighting of the exterior environment influenced participants' views on colour lighting for the interior, and many of the participants who saw the lighting as ‘warm’ (or ‘warmth’) did not prefer the lighting for this journey, mainly because the outside setting was a summery day. Therefore, they did not want to add extra, even if only perceived, warmth in the vehicle interior.

Reponses to blue/purple colour transition on motorways

The second part of the video sequences showed the blue/purple lighting for the motorway journey, in order to compare and contrast responses to red/orange lighting preferences. This was done for both driving simulations. It meant that the participants then saw the same journey with blue/purple lighting transitions in the same order and in the same three locations within the car interior, while on the motorway drive. There were no previous assumptions about an intended affect of the blue lighting on a boring motorway. After coding the interview responses, 56% still Preferred the blue/purple colour lighting on the motorway journey, 35% did Not Prefer, 7% was Neutral and 1% didn’t answer the question directly. Interestingly, in general there was preference for blue throughout the interviews rather than red/orange on the motorway.

Users preferred blue/purple lighting because it was a calming or relaxing way to continue the journey. Up to 20% found the blue lighting ‘calming’ and another 13% said ‘relaxing’, which makes up a third of those interviewed. The majority did not feel a strong emotional response, with a selection of answers around the look of the lighting, because purple was included in the blue/purple lighting. Looking at the language used in the interview responses, common associations that emerged were: 21% stated ‘artificial’, 8% ‘fun’, 7% ‘futuristic’, 4% ‘appealing’, 4% ‘attractive’, 4% ‘cooler’ (trendy), 4% ‘interesting’, 4% ‘luxurious’,1% ‘exciting’, and 1% ‘novelty’. That left 3% of responses that associated it with a cold temperature and 3% that found it was distracting (or 1% tiring to look at). In the headliner position, it was considered slightly more calming than in other places, although some found the headliner slightly more tiring or exciting. Overall, in all the positions shown users felt similarly about the blue/purple light. Therefore, rather than intervening, the coloured lighting was intensifying their mood in the motorway scenario.

In conclusion, the illumination had an impact on promoting a calming journey (the blue/purple version). For those who preferred blue, they found the purple lighting frequently artificial or neon-like and less of a calming effect, when compared with the blue colour lighting. It became clear that there is scope to test multiple colours and colour transitions in an affective interface like CHAMEOLit, because of diverse associations for users. Also, the findings suggest a study to view transitions under different settings (like day or night), summer versus winter, or sunny versus overcast weather. In the initial findings from the motorway scenario, the majority did not find the journey to be boring, as was assumed when the driving simulation was set up. There was a clear preference for blue/purple lighting on the motorway, over red/orange lighting which had equal likes, dislikes and neutral responses. Red and orange were found 'not energising' and for many, the colours were a signal for 'alert' or 'warm' temperature. Blue/purple was welcomed as calming because of the blue spectrum, regardless of whether they felt positive in the journey, and was rated by the majority as a strong aesthetic style in the car interior. This suggests that the users may equate red/orange with alerts, and blue/purple with calm or aesthetic values in the city street scenarios that are looked at next.

Busy City Scenario

The second journey that the user participants viewed in the video simulations was the busy city scenario. The first hypothesis for this driving scenario was to establish if the busy city was causing stress in the user participants. The first video in the series introduced the participants to the journey without any lighting transition shown, in order to find out their experience of the driving scenario itself, in the same way as it was done in the case of the motorway scenario. The hypothesis was that busy city driving is considered stressful and would cause similar emotional strain on the user participants. The majority of users reported they felt 'alert' (33%), the next largest group felt 'bored' (12%) and the rest reported different feelings in small numbers. However, when grouped, the next most common mood was 'nervous' or 'Anxious' (15%). To summarise, the remaining users communicated that they felt 'stressed', 'stressful' (situation), 'tensed' (12%), 'comfortable' or 'relaxed' (12%), 'annoyed' (6%), 'frustrated' or 'irritated' (6%) and 'travel sickness' (3%). Here also, results are not exactly stressful, as was intended in the research design; however, there is a spectrum of responses from 'alert' to 'stressed' that represent a different user reaction (than the motorway scenario). This video visualisation is closer to the expected reaction, than the motorway.

Hypothesis 2: Blue/Purple Lighting Intervention on Busy City Streets

The second hypothesis aimed to establish the same two points in relation to the colour lighting. Firstly, if the blue/purple colour transition is considered calming and secondly, if it is a preferred colour lighting for this journey. When asked if the blue/purple colour lighting was preferred or not, 64% said they preferred it during this journey. 18% did 'not prefer' the blue/ purple lighting on the city streets. In general, the assumption that blue/purple is a preferred intervention in the busy city scenario seems to be true. It was noted that the calming effect of the blue/purple leaned on the blue effect more rather than on the purple lighting. But for the busy city scenario, the users indeed preferred the blue/purple illumination, which they perceived to relax and calm them in this driving scenario. Regarding colour associations for the blue/purple lighting on the city streets, 42% of the responses called it 'calming', which was the intended purpose for this ambient lighting design. This was followed by 27% of the comments that found the blue-purple lighting 'artificial', 13% indicated it was 'distracting'. A small number of the remaining comments found its pleasing appearance as 'attractive', 'harmonious' or 'special'. Therefore, the hypothesis regarding colour lighting associations and preferences for this journey held correct: blue/purple is perceived by the majority as calming and it is preferred for this situation.

Orange-Red Lighting Effects on Busy City Streets

The second part of the video sequences tested the responses to red/orange lighting on the city streets, for comparison with the blue/purple lighting preferences. The interviews indicated that 49% Did Not Prefer, 22% Preferred, 29% had a Neutral response or no response for this colour lighting. This certainly shows that the user participants did not want the red/orange in this driving scenario. They were interpreted many times as warnings for hazards or as irritating and adding to an already busy, overwhelming scenario.

To conclude, in the initial analysis of answers to the close-ended questions on the busy city scenario, the majority found the journey to be more 'alerting' and saw it as a negative experience (overall), but not necessarily 'stressful'. However, this is closer to the hypothesis that, even if the driving scenario was not found stressful per se, it caused alertness, nervousness, irritation and frustration. Moreover, there was a clear preference for blue/purple lighting over red/orange lighting, which was found 'calming' versus 'alerting', which confirmed the hypothesis regarding colour preferences and associations.

With respect to places versus themes created in the previous section, the headliner and the dashboard were considered the places where colour lighting had an emotional, affective impact, and were found aesthetically pleasing. Respondents favoured A-pillars least as a form of emotional responsive lighting, although some found it aesthetically pleasing. The majority found the headliner lighting emotionally impactful, but a few reported its use was only utilitarian to increase brightness in the car. User participants considered the dashboard the most likely, and the A-pillars the second most likely, placements where they expected the illuminations to communicate to them or be a lighting feature.

The last part of the qualitative interviews asked user participants reflective questions about whether they find value in the CHAMEOLit system, as a deployment for future passengers in autonomous vehicles. Or if it can be beneficial for passengers and, if not in the way it was used in the simulations, then what would improvements could be considered. This part of the research was most interesting, as it helped to further analyse the video simulations and the CHAMEOLit system and find solutions for how it can be developed for further testing (Appendix IV). In general, the user participants suggested more lighting options, and a combination of placements for illumination. Regarding dynamic changes for colours blending with the outside environment, they suggested creating an immersive experience in the vehicle interior. Other appropriate suggestions for future testing included adapting the lighting per season or day, i.e., if overcast, rainy or gloomy weather, or for winter, use warm colours and for summer, cool colours.

Participants also suggested further testing of the lights during nighttime, or for special occasions, enhancing a moment in a journey or adding patterns and different transitions of colour, maybe following music rhythms or vehicle speed. In addition, they wanted to control colour intensity and brightness, with personal inputs on colour or having the system surprise them. One participant suggested different executions: to make it clear when the system is on and if it is, to inform or to adapt to the moods. Many preferred a combination of adaptive lighting to their moods, while the system can itself transform and become informative or utilitarian. This would probably be the ultimate smart textiles system, to 'respond intelligently' to human emotions and needs and to regulate the emotions of others, and potentially their own (Picard, 1997, p.3).

5.3 Conclusion of the Analysis

To conclude Phase 6, as a proof-of-concept, all the user participants found the CHAMEOLit smart light-emitting textile system valuable in the vehicle interior, however not all for the same reasons. The responses have been analysed and categorised under the four themes explained previously: Emotional Ambience, Informative, Utilitarian and Aesthetic. Again, to emphasise, the insights in this chapter should not be read as statistically significant, and are based entirely on qualitative interviews and thematic analysis of the transcripts. The majority did perceive the coloured lighting as having an affective emotional influence over moods, emotional states or strains. This happened despite the fact that the hypothesis regarding boredom (in the motorway scenario) was not fully accepted. However, it did prove that blue/purple had a calming effect even though it was not the anticipated choice for the motorway. In this case, CHAMEOLit did not apply as an intervention, rather, as a means to continue the calm and relaxed mode that the user participants reported for this journey. With regards to the busy city scenario, their mood or emotional strain was closer to the target emotional state. It caused people to become more ‘alert’, ‘tensed’, ‘annoyed’, ‘frustrated’ or ‘irritated’ and ‘annoyed’ – overall, negative emotional states and strains. In this case, blue/purple was preferred to the red/orange, as it was still perceived as having a calming effect, unlike the red/orange, which was perceived even more as a warning signal or an irritating element that added to the busy city traffic.

In addressing the main research question, the analysis from qualitative interviews showed that the smart light-emitting textiles system did have the potential to create an affective ambience, for most users with specific colour transitions. Concluding thoughts also revealed that blue/purple does have a calming effect, which was desired and appreciated in the context of the driving simulation. However, further testing of the CHAMEOLit system has to be conducted in order to understand which colour change is needed, in which situation, and for what purpose or need. What the study has shown is that user participants are the key to developing this type of smart textiles system. With learnings from the qualitative research, the next testing strategy should be carried out on-road, even if autonomous vehicles are not yet in production. Testing could be conducted with passengers and CHAMEOLit could be taught to learn from different scenarios, people’s preferences and how to adjust colour illuminations according to data extracted from sensors that are already being deployed in current in-vehicle monitoring and infotainment systems.

Chapter 6: Prototype Development Process

The outcome of the qualitative research findings became important in producing an improved version of the CHAMEOLit. The most inspirational aspect was the feedback from user participants on how to improve it, as well, other comments deemed significant. A detailed description of how it was created is in the body of practice of this thesis as well as the video simulations (see the CHAMEOLit video simulation prototype MP4 video).

Chapter 7: Conclusion, Future Work and Design Direction

This study proposed the CHAMEOLit smart illuminated-textiles for affective interfaces in an autonomous vehicle to create an affective atmosphere with colour changes which can change or alleviate emotional states or strains and moods of vehicle users. The trend for vehicles to become advanced, with the aim in the near future for autonomous vehicles, prompted this research. This represents a paradigm shift for the automotive industry. With no distinction between passenger and driver, the vehicle's interior transforms from a 'driving' to 'living' space and the users' experiences within that environment are the primary focus. Technological advances in Human-Machine Interfaces (HMI) and specifically, affective interfaces mean that smart reactive systems can now sense and respond to human psychological and emotional states to create dynamic and individual user experiences. Affective interfaces are an important area for investigation for user-centred research.

Recent developments in smart material systems and smart textiles mean that the HMI in a vehicle interior could potentially incorporate these materials in smart material systems to respond to electrical, magnetic, thermal, chemical, mechanical or optical stimuli and to adapt their responses to users' needs. In other words, technology is now available so that smart dynamic material systems can identify and react to various stimuli and can be made to respond to human emotions. This creates an opportunity for smart material systems to be pre-programmed and deployed in affective interfaces responsive to the vehicle user's emotional states or strains, moods or needs. Human emotions and moods can be (often significantly) impacted by the lighting and colour of their surrounding environment. One way of addressing the emotional state of a user in the vehicle during a journey is by creating affective interfaces that utilise smart light-emitting materials and textiles systems. They change ambient lighting within the vehicle either by turning on (or off) or changing colour or intensity. Such changes can be delivered in a vehicle's interior through 'smart' light-emitting materials and textiles with changing colour or intensity.

7.1 Research Methodology

Using qualitative procedures, the study aimed to answer the following questions:

- Can smart light-emitting textiles that use adaptive lighting influence the emotional states of the participant in a driving scenario?

- Can the colour changes in a vehicle environment benefit passenger emotional states or strains?
- Can the system change a person's mood by changing the colour of their environment?

In order to answer these questions, CHAMEOLit smart light-emitting textiles was simulated in two driving scenarios, motorway and busy city streets. The scenarios were chosen because of their possible effects on the emotional states, strain and moods of a vehicle user. The hypothesis was that motorway scenario would cause boredom and busy city scenarios would cause stress. The coloured lighting transitions consisted of two colour groups: warm red/orange and cool blue/purple. Based on the literature review, the hypothesis was that these colours would invigorate (warm colours) or would have a calming effect (cool colours). Therefore, smart illuminating textiles were deployed in three places in the interior of the vehicle. Video simulations were used in semi-structured interviews to understand if the smart textiles system could change (with the colour lighting) the emotional states or strains of the vehicle user, if deployed as affective interfaces.

The interviews were analysed using the six phases of thematic analysis and the answers were organised and categorised into four themes: Emotional Ambience, Informative, Utilitarian and Aesthetic. The first theme is most closely linked to the original intention of the dynamic lighting system: Emotional Ambience. In the analysis, the majority of the responses were categorised in this section, followed closely by Aesthetic, with responses in between that could be added to either theme. The majority of the participants did see the coloured lighting as having an affective emotional influence over their moods, emotional states or strains. Boredom in the motorway scenario was not experienced by all the interviewees, but there was agreement that the blue/purple had a calming effect, even though it was not the anticipated choice for the motorway. CHAMEOLit was not seen as an intervention but rather as a means to continue the calm and relaxed mode that the user participants mainly reported for this journey. With regards to busy city scenario, the mood or emotional strain was closer to the target mood. It caused people to become more 'alert', 'tense', 'annoyed', 'frustrated', 'irritated' and 'annoyed' – overall, negative emotional states and strains. In this case, blue/purple was preferred to the red/orange as it was still perceived to have a calming effect, unlike the red/orange, which was perceived more as a warning signal or an irritating element that added to the busyness of the busy city traffic.

7.2 Contribution to Academic Study

These findings contributed to the academic literature by using qualitative methodology to explore and understand directly from the user participants if the CHAMEOLit smart light illuminating textiles can be considered for car user. The user participants found the colour blue calming and, therefore, this study aligned with previous studies, and indicated it is a promising subject to be researched and tested further. Though the study only tested a sample of 33 user participants, there is value in researching the topic further and testing either the blue colour or testing the common feedback improvements with a larger group of participants. Since the in-vehicle technology already exists for sensors, AI and feedback modalities, this testing can be done on-road with many different scenarios and user group participants. This could further improve and 'teach' the system to react according to situation and user, as per vehicle users' emotional needs, states and strains and improve uncomfortable journeys by building intuitive communication with the vehicle and trust in the system. Furthermore, in the field of the CMF automotive, this can contribute to exploring new smart materials for delivering experiences that use adaptive colour applications and colour lighting which can be tailored for different models, user groups and diversifying customer choices with different levels of personalisation.

7.3 Limitations, Future Work and Design Direction

From analysing the data, certain limitations of the research design became obvious. Participants commented frequently on small differences in the video backgrounds because repeating the same driving scenarios made them more alert to the journey instead of the immersive experience of the car interior lighting. Suggesting that the next research stage should be in-person and in-vehicle to centre the experience on the light-emitting textiles of the interior. Limitations of the tested simulations showed that more testing is needed to clearly establish which specific colour can target an emotional state or strain; precisely, who is the user participant and what is start-end of the journey, as well as the settings of the journey itself.

While there were concerns that the analysis did not attempt to attribute differences in colour associations with users' characteristics (age, culture, nationality, etc.), the majority of colour associations reflected 'universal' meanings of colour taken from nature or warming and cooling properties of red and blue, like the studies in the literature review. Since there was limited culturally-specific feedback, the data collected provided largely consistent feedback on the associations to red and blue lighting. It was interesting that many responded with comparisons to situations and spaces they had experienced through travel, retail or leisure. For instance, purple and neon hues that recalled clubs, night lighting or specific brands, like Virgin Atlantic Airways. This feedback could not be directly related to 'calming' or 'activating' properties of the light, because the anecdotes are subjective, this would need to be studied further to understand the exact colour and lighting effects on mood.

To make future testing more immersive, the next step should not necessarily be in a laboratory because the passenger needs to be in a vehicle in motion on a journey. The journey start, end and route should be fixed, as well as the specific colours to test, with a driver present (since there are not driverless cars to test with) so that the user could sit as a passenger. These test cars would be fitted with prototypes of the light-emitting textiles so that it can also achieve prototype testing. With prototypes, the luminescence, duration and hue saturation can all be calibrated so that these technical aspects can be assessed, potentially with a feedback loop to the user. It is true that currently there are no autonomous vehicles in production, but studies can first be conducted with passengers in a regular car, so the system can learn through driving scenarios, user's needs and moods and via colour illumination preferences. Users would be interviewed after the car journey, and compared to the detailed questioning after each video simulation in this research, the responses would likely be more authentic to actual driving experiences. If physiological testing is included in the research, then quantitative data on biological responses could add another layer of information on stress or relaxation during the journey. Once this has been carried out, findings need to be tested when autonomous vehicles will be in use. This will be necessary, as the system might have to change and adapt again in an interior where it can potentially become a way to communicate with the vehicle, inspiring trust in the automated system.

7.4 Final Conclusion

In making smart light-emitting textiles systems relevant for future investigation and development, this research shows promising results. Using colour changes that are currently still in research phases for car interiors, open up opportunities for other chromatic materials. The adaptability of such materials will provide opportunities for CMF and UX designers to develop products for, and with, user participants that will be individually tailored to their needs. As such, it will offer the means to refine personalisation aspects of a product which can be replicated and dynamically adapted to each vehicle user. Thus, CHAMEOLit serves as a concept that points to new potential thinking in how future smart materials can add value to a vehicle's interior.

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