Title	Thermal display for presenting system situation awareness in automated driving
Sub Title	
Author	孟, 夏如(Meng, Xiaru) Kunze, Kai
Publisher	慶應義塾大学大学院メディアデザイン研究科
Publication year	2021
Jtitle	
JaLC DOI	
Abstract	
Notes	修士学位論文. 2021年度メディアデザイン学 第897号
Genre	Thesis or Dissertation
URL	https://koara.lib.keio.ac.jp/xoonips/modules/xoonips/detail.php?koara_id=KO40001001-00002021-0897

Master's Thesis
Academic Year 2021

Thermal Display for Presenting System Situation Awareness in Automated Driving

Keio University
Graduate School of Media Design

Xiaru Meng

A Master's Thesis
submitted to Keio University Graduate School of Media Design
in partial fulfillment of the requirements for the degree of
Master of Media Design

Xiaru Meng

Master's Thesis Advisory Committee:

Professor Kai Kunze	(Main Research Supervisor)
Professor Akira Kato	(Sub Research Supervisor)

Master's Thesis Review Committee:

Professor Kai Kunze	(Chair)
Professor Akira Kato	(Co-Reviewer)
Professor Matthew Waldman	(Co-Reviewer)

Abstract of Master's Thesis of Academic Year 2021

Thermal Display for Presenting System Situation Awareness in Automated Driving

Category: Science / Engineering

Summary

As the level of automation increases, the main goal of user experience in autonomous driving has changed significantly and human-vehicle interaction is in urgent need of innovation. To address the problems encountered by humans in autonomous driving during the transition period, this study builds a thermal haptic display to present system situation awareness. The display contributes to user experience by enabling the driver to understand the system's perception of the surroundings and to predict the system's selected actions. The display provides spatial information related to traffic objects through thermal stimuli.

In this study, the impact of providing system situation awareness information via thermal feedback in scenes of the highly autonomous vehicle driving in a mountain road was investigated. The results of this experiment, conducted in a VR driving simulator, show that the thermal display influences people's experience in highly autonomous driving. In particular, people preferred cold thermal feedback, and cold thermal feedback had an enhancing effect on human trust in the autonomous driving system.

Keywords:

thermal display, highly automated driving, system situation awareness, human-vehicle interaction, trust

Keio University Graduate School of Media Design

Xiaru Meng

Contents

List of Figures

List of Tables

Acknowledgements

I would like to thank Professor Kai Kunze and Professor Akira Kato for their help and guidance while conducting this research. Many thanks to Karen, Dingding, George and Kirill for their help in selecting the topic, experiment and data analysis. Thanks to all the participants who participated in the experiment. Many thanks to my good friends for their support and help.

Thank you to all the wonderful students and faculty at KMD!

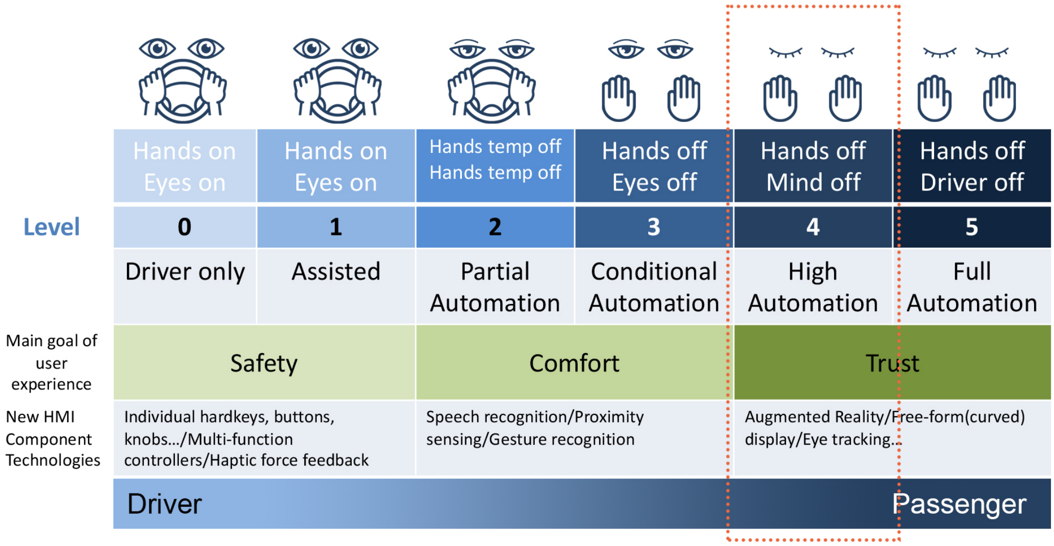
Chapter 1
Introduction

1.1. Background

In the 21st century, the influence of Internet, digitalization and intellectualization on vehicles cannot be ignored. What is clear is that the automotive industry has made the decision to undertake the development of self-driving cars, pushing the process of transforming from cars driven by human drivers to intelligent robots that transport humans on the road [1] [2].The interaction between drivers and their vehicles will change significantly with the introduction of intelligent technology. The role of the driver will change, shifting from driving as we currently know it to supervisory control of his or her autonomous vehicle. The eventual release from the task of driving will allow a whole new field of research and practice in human-vehicle interaction. Therefore, the exploration and innovation of human-vehicle interaction of autonomous vehicles should not be overlooked in importance.

Five levels of driving automation

In order to conduct research on human-vehicle interaction under autonomous driving scenarios, it is essential to understand the performance and the status of autonomous driving technology at different stages. Currently, one of the recognized standards for autonomous driving classification is developed by SAE (SAE International, previously known as the Society of Automotive Engineers). According to SAE classification, autonomous driving technology is divided into six levels, from Level 0 to Level 5. Most vehicles running on the road today are Level 0, where a human driver performs the driving task through manual control. Level 5 is the most ideal state, the ultimate goal of autonomous driving. Level 3 autonomous vehicles are capable of detecting their surroundings and could make decisions based on information, such as accelerating to pass a slow-moving vehi-



	Hands on Eyes on	Hands on Eyes on	Hands temp off Hands temp off	Hands off Eyes off	Hands off Mind off	Hands off Driver off
Level	0	1	2	3	4	5
	Driver only	Assisted	Partial Automation	Conditional Automation	High Automation	Full Automation
Main goal of user experience	Safety		Comfort		Trust	
New HMI Component Technologies	Individual hardkeys, buttons, knobs…/Multi-function controllers/Haptic force feedback		Speech recognition/Proximity sensing/Gesture recognition		Augmented Reality/Free-form(curved) display/Eye tracking…	
	Driver					Passenger

Figure 1.1 SAE levels of driving automation

cle. But vehicles at this level still require human intervention. The driver must remain aware and respond appropriately to requests for intervention if the system is failing to perform its task.

At Level 4, the vehicle does not require human intervention in most cases. The driver still has manual control, but does not need to respond to the system's requests for intervention. In practice, however, due to a lack of legislation and infrastructure development, autonomous vehicles in Level 4, also known as highly automated vehicles, can only be used in restricted areas.

It is obvious that at each level, users' needs for human-computer interaction are different, and in order to provide a better user experience, researchers need to make assumptions, deduce and verify around the characteristics of different stages. As the level of automation increases, providing comfort and trust will take precedence over providing drivers with a sense of safety and become the focus of research. This study focuses on the innovation of human-vehicle interaction in highly automated driving(Level 4).

Complex human-vehicle interaction process

Figure 1.2 presents the complex human-vehicle interaction process. Internally, a universal human-vehicle interaction process relies on the integrated implementation of various stages of information processing, through information acquisition, information aggregation and information provisioning, and ultimately the information reaches the user end. A user-side demand feedback will then be delivered to the information acquisition side through the user's behavior and the user's operation of the system, and this process forms a cycle. Externally, the environment (e.g., weather conditions) and uncertainties (e.g., the actions of surrounding objects) in the driving scenario also introduce uncertainty into the human-vehicle interaction process. Human-vehicle interaction is a highly complicated process influenced by multiple factors, and the introduction of changes in the external environment can also have an impact on the interaction process, therefore, this research focuses on in-vehicle interaction process. While considering the status of internal and external factors of influence, targeted information manipulation and transmission around user characteristics is one of the key points to be considered in the research.

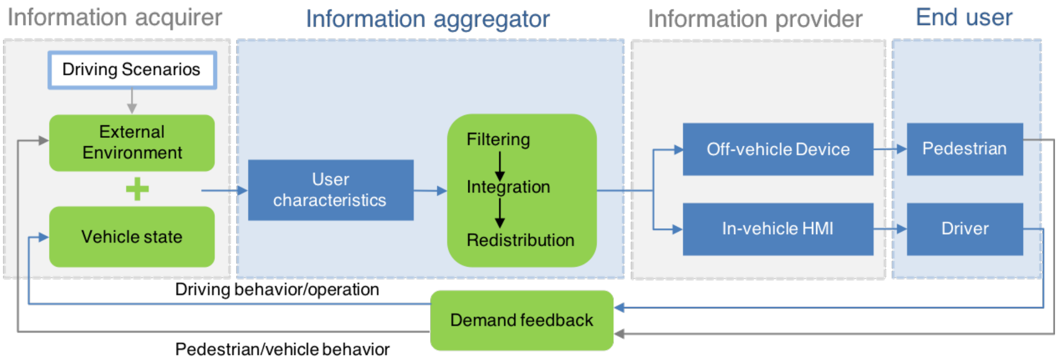


Figure 1.2 Human-vehicle interaction process

As technology evolves and multiple new technologies are integrated in the car, the human-machine interaction in the car is becoming more and more complex. Obviously, as new vehicle models are updated constantly every year, the number of in-vehicle screens becomes larger, the amount of information the driver has to handle becomes larger, and the functions of the in-vehicle system become more and more cumbersome. This results in a driver's cognitive and muscle memory that does not match the human-machine interface.

During the transitional period between traditional vehicles and the fully autonomous vehicles, it's necessary to introduce an innovative new human-machine interface between driver and vehicle. A good HMI (Human-Machine Interface) can guide the driver in actual conditions. It can also encourage appropriate trust on transition period. This project will focus on the innovation of human- vehicle interaction in the case of driving operation by autonomous systems.

1.2. Problem statement

The automotive industry is now set to see disruptive changes as technology evolves. How to gain more users during the transition period when automation is increasing and new technologies are gradually being introduced is an urgent issue to be addressed. This has made the issue of trust a hot issue in the field for many companies. For example, BMW[1] has worked with T Brand Studio to explore engineering trust in Level 2 autonomous driving, BMW has also introduced an innovative visualization concept that aims to create trust between the driver and the self-driving car and expresses that trust is the ability to enjoy the journey.

The American Automobile Association's annual self-driving car survey[2] found that 71 percent of people are afraid to ride in a fully self-driving car. In 2019, Audi[3] surveyed 21,000 respondents from around the world about their thoughts on autonomous driving. Based on the results of the research, it is clear that there are concerns about handing control over to the vehicle. 41 percent of respondents said they are skeptical about autonomous driving, and 38 percent of respondents said they feel anxious about it. It appears that people are still skeptical that autonomous vehicles can operate consistently in all situations. At a time when the human-machine relationship is about to enter a new phase, trust issues need to be addressed.

---

[1] `https://secure.brightcove.com/services/mobile/streaming/index/master.m3u8?videoId=6090783198001&pubId=5114477769001&secure=true`

[2] `https://newsroom.aaa.com/2019/03/americans-fear-self-driving-cars-survey/`

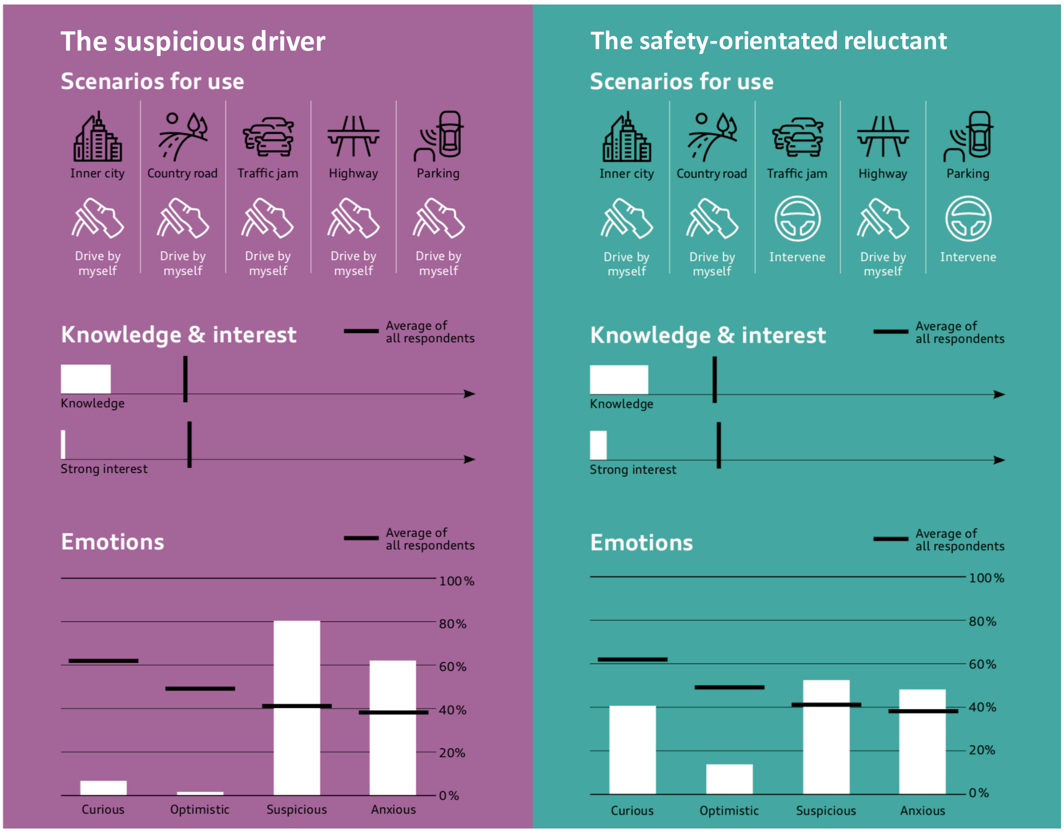
[3] `https://www.audi.com/en/company/research/and-audi-initiative/study-autonomous-driving.html`

Audi divided respondents into five user types, the suspicious driver, the safety-orientated reluctant, the open-minded co-pilot, the status-oriented trendsetter, and the tech-savvy passenger, based on their attitudes toward autonomous driving, with types the suspicious driver and the safety-orientated reluctant being the user types of interest in this study. 14 percent of respondents worldwide fall into the category of the suspicious drivers. The suspicious drivers have a hard time accepting new technology and are critical of the unknown. In all scenarios, they prefer to drive by themselves, as shown in Figure 1.3. The safety-oriented reluctant respondents made up 24 percent of those surveyed. This type of user is focused on driving safety and does not like to take risks, so they have reservations about autonomous driving. Unlike the suspicious drivers, they are more likely to try autonomous driving in specific scenarios, such as congested roads or parking, under the premise that they can take over. For its part, Audi points out that different user types derived from differences in people's attitudes toward autonomous driving correspond to different user demands. These demands should be met by providing specific services for autonomous driving, such as providing specific information, or experiences with the technology in different scenarios.

However, enhancing trust involves too many dimensions, such as promotion and policy development, this study only focuses on enhancing user experience and human trust in automated systems in the area of human-vehicle interaction. To figure out the key factors that could help improve user experience in the process of human-vehicle interaction, it's necessary to collect problems people might have when interacting with vehicles. As mentioned above, due to the introduction of intelligent technologies, the process of communication and interaction between people and vehicles is becoming increasingly complex. There are some problems people may encounter in automated driving process.

Lacking of understanding in AV

Due to insufficient experience and basic knowledge, human drivers lack the required understanding of AV capabilities and status. In most scenarios, the algorithms by which AV makes decisions is largely invisible to the user. If something unexpected occurs, the driver can only speculate what happened. The opacity of self-driving systems is likely to cause negative emotions in human users, and



(Source: A survey by Audi)

Figure 1.3 Survey results for two user types the uncertainty of the vehicle's actions is detrimental to the formation of trust. This will lead to the lack of trust which affects user acceptance, comfort and even safety. With limited experience and knowledge, it is not easy for human drivers to accept autonomous driving systems.

Complex in-vehicle HMI

The interaction between human and the vehicle is becoming more and more complex. The introduction of intelligent technologies in the vehicle has led to a mismatch between the human-vehicle interaction interface and people's cognitive patterns and muscle memory built up from long driving experience. Increasingly complex in-vehicle hardware and highly automated functions confuse drivers as they perform operations.

On the one hand, due to the improvement of software and hardware, there are more channels to provide drivers with all kinds of information, so In-vehicle systems always burden a driver with too much information. On the other hand, the information provided to the driver is not properly organized, and the lack of information filtering and layering prevents the system from providing information in a reasonable manner that has a positive effect on efficiently attracting the driver's attention, enhancing the driver's perception and naturally guiding the driver's actions. The entrance of smart portable devices such as smart phones further adds the interference of secondary tasks, making the interaction process even more complex. Ultimately, complex operating systems and disorganized information structures make it difficult to develop trust in autonomous driving systems.

Complex transport situation

In complex traffic scenarios, multiple objects act in concert to form an orderly operating transportation system. In transitional period, people, bikes and vehicles in different levels lead to a chaotic situation. Vehicles operate in a complex human–vehicle–road environment involving numerous levels of interaction among drivers, vehicles, and the ambient within which they travel. With the rise of automation, the way people and vehicles move will begin to change, so transportation systems will be deconstructed and reconfigured. Due to the integration of AVs and non-AVs, the old formulation for traffic management will fail to adapt to changing environment. The new traffic system which involves Vehicle-to-vehicle (V2V) communication and Vehicle to Environment (V2E) communication may confuse people.

Lack of trust in automated driving system

All of the above problems lead to the lack of trust in human-vehicle interaction. Although over-trust may cause some unexpected problems, complex systems like autonomous driving systems always requires high level of trust. Therefore, with a focus on helping the side of people who don't trust automated driving systems, this project concentrates on increasing trust through the design of human-vehicle interaction in highly automated driving.

1.3. Purpose

My research goal is to increase user's trust in autonomous driving during the transition period and provide user with an in-vehicle display which is easy to accept, effective to use and provide an enjoyable driving experience.

As trust evolves over time, based on the accumulated experience with self-driving cars, ultimately people will become accustomed to sitting in a self-driving car as passengers. During this process, it is still important to consider how we will adapt as drivers and eventually emerge as passengers. During the transition period, we need a good human-machine interface that could encourage appropriate trust.

Chapter 2

Literature review

2.1. Trust in automation

2.1.1 Trust modeling in autonomous system

To propose a new HMI that can encourage appropriate trust, it's necessary to review studies on human trust modeling in autonomous system. Much of the existing research on factors that guide interaction between humans and automation is centered around trust, which has clearly been defined differently from trust in a broad sense [3]. To investigate how to improve the design of automated systems to encourage appropriate trust in automation during interaction process, the researchers discussed how to extrapolate the concept of trust in people to trust in automation and proposed models and methodologies [4] [5].

Currently, the most widely recognized and applied definition of trust in automation in empirical studies of trust in automation is that proposed by Lee and See in 2004, who evaluated trust as an attitude. They considered trust as the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability [4]. Trust can be classified into three categories: dispositional, situational, and learned [6]. Learned trust is based on the accumulation of experiences with autonomous systems and influences the initial mindset of the human [7].

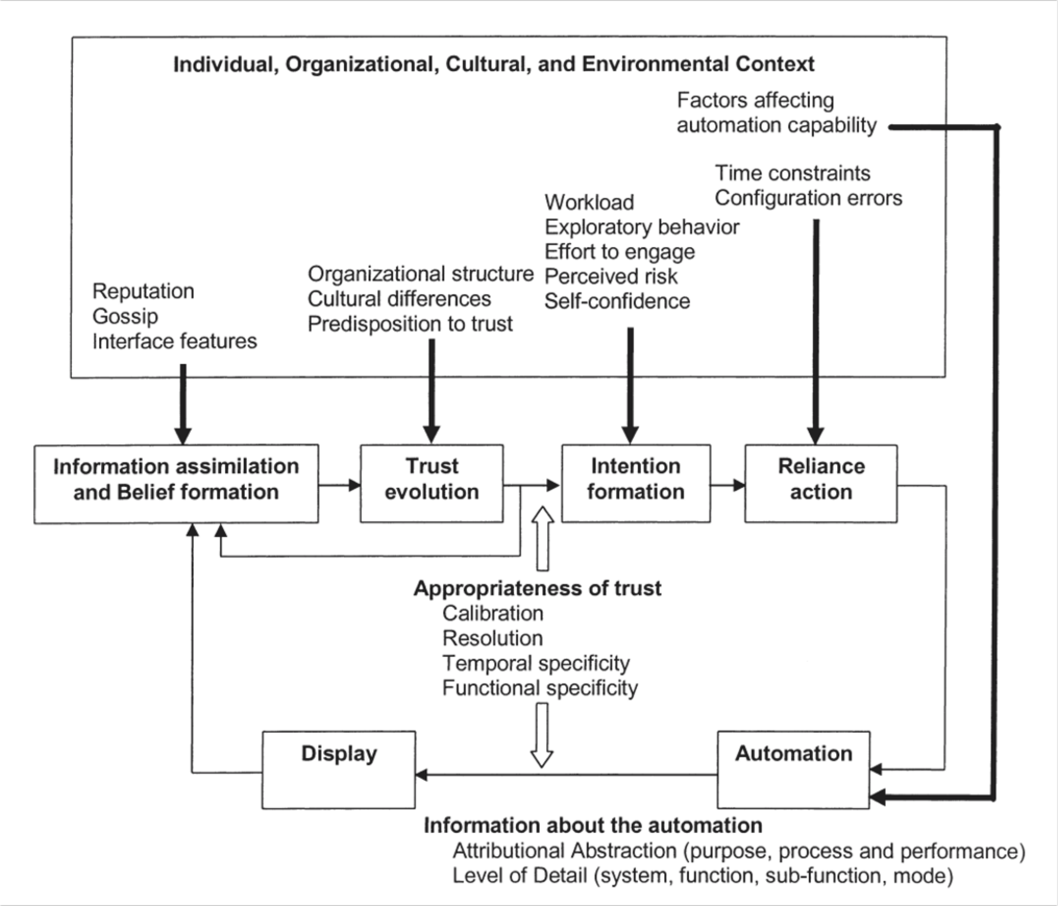
Unlike human-to-human trust, in trust between humans and automation, design and display characteristics have an impact on trust in automation [8]. In 2014, Kevin Anthony Hoff and Masooda Bashir proposed a three-layered trust model which conceptualizes the variability of trust. Its structure can be applied to help guide future research and develop training interventions and design procedures that encourage appropriate trust [6]. Researchers found that the formation of trust involves both thinking and feeling, but emotions are the primary determinant of trusting behavior [4]. The formation of trust is always known as a dynamic process. According to previous research and modeling of human trust in automated systems, the change in human trust is a dynamic process [7].The value of users' trust in the automated system changes continuously with the performance of the automated system, and it is possible to raise their trust again after they experience the low performance of the system.

The conceptual model integrates research regarding trust in automation and describes the dynamics of trust, the role of context, and the influence of display characteristics [4]. As can be seen in Figure 2.1, the dynamic interaction with the automation affects trust, which in turn influences the interaction with the automation. This model shows how the interaction between human, automation and environmental contexts affects trust, with the automation display and the impact of the information it conveys on trust being the focus of this study. Since trust is mainly based on the observation of the behavior of the automation, the display of information about the automation is very important [9].

Figure 2.2 depicts the basis of trust, which is the information that allows user to understand the trustee's ability to achieve the trustor's goals [4]. This reflects the different types of information needed to moderate user expectations and maintain an appropriate level of trust, which is divided into three dimensions: purpose, process, and performance [10]. The transmission of these trust-supporting messages plays a role in human trust in the automated system during the interaction.

2.1.2 Measurement of trust in automation

Currently, although there are explorations on measuring trust with methods such as EEG, GSR, HRV, and other methods of collecting physiological data, the correlation between physiological data and trust values is not clearly established, and subjective measurement methods are essential in measuring trust [11] [12] [13] [14].There are three main standard questionnaires that have received wide acceptance and can be used to measure trust in automated systems: the ED questionnaire [15], the HCT questionnaire [16] and the SATI questionnaire [17]. They have all been confirmed reliable by validation studies and have been applied in various experiments studying trust in automation [18] [19] [20].



(Source: A paper by John D Lee and Katrina A See [4])

Figure 2.1 A conceptual model of the dynamic process

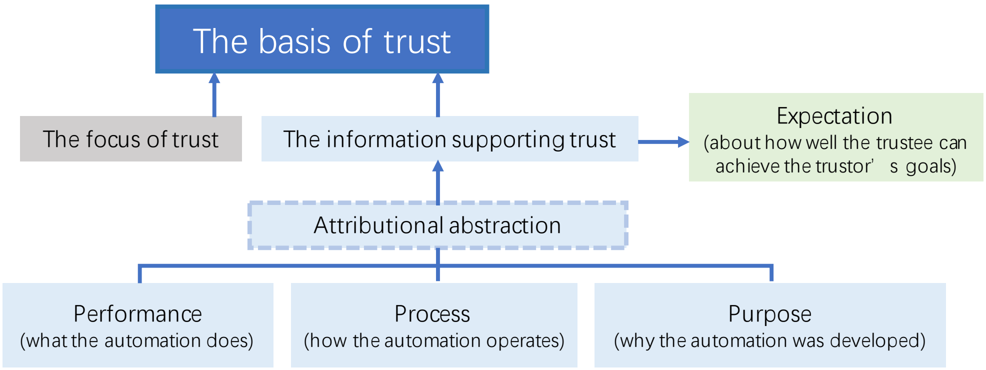


Figure 2.2 The basis of trust

The ED (Empirically Determined) questionnaire used in this study is a 7-point Likert scale consisting of 12 items that can be used to measure human trust in automation. Buckley, Kaye, and Pradhan applied this scale in a study of simulated driving and confirmed its internal reliability [21].

2.2. Methods for enhancing trust

In order to explore ways to enhance trust, it is important to first explore the factors that influence trust in automated systems. There are many factors that influence trust, and this study focuses on automated system factors rather than human or environmental factors.

The specifics, objectives, and examples of the three dimensions of information that support trust in autonomous driving scenarios are shown in Figure 2.3. The researchers suggest that visibility of the system's purpose, process and performance can increase the transparency of the system and further improve trust [22], with the caveat that the presentation should be in a simplified form [23] [24]. In autonomous driving scenarios, purpose information is usually categorized as system situation awareness information in HMI-related studies, while process information is usually presented as uncertainty information applied to human-vehicle interaction.

Based on the above analysis and previous studies, and considering the focus of this study, there are some methods that have a positive impact on the formation

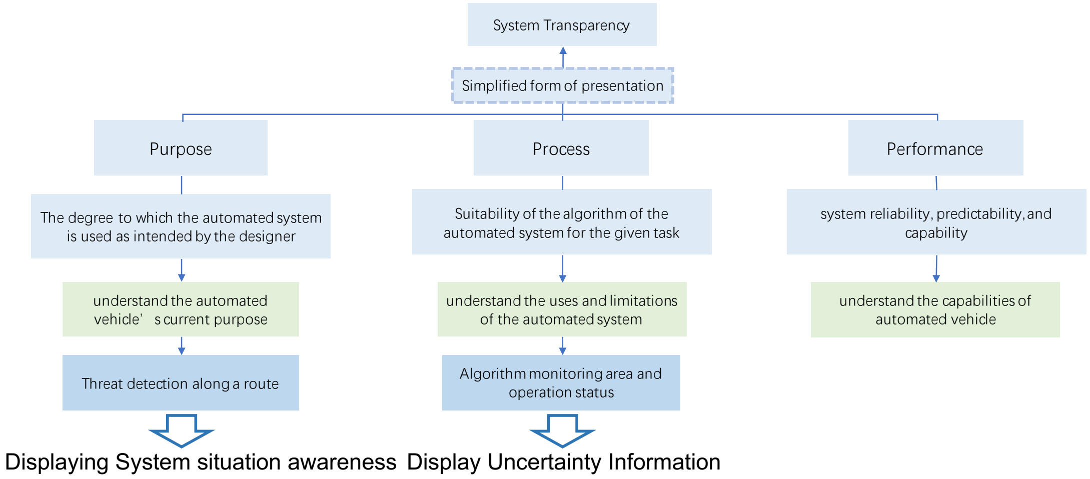


Figure 2.3 Information supporting trust in autonomous driving scenarios

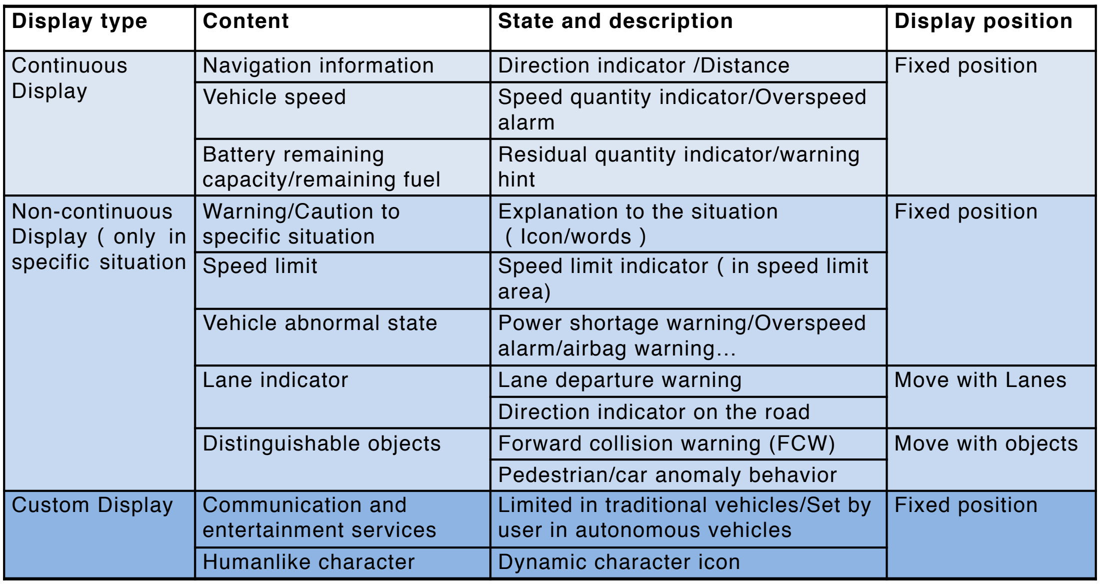
of trust.

1) Transparency of the system

Seong and Bisantz proposed that the inner workings or logic the automated systems are known to human operators to assist their understanding about the system [25].Research shows that designing systems that provide users with accurate feedback about their reliability or how they operate can better facilitate appropriate trust [26] [27].A display that show user how the autonomous car makes decisions and takes actions might have good influence on interaction process. By showing the internal process in a visible way, the autonomous car could communicate with user, show him or her how well the automation handles the situation and bring him or her a sense of trust.

2) High-efficiency of the information structure

As mentioned in the previous analysis, to ensure a positive impact on trust, information should be presented through a simplified format. Human and vehicle should accurately comprehend each other's intentions and actions. The system should be designed to make user feel comfortable and improve the efficiency of interaction. A high-efficient information display could provide information in a logical structure and help user act in the right way at the right moment. A well-designed system could contribute to influencing trust beliefs about using and monitoring autonomous vehicles.



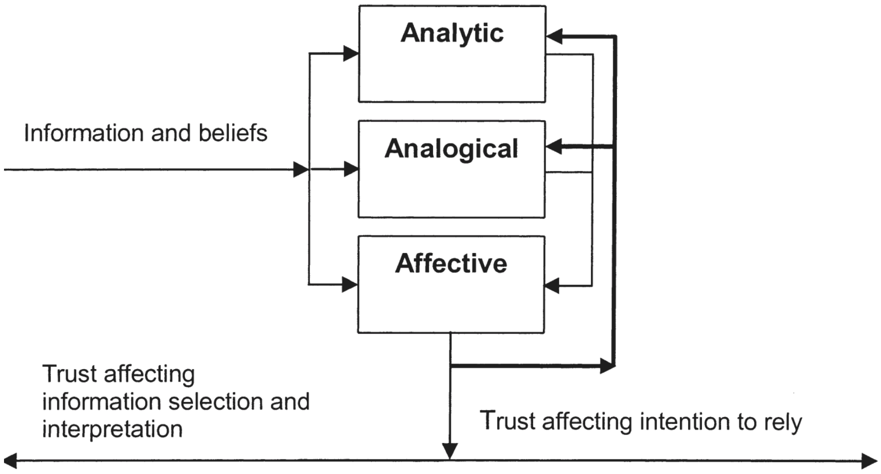
Display type	Content	State and description	Display position
Continuous Display	Navigation information	Direction indicator /Distance	Fixed position
	Vehicle speed	Speed quantity indicator/Overspeed alarm	
	Battery remaining capacity/remaining fuel	Residual quantity indicator/warning hint	
Non-continuous Display (only in specific situation	Warning/Caution to specific situation	Explanation to the situation (Icon/words)	Fixed position
	Speed limit	Speed limit indicator (in speed limit area)	
	Vehicle abnormal state	Power shortage warning/Overspeed alarm/airbag warning...	
	Lane indicator	Lane departure warning	Move with Lanes
		Direction indicator on the road	
	Distinguishable objects	Forward collision warning (FCW)	Move with objects
		Pedestrian/car anomaly behavior	
Custom Display	Communication and entertainment services	Limited in traditional vehicles/Set by user in autonomous vehicles	Fixed position
	Humanlike character	Dynamic character icon	

Figure 2.4 Interaction Information Classification

3) Anthropomorphism of the vehicle

Researches suggest that the Anthropomorphism of an interface can be a significant variable [28] [29] [30]. Human-like features such as name, emotion, voice, and animal heat could increase user's willingness to trust autonomous vehicles. Human-like mental capacities can improve the quality of interaction between humans and vehicles.

As shown in Figure 2.5, the information that constitutes the basis of trust can be received through three processes of different properties: affective process, analytic process, and analogical process , of which the affective process has a greater influence on the other two than they do on the affective process [31]. As mentioned above, emotion is a key influencer of trust. The anthropomorphic features of the automated system can serve as an affective complement to the analytic information and have a positive impact on the trust level.



(Source: A paper by John D Lee and Katrina A See [4])

Figure 2.5 The interplay between analytic, analogical, and affective processes behind trust

2.3. Haptic feedback in autonomous driving

2.3.1 Introduction of multi-sensory model

Human physical interaction is naturally multi-sensory, using hearing, vision, smell, touch, and taste [32]. With the development of recent technologies in mobile, sensors, and wearable devices, there is a growing international interest in multi-sensory experiences [33]. It could improve human situational awareness and encourage appropriate human trust towards new technologies such as automated systems. The multi-sensory model provides opportunities for new forms of human-computer interaction, and information other than visual and acoustic information should be introduced in the process of human-computer interaction. In driving scenarios where visual and auditory interactions are the main focus, haptic feedback has been introduced by some researchers to further improve human-vehicle interaction and enhance human trust in the autonomous driving system.

2.3.2 Displaying system situation awareness

System situation awareness is defined as system comprehension of traffic situation [34]. In a highly autonomous driving scenario, presenting the driver with system situation awareness can help the driver further understand the inner workings of the system, which is in line with the principles of advancing system transparency and improving the efficiency of information transfer mentioned above.

Kohei Sonoda and Takahiro Wada use a vibrotactile display with an autonomous driving system to provide situational awareness, which allows the driver to predict or perceive the system's chosen action. The display contributes to driver trust by providing spatial information related to traffic objects through tactile stimuli [35].

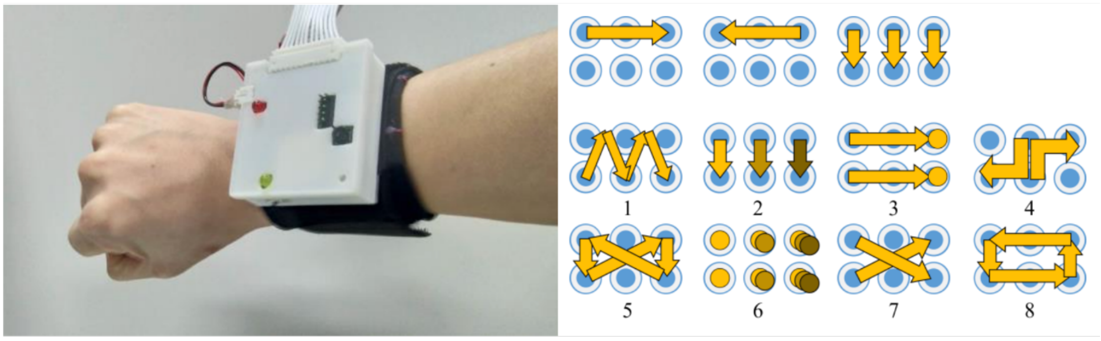
In previous studies, similar to presenting system situational awareness is enhancing driver situational awareness and providing system uncertainty information [36] [37]. Both of these have a positive impact on encouraging appropriate trust in the automated driving system [36] [38].

2.3.3 Vibrotactile feedback in autonomous driving

Vibrotactile feedback in the context of haptic feedback has been much studied in autonomous driving situations. Vibrotactile feedback is often used to provide guidance, alerts, and other specific information, and furthermore can enhance driver situational awareness and driver trust in the automated system. Researchers have provided vibration feedback through various vehicles such as wearable devices, driver seats, and steering wheels [39] [40] [41]. Multiple vibration patterns have been designed and tested to respond to a variety of specific messages [42] [43].

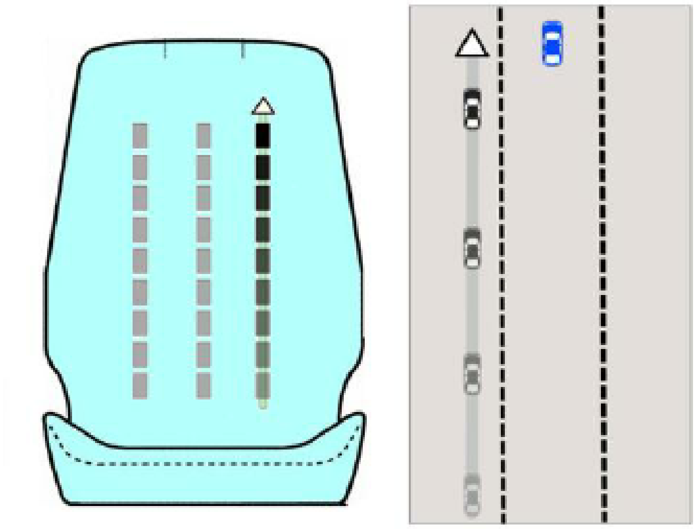
Based on the tactile illusion, Ma and Liu used six motors on the wristband to design 11 vibration patterns according to the corresponding graphic markers in relation to road conditions, as shown in Figure 2.6 [39]. And vibration feedback was tested in a virtual self-driving simulator

Telpaz and Rhindress built a vibrotactile interface composed of 27 vibrating motors to map the position of the approaching vehicle, as shown in Figure 2.7 [41].



(Source: A paper by Z Ma *et. al.* [39])

Figure 2.6 Vibration patterns on vibrotactile wristband for automated vehicles



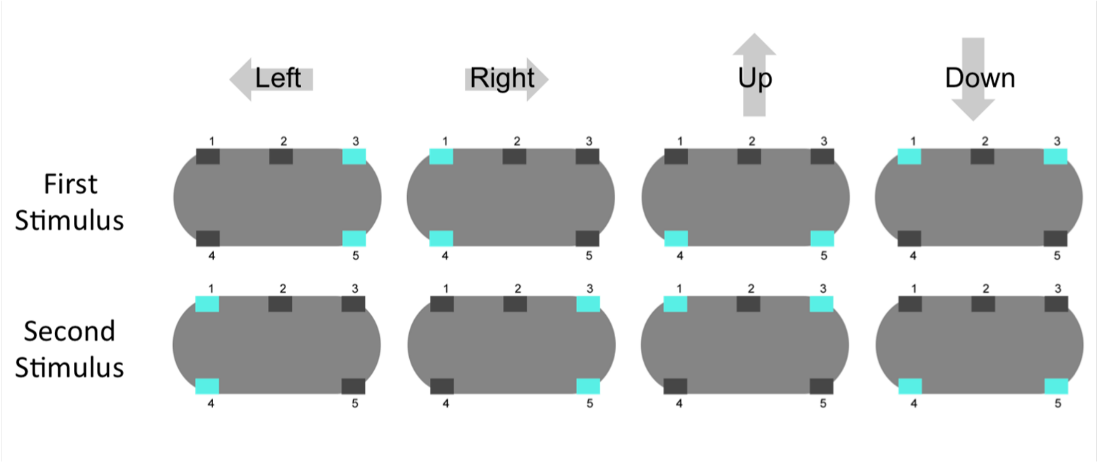
(Source: A paper by Telpaz and Rhindress [41])

Figure 2.7 An illustrative example of spatial mapping of a single vehicle approaching from behind

2.3.4 Pattern design for thermal feedback

The thermal feedback introduced in this study has rarely been applied in autonomous driving contexts before. To provide more complex information during interactive tasks, corresponding tactile patterns could be created by controlling a set of actuators. One of the typical examples is applying vibration patterns in navigation [44] [45].

Since the left-right-top thermal elements on the headset can be controlled individually, these elements can generate various thermal patterns related to different environmental conditions. Chen designed four initial dynamic thermal patterns for Peltier modules integrated on an HMD and evaluated the accuracy of recognition of dynamic stimuli [46].



(Source: A paper by Chen Z *et. al.* [46])

Figure 2.8 Design of operation patterns of Peltier modules on HMD for simulating movement in four basic directions (User View)

Ranashinghe used a wearable accessory for HMD, focusing on thermal actuation on the neck, throat, and behind the ear to increase immersion simulating wind and temperature [47]. It might be interesting to apply thermal or haptic actuation on different parts of the human body in automated driving scenarios, to increase human situational awareness or encourage appropriate trust towards the autonomous driving system.

2.4. Summary

From the literature review, it is clear that in order to improve user trust in autonomous driving, transparency and effective information transfer from the system should be achieved or some anthropomorphic features should be introduced. User trust in the autonomous driving system can be measured using psychological questionnaires that have been proven to be reliable. Based on previous research in this area of driver trust in autonomous driving, presenting system situation awareness to the driver is an effective way to enhance human trust in the autonomous driving system and improve the user experience. Presenting system situation awareness to the driver can be done through various channels, such as visual, auditory, and tactile. Among the various types of feedback, vibration feedback from haptic feedback is often introduced into the human-vehicle interaction process since it does not interfere with non-driving tasks in autonomous driving contexts. There are very few applications about thermal feedback in autonomous driving contexts. Therefore, in this study, thermal feedback with haptic feedback was introduced during highly autonomous driving to investigate how presenting system situation awareness information through different types of thermal feedback affects the driver's trust in the autonomous driving system.

Chapter 3

Concept

3.1. Presenting system situation awareness

From the literature review, it is clear that in order to improve user trust in autonomous driving, system transparency and efficient information transfer should be achieved. According to previous studies in this area of driver trust in autonomous driving, presenting system situation awareness to the driver is an effective way to enhance human trust in the automated system and improve the user experience. Therefore, this study hopes to improve trust in highly automated driving systems by presenting system situation awareness.

In a driving context, system situation awareness is defined as system comprehension of traffic situation. It is clear that the system's comprehension of the traffic situation contains many kinds of information. To conduct a controlled variable experiment, spatial information of the surrounding environment was selected for this study.

3.2. Application of haptic feedback in level 4

In the Level 4 driving scenario, the driver does not need to keep his hands on the wheel and can take his eyes off the road to perform some non-driving tasks, as shown in Figure 3.1. This is because in most cases, the driver is out of the control loop. While drivers can access information through multiple channels such as visual, auditory, and tactile, haptic feedback can provide effective feedback that captures the driver's attention without interfering with non-driving tasks.

When discussing how to convey information in a highly autonomous vehicle, visual or auditory representation is also considered as a potentially effective way

Figure 3.1 The driver in a highly autonomous vehicle (Photo by Junior REIS)

to display system situation awareness. However, in this study, it is expected that haptic information is more appropriate considering the absence of careful monitoring by the driver during level 4 autonomous driving. The purpose of this study was to explore the possibility of a tactile display that presents system situation awareness without interfering with the driver's activity on non-driving tasks.

3.3. Establishment of thermal feedback interface

Regarding the application of haptic feedback in driving situations, vibration feedback has been studied a lot in the context of autonomous driving, but little research has been done to introduce thermal feedback in the context of autonomous driving.

As a type of haptic feedback, thermal feedback has its own unique advantages. First, the thermal feedback interface can use an invisible carrier such as airflow rather than a solid wearable device as a carrier, which can reduce the limitations of human activity in the vehicle. Second, as a daily high-frequency activity, temperature exchange is very natural for people, which is beneficial for improving user experience. Third, thermal stimulation can serve as an affective complement to the analytic information, which contributes to the enhancement of trust in the automatic system .

In order to establish a human-vehicle interaction system that can enhance user experience in autonomous driving and convey the system situational awareness of the autonomous driving system in specific scenarios, this study introduces thermal feedback in haptic feedback during human-vehicle interaction and explores the effect of thermal feedback on human trust in the autonomous driving system in a virtual autonomous driving simulator. Since it was not possible to use a real autonomous vehicle and set up a non-solid thermal interface in the vehicle. In this study a virtual driving simulator was used, where thermal elements were attached to a VR headset to simulate the thermal interface, providing participants with thermal feedback in different pattern designs. The real-world application of the thermal feedback interface is shown in Figure 3.2.

In the experiment, the virtual automated system showed users the system sit-

Figure 3.2 Thermal feedback interface introduced in highly automated driving

uation perception through hot thermal feedback and cold thermal feedback, respectively, and the effect of different feedback on their trust in the automated system can be compared by psychological measures. This study investigated how hot thermal feedback and cold thermal feedback affect human trust in the autonomous system by conducting the experiments.

Chapter 4

Implementation

4.1. Feasibility experiment

4.1.1 Introduction

In order to introduce thermal feedback in the haptic feedback during human-vehicle interaction and to explore the effect of thermal feedback on human trust in the autonomous driving system in a virtual autonomous driving simulator, it was first necessary to test the feasibility of the prototype used for the experiment. In this study, a thermal feedback device is combined with a VR headset to provide thermal feedback while presenting a virtual environment to participants, so it is necessary to test the role of thermal feedback in the virtual environment and to record the driver's response and evaluation of thermal feedback.

This experiment tested the effect of the thermal feedback provided by the prototype on the user's VR experience through a questionnaire in simple virtual environments, and explored the utility and effect of different kinds of thermal feedback through interviews.

This experiment was done in collaboration with PhD student Kirill Ragozin, and more details can be found in his PhD thesis.

4.1.2 Method

Software and hardware setup

Peltier elements were mounted into the removable foam face interface of the Oculus Quest HMD, as shown in Figure 4.1. A total of 6 elements is assembled, each with a size of 15x15mm and rated at 2A 3.7V max. 6 elements are split into 3 channels: front (2 on the forehead), left and right (1 on temple and 1 on cheek). Each of 3 groups is controlled with an Allegro A3909 H-bridge chip. Each channel is powered through a PTC (Positive Temperature Coefficient) fuse for safety reasons. The feedback module is controlled by an esp32 module, acting as a Wi-fi Access Point (AP) with Oculus connecting to this AP directly and communicating with the thermal device over Wi-Fi. The device is powered from a 3.7v lithium-polymer battery with another PTC fuse on the power line. There are no cooling mechanisms being used on the Peltier elements and constant power supply to them must be avoided to prevent overheating. The thermal sensation is supplied in repetitive pulses. Computer graphics in VR driving simulations are generated using software (Unity 3D; Unity Technologies).

Figure 4.1 The prototype of mobile head-mounted display with thermal feedback

Participants

The group of participants consisted of 6 men and 9 women, aged 21 to 30 years. Before starting the experiment, they were informed about the procedure of the experiment and signed the informed consent form and the data protection policy.

Experimental Design

The prototype used in the experiments consisted of two parts, a device capable of providing thermal feedback in short repetitive pulses and a mobile VR headset running a virtual environment. The experiment had three control conditions: no thermal feedback, normal thermal feedback, reversed thermal feedback.

In the normal thermal feedback condition, participants feel thermal feedback that corresponds to the temperature of the environment or object in the virtual environment. Campfires and desert environments corresponded to high temperatures, and waterfalls and winter environments corresponded to low temperatures. In the reversed thermal feedback condition, participants feel the thermal feedback opposite to the temperature of the environment or object in the virtual environment. The campfire and desert environment corresponded to low temperatures, and the waterfall and winter environment corresponded to high temperatures. In the no thermal feedback condition, there is no thermal feedback.

The virtual environment contains six scenes, two of which are neutral and have no thermal feedback, two scenes contain objects that act as temperature sources (waterfall and fireplace), and two scenes are temperature-themed (winter environment and desert environment), as shown in Figure 4.2. Each scene lasts 30 seconds and the user's avatar is transported to a new view location at the end of each scene. When the virtual experience is performed under conditions with thermal feedback, the thermal feedback is automatically activated when the scene is switched. The user is equipped only with a VR headset and can interact with the environment through rotation and small movements. No other interaction is provided, and participants can only receive thermal sensations unilaterally.

A counterbalanced order was used for the trials between participants, To account for possible ordering effects, the Witmer and Singer Presence Questionnaire (version 3.0) was used to obtain quantitative data on self-estimation in the virtual environment, while qualitative feedback on the user experience was also collected.

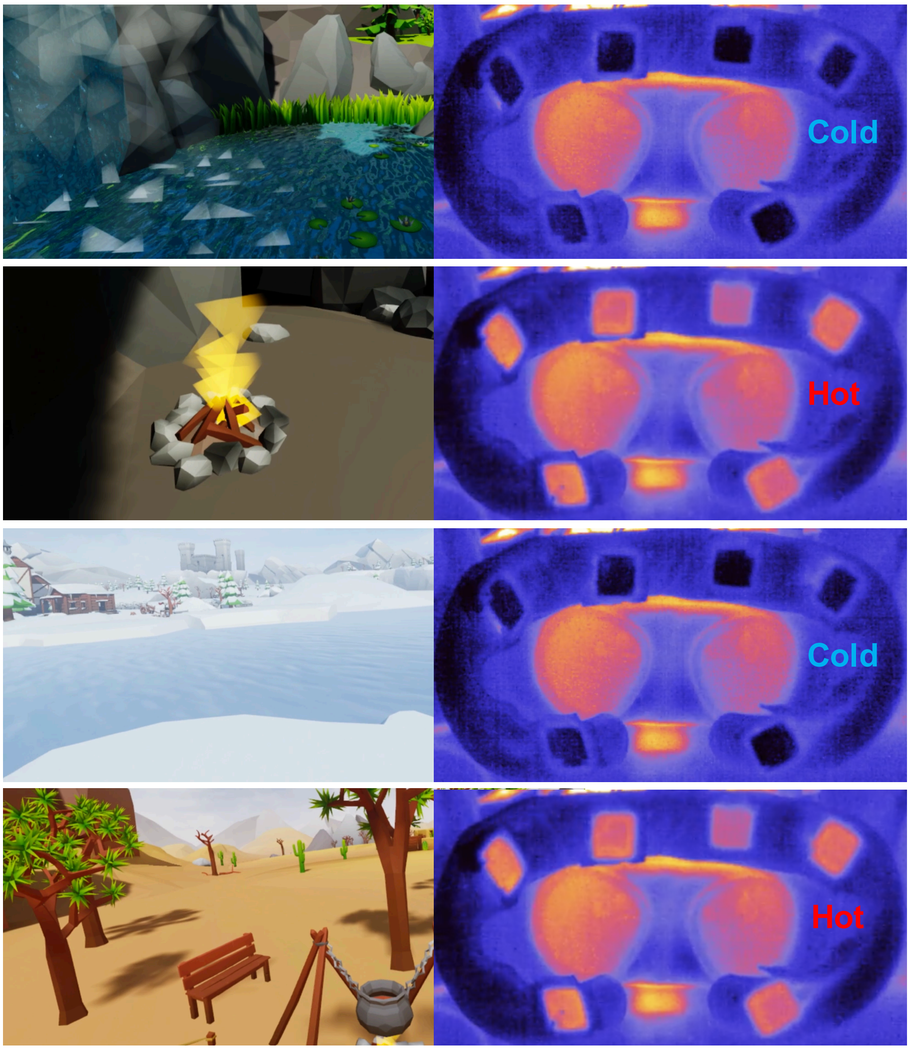


Figure 4.2 Normal thermal feedback in virtual environments

The ambient room temperature was set at a constant level during the experiment.

Procedure

At the beginning of the experiment, participants were asked to indicate their personal information (age and gender) on a digital spreadsheet.

After that, participants put on the virtual reality HMD, adjust the headset settings, and start the virtual environment experience under the control conditions that were set in advance. The user has plenty of time to get ready. Participants experience a total of six scenes in the virtual environment, each lasting 30 seconds. The participant in Figure 4.3 is experiencing the virtual environment.

Figure 4.3 The participant experiences the virtual environment

After experiencing six virtual scenarios, participants removed the headset and filled out 32 questions from the Witmer and Singer Presence Questionnaire (version 3.0), scoring them on a Likert scale from 1 to 7. In addition, they were provided with a secondary questionnaire that asked them to answer the following questions.

> What supported your feeling of immersion in the VR scene?
>
> What reduced your feeling of immersion in the VR scene?
>
> What did you like about the presented feedback?
>
> What did you NOT like about the presented feedback?

Then the experiment was repeated for the remaining two conditions. The steps of experiencing the virtual scenario and filling out the questionnaire were repeated. For example, if the first trial was without any feedback, the consecutive trial would contain normal thermal feedback and then reversed thermal feedback.

Upon completion of the three virtual experiences, participants were asked to explain in detail their responses to the questions in the questionnaire and to share their overall opinions and comments about the overall experience.

4.1.3 Results

A total of 15 participants (6 male, 9 female, age 21 to 30) have taken part in the experiment. Initial analysis of the data conducted with a Friedman test had shown that there was a statistically significant difference in the reported sense of presence depending on the type of feedback presented to the users while in VR, x2=19.600, p=0.000055.

Median presence evaluation levels for the no feedback, normal expected feedback and reversed unexpected feedback were131 (104 to 174, std = 17.578), 149 (129 to 163, std = 18.019) and 119 (106 to 128, std = 20.786), respectively.

There were significant differences between three trial category pairs: non-feedback and normal feedback trials(Z=-3.238, p=0.001204), non-feedback and reversed feedback(Z=-2.473, p=0.013394), normal feedback and reversed feedback (Z=-3.409, p=0.000652)

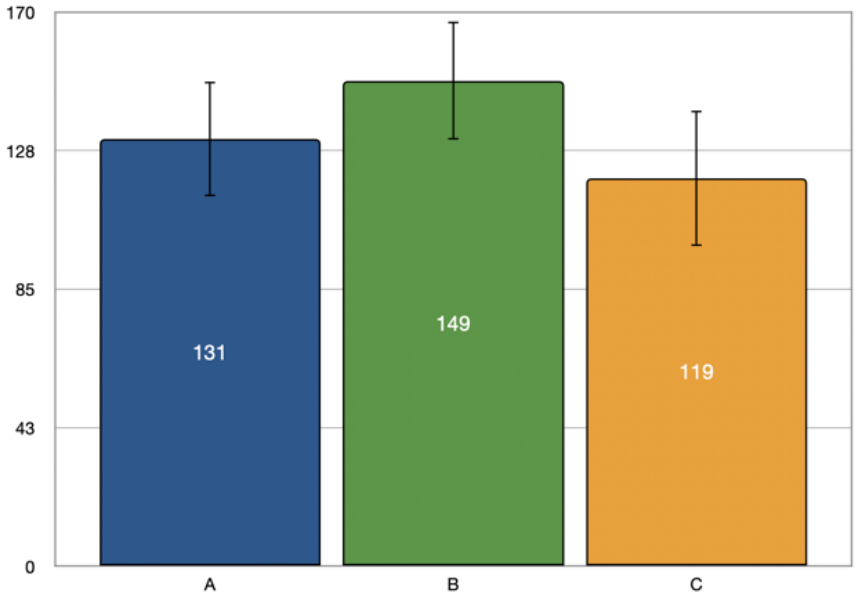


Figure 4.4 Median presence scores with standard deviations for 3 experimental conditions: A - non-feedback, B - normal feedback, C - reversed feedback.

4.1.4 Discussion

Based on the results of the data analysis, the regular temperature feedback is effective in increasing the sense of presence in the virtual environment, while the reverse thermal feedback reduces that sense. This shows that regular thermal feedback performs well in a virtual environment. Situational awareness or situation awareness (SA) is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status. Thermal feedback enhances the immersion of a person in a virtual environment, so it's obvious that it can enhance situation perception.

According to the interviews, the version of the experience with regular thermal feedback was overwhelmingly described as "the best," with participants expressing positive comments such as that the changes in sound and heat supported their perceptions and that the thermal feedback was cool.

In the interviews, some participants indicated that when they felt the thermal sensation, they would subconsciously start to look around and try to find the cause of the temperature change. They would look for objects around them in the virtual environment that corresponded to the thermal sensation, such as a campfire corresponding to high temperature and water corresponding to low temperature. Most participants were able to quickly understand the association between thermal feedback and the surrounding environment. Some participants mentioned that thermal feedback enhanced their awareness of the virtual environment when the thermal sensation was consistent with the feeling given by the surrounding environment, and they felt that consistency was important. Two participants stated that there was a sense of inconsistency when perceiving " strong" warm feedback from a visually small object. It follows that they go to the strength of the specific thermal feedback and compare it with the object property information and determine whether these two remain consistent.

Also, some participants mentioned that they elevated their attention to find out what was happening when receiving thermal feedback, especially reversed thermal feedback. Some participants showed a high level of alertness and a desire to find out what was wrong. One participant described the exact process, saying that this feeling lasted for a few seconds before he realized that it was just an opposite temperature setting and that there were no other changes in the environment. One participant mentioned that this feeling of thermal feedback being disconnected from the virtual environment felt like a reminder that drove him to look around. This suggests that it may be possible to use thermal feedback as a way of reminding or alerting people to get their attention.

The participants' feedback on this experiment provided a very valuable reference for the subsequent experiment . After confirming that the somatosensory effect of thermal feedback is good, and that the thermal feedback is naturally integrated with the virtual environment and plays a good role in enhancing awareness and conveying information, it is feasible to use this prototype in subsequent experiment to study the effect of thermal feedback on human trust in autonomous driving systems in autonomous driving scenarios. Therefore, based on the feedback received in this experiment, the next step is to construct a more complex virtual scene to simulate the autonomous driving experience and to design more complex thermal patterns to convey information corresponding to the surrounding environment.

4.2. Pre-test for autonomous driving scenes

The hypothesis is that presenting system situation awareness with thermal feedback can enhance user trust in automated driving system. Comments from 2 participants on the scene setting as well as on the thermal feedback were collected in the pre-test.

4.2.1 Method

In VR driving simulator, the automated vehicle passed a rock when the other vehicle was approaching from behind. The autonomous vehicle and the vehicle approaching from behind are traveling in the same direction on a one-way mountain road. The autonomous vehicle is traveling at 40km/h and the vehicle behind is traveling at 50km/h, and the distance between the two vehicles keeps closing. However, the vehicle behind does not overtake the autonomous vehicle until the autonomous vehicle passes the rock. The automated vehicle had two methods of passing the rock: straight and over,as shown in Figure 4.5.

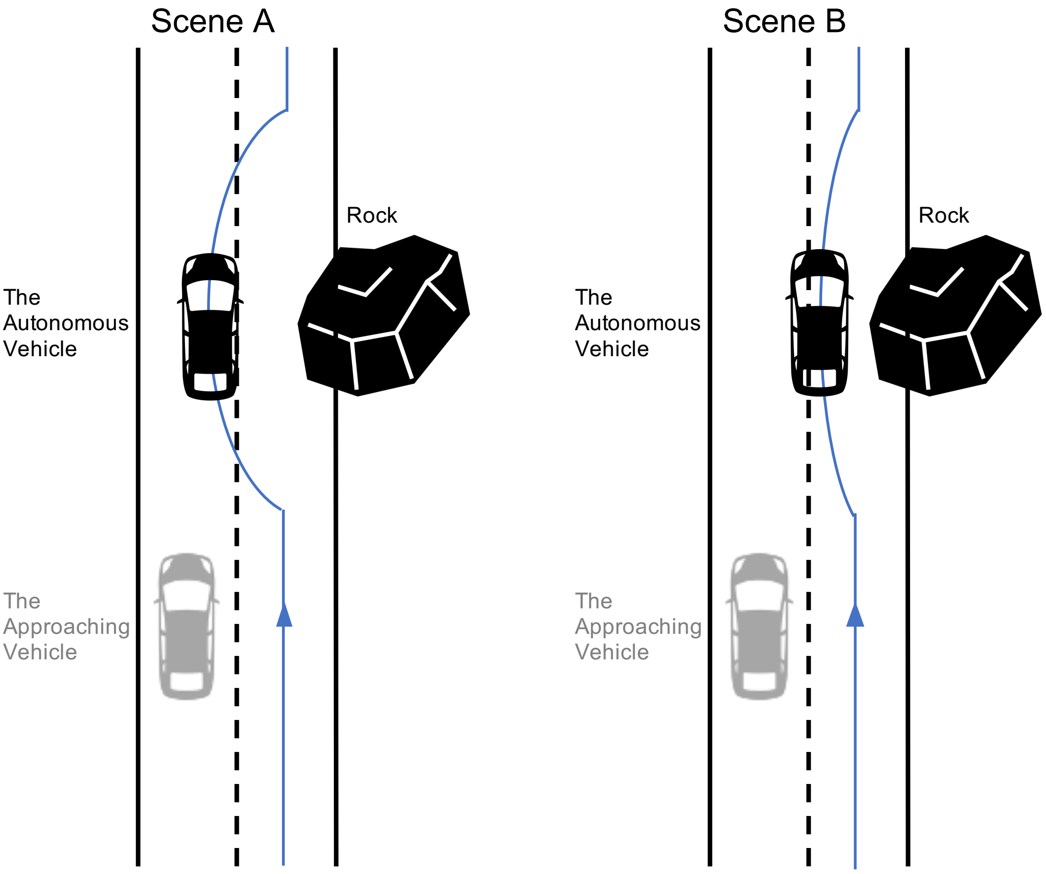


Figure 4.5 Two methods for autonomous vehicle to avoid rocks

The straight method avoids the rock while running slightly over the left white line when passing and then returned to the right lane. The over method avoids fully crossing into the left lane of the two-lane road when the following vehicle approached closely when returning to the right lane.

The participants could experience each scene (straight and over) three times with non-thermal feedback, hot thermal feedback and cold thermal feedback.The pattern of thermal feedback corresponds to different traffic condition information. When other vehicles are close to the automated vehicle, the thermal element on the left side will become hot or cold. The following car does not overtake the self-driving car as it passes over the rocks. For example, in the cold thermal feedback condition, when a vehicle is approaching from the left side of the autonomous vehicle, thermal elements on the left would become cold.

4.2.2 Discussion

To conduct the pre-test, a virtual scene in Unity was run on a computer, using Oculus as a real-time display via Air Link. TCP messages were sent manually to the prototype, a brief test was done with two participants and their opinions on the hot feedback and autonomous driving scenes were asked. The participants found it confusing because the thermal feedback only indicated the position of the approaching car, but not the position of the rock. Generally, only the left and right thermal elements can be activated when the car is approaching from behind, so it is not easy to realize what is happening in a short time. Therefore, in later experiments, simpler driving scenarios were set up to provide more direct information that participants could easily understand.

4.3. Experiment with autonomous driving

4.3.1 Introduction

According to the above, system situation awareness, or how the system senses the surrounding traffic environment, is a key factor that is considered to affect the driver's trust in the autonomous system. In driving scenarios, an autonomous driving system operates with a process that detects the traffic environment, makes

Figure 4.6 The virtual autonomous driving that happens on the headset is shown on the PC

decisions, and executes actions, such as controlling the steering wheel, gas pedal, or brake pedal at the appropriate time. Without a reminding system, it is not easy for human drivers to know the next action of the autonomous driving system before the system executes a specific action. Also, they have no way of knowing the system's real-time state of operation. They can only evaluate the autonomous driving system after its performance. Sometimes drivers may need to observe how the system is planning by watching the movement of the steering wheel or wheels, and then compare the system's performance with their own driving experience to determine their trust level in the system. For the driver, the lack of information about the planning process of the automated driving system makes it more difficult for them to trust the automated system [4].

Information that shows the system's comprehension of traffic conditions can influence the user's trust in the automated system. An interactive interface that conveys information about the system's situational awareness needs to be built. In this study, a thermal tactile display was constructed to provide the user with spatial information about close traffic objects through tactile stimuli, which is equivalent to the situational awareness of the autonomous driving system. The thermal display shows the driver the system's perception of the surrounding traffic environment. With the aid of the display, the driver can predict the decisions and actions of the autonomous driving system. Effective communication and accurate predictions may contribute to the user's trust in the autonomous driving system.

This experiment was conducted to confirm whether presenting system condition awareness with thermal feedback could improve user trust in the autonomous driving system. A thermal tactile display providing system situation awareness information were tested in VR driving simulation scenarios.

4.3.2 Method

Software and hardware setup

Peltier elements were mounted into the removable foam face interface of the Oculus Quest HMD. A total of 6 elements is assembled, 15x15mm in size, rated at2A 3.7V max. 6 elements are split into 3 channels: front (2 on the forehead), left and right (1 on temple and 1 on cheek). Each of 3groups is controlled with an Allegro

A3909 H-bridge chip. Each channel is powered through a PTC fuse for safety reasons. The feedback module is controlled by an esp32 module, acting as a Wi-fi Access Point (AP) with Oculus connecting to this AP directly and communicating with the thermal device over Wi-Fi. The device is powered from a 3.7v lithium-polymer battery with another PTC fuse on the power line. There are no cooling mechanisms being used on the Peltier elements and constant power supply to them must be avoided to avoid overheating.

Computer graphics in VR driving simulations are generated using software (Unity 3D; Unity Technologies). The vehicle motion behavior is calculated using RCC (Realistic Car Controller).

Participants

The group of participants consisted of eight men versus eight women, aged 22 to 31 years. Fourteen of them had driving experience. Before starting the experiment, they were informed about the procedure of the experiment and signed the informed consent form and the data protection policy.

Driving Scenario

1) Virtual driving environment

In the experimental setup, driving scenarios in which an autonomous vehicle passes over a mountain road with fallen rocks in the way were considered. The driving automation level was defined as level 4. The driving route is a two-lane mountain road with no signals or intersections, and each lane is 3.5 meters wide. As shown in Figure 4.7, the driving route contains both curves and straights.

The vehicle type is BMW's M3, with a height of 1.37 meters, a width of 1.78 meters and a length of 4.49 meters. The autonomous vehicle maintains a speed of no more than 60 km/h in the right lane of the dual carriageway, and in the absence of obstacles the autonomous vehicle tends to stay on the right side of the road. In this scenario, in order to pass this section of road, the autonomous vehicle must continuously make turns to dodge the rocks in front of it, and the driver may be looking around at the surrounding traffic conditions even when being engaged in non-driving tasks.

Figure 4.7 Mountain road scene in virtual environment

2) Two different autonomous driving systems

There are two main scenes set up in Unity. In scene A, the self-driving car is controlled by system 1, and in scene B, the self-driving car is controlled by system 2. Therefore, the self-driving car has different decisions and performance in scene A and scene B, as shown in Figure 4.8.

This setting was designed to allow participants to experience different automated systems. System 1 performed differently from system 2, so whether participants could feel their difference and whether participants' trust in the different systems would be different. This allowed this study to explore in more depth the effect of thermal feedback on people's trust in the automated systems.

For example, when passing the first rock (Rock 1), system 1 and system 2 take different performances, as shown in Figure 4.9. In scene A, the car avoids fully crossing into the left lane, the car passes the rock at a great distance from it. In scene B, the car which is controlled by system 2 avoids the stone while running slightly over the left line. The car passes by the rock in close distance to it.

3) Specific settings for the three rocks

The simulated driving experience in the virtual environment, the autonomous vehicle passes a total of three rocks (Rock 1, Rock 2, and Rock 3) that are in the way of the driving route. In Scenario A, the vehicle is controlled by system 1. When the vehicle passes Rock 1, it is at a minimum distance of 1.2 meters from Rock 1; when it passes Rock 2, it is at a minimum distance of 0.6 meters from Rock 2; when it passes Rock 3, the minimum distance between it and Rock 3 is 1 meter. In Scenario B, the vehicle is controlled by system 2. When the vehicle passes Rock 1, it is at a minimum distance of 0.36 meters from Rock 1; when it passes Rock 2, it is at a minimum distance of 0.24 meters from Rock 2; when it passes Rock 3, the minimum distance between it and Rock 3 is 0.36 meter.

Rock 1, Rock 2 and Rock 3 vary in size and location, but they are all set up in a way that they are not easily detected by the driver. This setting is designed to enhance the effect of providing system situation awareness information to the participants. Rock 1 is 1.8 meters high and its edge touches the center of the right-hand lane. The portion of it that enters the lane is 3 meters long and 0.6 meters wide. However, Rock 1 is blocked behind a small hill, so it does not appear in

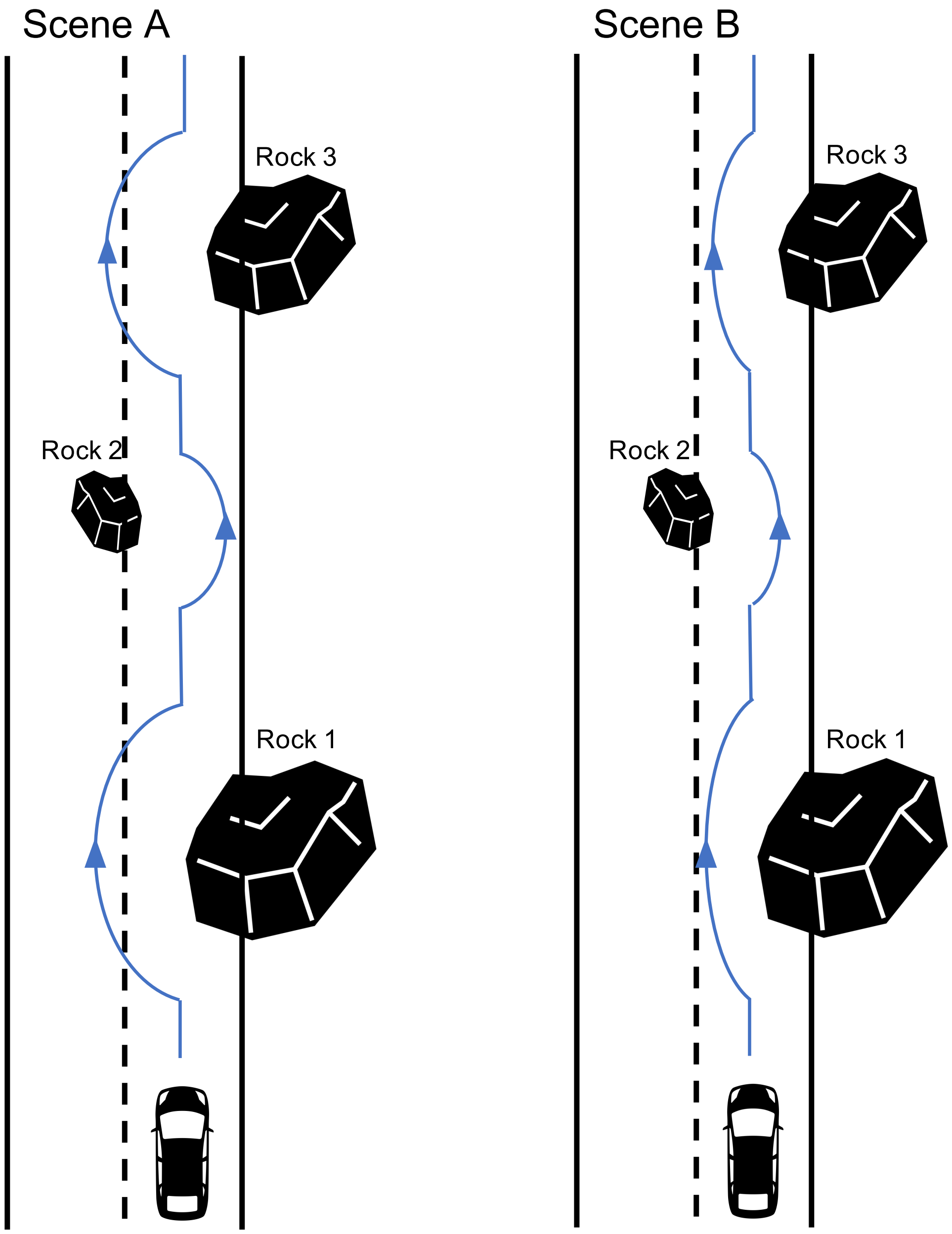


Figure 4.8 Schematic diagram of the driving route of the autonomous vehicle in scene A and scene B

Figure 4.9 Distance between the autonomous vehicle and the Rock 1 in the virtual environment

the driver's view when the autonomous car passes the first curve.The participant view is shown in Figure 4.10.

The size of Rock 2 is the smallest, with a height of 1 meter. Rock 2 is located in the middle of the left and right lanes, blocking the left side of the right lane, which allows the autonomous car to dodge only to the right, with little space to evade. The portion of Rock 2 entering the right lane is 1.5 meters long and 1 meter wide. Rock 2 is not blocked by other obstacles, but because of its small size, low height and similar color to the lane, it is not easily detected by drivers. The participant view is shown in Figure 4.11.

Rock 3 is large, it is 2 meters high, but its edges are not sharp. The portion of Rock 3 entering the lane is 3 meters long, but only 0.6 meters wide. it only touches the right-hand border of the right lane. Rock 3 is also blocked behind a small hill like Rock 1, but the hill has a gentler slope. Rock 3 appears in the driver's field of view as the autonomous car passes the second curve.The participant view is shown in Figure 4.12.

Figure 4.10 Rock 1 in the participant 's field of view

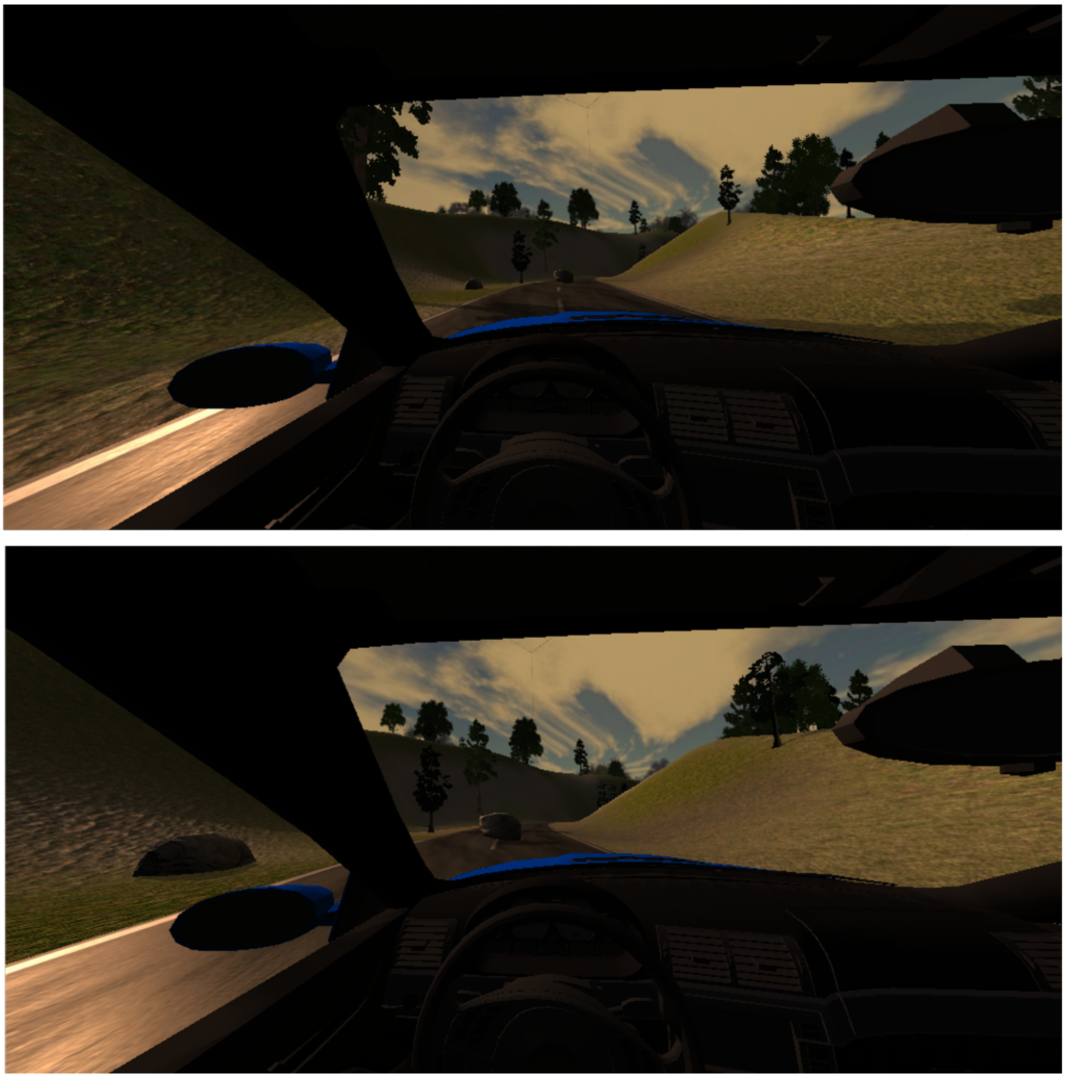


Figure 4.11 Rock 2 in the participant 's field of view

Figure 4.12 Rock 3 in the participant 's field of view

Experimental Design

1) Autonomous driving experience under three different conditions

Each participant engaged in three identical 2 scenes, and each participant experienced a total of six virtual autonomous driving experiences, as shown in Table 4.1.

Table 4.1 Description of the events that occurred during each virtual autonomous driving experience

Autonomous driving experience	System (Scene)	Performance of the autonomous vehicle	Thermal feedback
1	system1 (scene A)	Large steering angle; keep a long-distance when passing the rocks	Non-thermal feedback
2	system2 (scene B)	Small steering angle; keep close distance when passing the rocks	Non-thermal feedback
3	system1 (scene A)	Large steering angle; keep a long-distance when passing the rocks	Hot-thermal feedback
4	system2 (scene B)	Small steering angle; keep close distance when passing the rocks	Hot-thermal feedback
5	system1 (scene A)	Large steering angle; keep a long-distance when passing the rocks	Cold-thermal feedback
6	system2 (scene B)	Small steering angle; keep close distance when passing the rocks	Cold-thermal feedback

The participants experienced the two scenes a total of three times under three different conditions. The three conditions are: no thermal feedback, with hot thermal feedback, and with cold thermal feedback. The thermal feedbacks under three conditions are shown in Figure 4.13.

The order of the conditions was randomized, and the scenes in each condi-

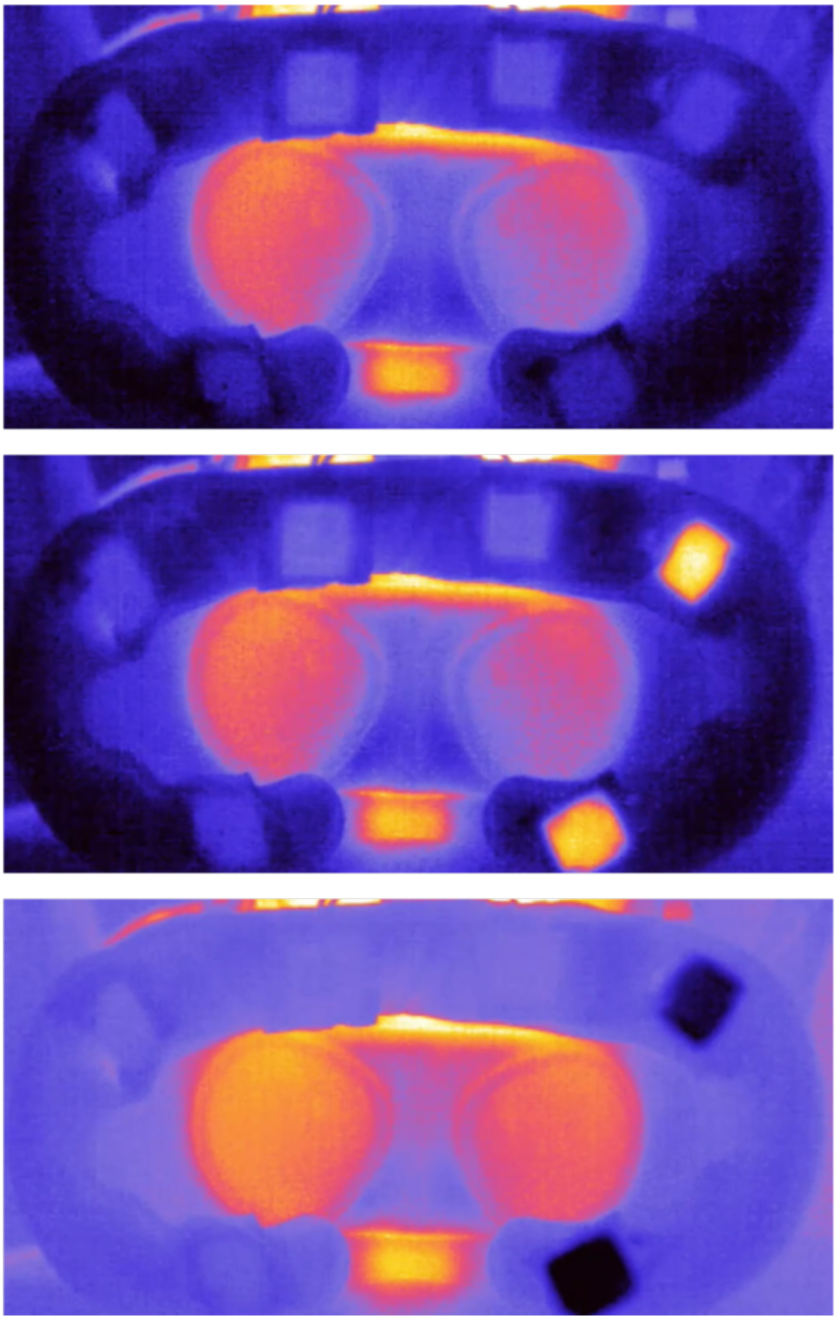


Figure 4.13 The three conditions: no thermal feedback, hot thermal feedback, and cold thermal feedback

tion block were randomly ordered for each participant. At the beginning of each session, participants were not informed whether the scenario involved thermal feedback or not.

After each time the subjects experienced the scenario, they were asked to evaluate the system (a standard questionnaire could be used to measure their trust in the automated system). So we can see how the thermal interaction affects their evaluations.

2) Temperature setting for thermal feedback

The thermal interface is composed of 6 embedded Peltier elements. 6 elements are split into 3 channels: front (2 on the forehead), left and right (1 on temple and 1 on cheek),as shown in Figure 4.14. Each of 3 groups is controlled individually with an Allegro A3909 H-bridge chip, capable of providing both cold and hot sensations on the same element. At a room temperature of 23.5 degrees Celsius, the thermal element is usually 27 degrees Celsius, reaching a maximum of 28 degrees Celsius after heating and a minimum of 26.7 degrees Celsius after cooling.

Figure 4.14 6 Peltier elements are split into 3 channels

Based on the above hardware performance, under the hot thermal feedback condition, in the case of the thermal element in contact with the human face, when the thermal element is activated, the person can immediately feel the temperature rise, in the interval from 0 to 1 second, the temperature rise can be obviously felt, after 1 second there is already a very strong feeling, after 2 seconds the temperature reaches the highest, in the interval from 2 to 3 seconds the temperature drop is felt, after 3 seconds there is almost no longer obvious feeling, and the perceived temperature returns to the initial state.

Under the hot thermal feedback condition, in the case of the thermal element in contact with the human face, when the thermal element is activated, a person can immediately feel the temperature drop, in the interval of 0 to 1 second, the temperature drop can be clearly felt, after 1 second the temperature reaches the minimum, after 2 seconds there is still a very obvious feeling of low temperature, in the interval of 2 to 3 seconds, the temperature drop can be felt, after 3 seconds it is almost impossible to feel the obvious low temperature, and the perceived temperature returns to the initial value.

3) Pattern design for the specific scene

Based on the above conditions, the thermal tactile displays provide information related to close traffic objects in three modes: non-thermal feedback, hot thermal feedback, and cold thermal feedback. The information provided by the thermal display is directed so that the position of the activated thermal elements corresponds to the position of the traffic object relative to the autonomous vehicle as the autonomous vehicle approaches the traffic object.

In the experiment setup, the thermal feedback directly indicates the location of surrounding rocks. The position of the rock that the autonomous vehicle is about to pass is directly mapped to the thermal interface related to the position of the rock with respect to the driver.

In the hot thermal feedback condition, the thermal element is activated to start heating when it is possible for the participant to notice the rock. If the rock is on the left (right) side of the autonomous vehicle, the thermal elements on the left (right) side of the prototype vehicle is activated. The hot thermal feedback will last for three seconds and will disappear before the autonomous vehicle takes avoidance action.The pattern design for the hot thermal feedback condition is shown in Figure 4.15.

In the cold thermal feedback condition, the thermal element is activated to start

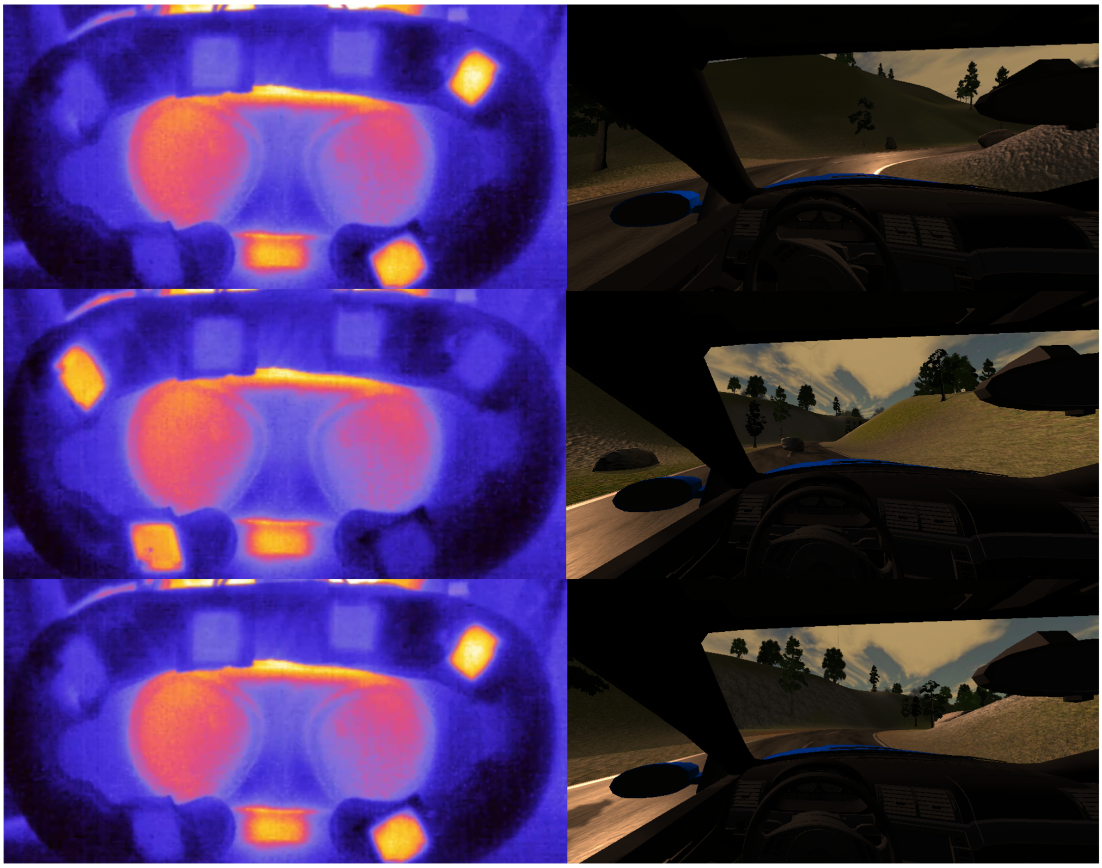


Figure 4.15 The pattern design for the hot thermal feedback

cooling when it is possible for the participant to notice the rock. If the rock is on the left (right) side of the autonomous vehicle, the thermal elements on the left (right) side of the prototype vehicle is activated. The cold thermal feedback will last for three seconds and will disappear before the autonomous vehicle takes avoidance action.The pattern design for the hot thermal feedback condition is shown in Figure 4.16.

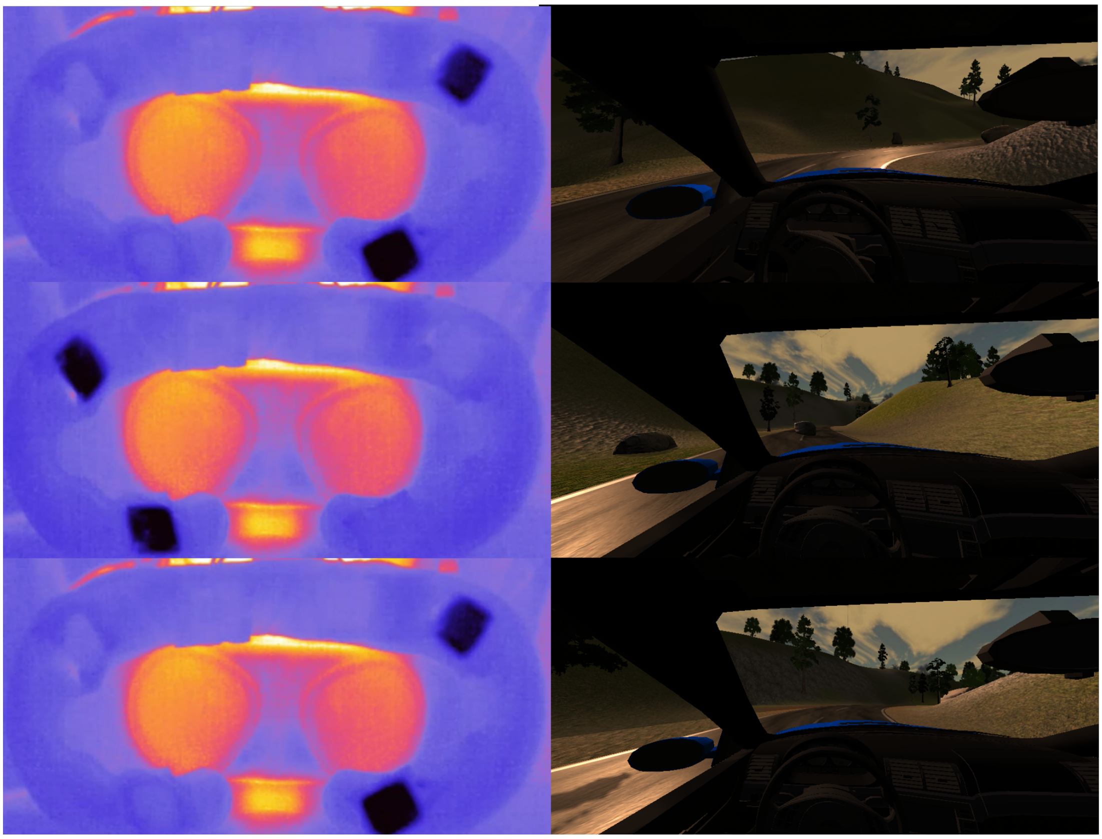


Figure 4.16 The pattern design for the cold thermal feedback

4) Timeline setting for the autonomous driving experience

The basic settings of the timeline in Scene A and Scene B are the same, as shown in Figure 4.17.

At 0 seconds, the participant enters the virtual driving scenario and the vehicle begins to go straight. From 0 to 12 seconds, the autonomous vehicle goes straight

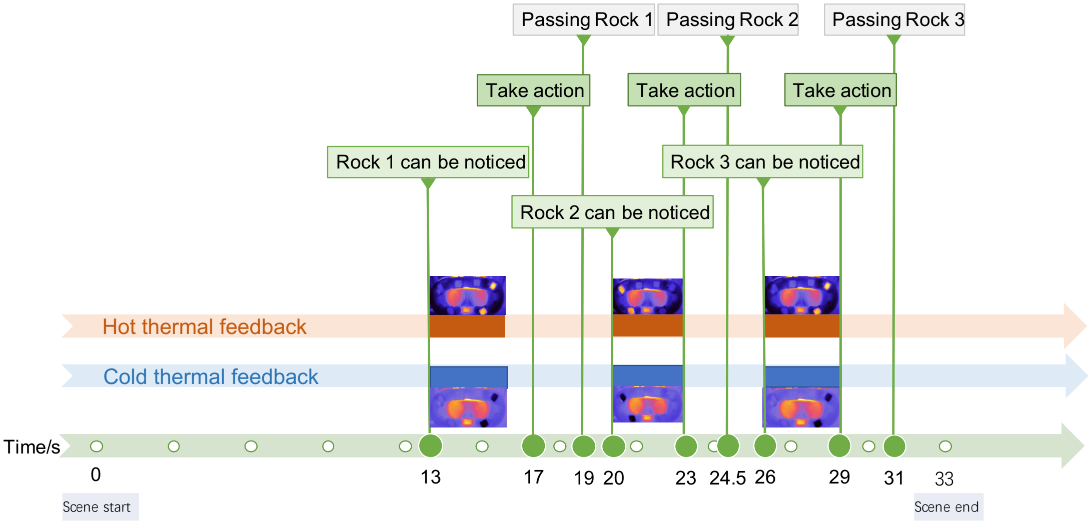


Figure 4.17 The timeline in virtual scenes

in the right lane. At 13 seconds, the autonomous vehicle slows down and enters the right turn lane. At 13 seconds, the participant is able to detect Rock 1, at which point thermal feedback is activated. From 13 to 16 seconds, the participant can continuously feel the thermal feedback of heating or cooling on the right side of the interface. At 16 seconds, the thermal feedback disappears. At 17 seconds, the autonomous vehicle leaves the curve and returns to the straightaway. At 17 seconds, the vehicle begins to turn into the left lane to avoid Rock 1. At 19 seconds, the vehicle passes Rock 1 on its left side and begins to return to the right.

At 20 to 23 seconds, the autonomous vehicle is moving forward on a straight road. 20 seconds in, the participant can see Rock 2, at which point thermal feedback is activated. 20 to 23 seconds, the participant can continuously feel the thermal feedback of heating or cooling on the left side of the interface. At 23 seconds, the thermal feedback disappears. At 23 seconds, the vehicle turns to the right to avoid Rock 2 on the left side. At 24.5 seconds, the vehicle passes right over Rock 2 and begins to return to the left. At 26 seconds, the autonomous vehicle returns to the original track straight ahead.

At 26 seconds, Rock 3 appears in the driver's field of view and thermal feedback is activated. From 26 seconds to 29 seconds, the thermal feedback on the right side of the interface is continuously hot or cold. From 27 seconds to 29 seconds, the autonomous vehicle passes through the right turn curve. At 29 seconds, the vehicle turns slightly to the left to avoid Rock 3 on the right. At 31 seconds, the vehicle passes right over Rock 3 and returns to the right. 32 seconds to 33 seconds, the vehicle drives in a straight line. At 33 seconds, the virtual scene ends.

The virtual environment used in the experiment is a section of mountain road, which contains three straight sections as well as two curved sections. In addition, the road on the mountain is not horizontal and has a slope all the time. Due to the frequent steering and going up and down the hill during the driving process, the speed of the autonomous vehicle varies from 46km/h to 60km/h, and the maximum speed does not exceed 60km/h. The thermal feedback in the experiment is a simple binary switch that exists only in two states, on and off. The thermal feedback lasted for 3 seconds after being activated. Thermal feedback was activated each time after the participant was able to detect the obstacle and disappeared before the autonomous vehicle took steering action to present system situation awareness to the participant.

Procedure

1) Informed Consent

Participants were welcomed to the study site and informed of the details of experiment procedures. I then explained the consent form and data protection policy and asked participants to read and sign it.

2) Personal Data Gathering and Pre-experimental

Participants are asked to fill in their basic information (age, gender, whether they have driving experience) on a digital spreadsheet. Before conducting the experiment, participants were informed that they would experience autonomous driving, and that the car they were driving in the simulation was controlled by an automated driving system. They were going to evaluate this system.

3) Experiencing Virtual Autonomous Driving

The virtual reality headset was handed to the participant.In Figure 4.18, the participant is putting on the VR headset.

Figure 4.18 The participant with the VR headset prototype

After the participant puts on the headset, the person conducting the experiment selects a scene in random order and plays it, and the participant begins a simulated autonomous driving experience. Each scene lasted 30 seconds. When participants experience the virtual driving scenario under hot thermal feedback or cold thermal feedback conditions, each time the self-driving car approaches a rock in the way, the thermal elements at the corresponding location on the VR headset will be passively activated and the participant's face will feel the thermal stimulus. The participant was equipped with only the VR headset and could interact with the virtual environment through rotation and small movements while sitting in the seat. No other means of interaction were provided.The participant in Figure 4.19 is experiencing virtual autonomous driving.

Figure 4.19 The participant experience virtual autonomous driving

4) Filling in the questionnaire

After experiencing a virtual scene, subjects completed the twelve-item questionnaire developed by Jian, Bizantz, and Drury to evaluate the automated system in this scene on a Likert scale of 1 to 7 [15]. In addition, they were provided with a secondary questionnaire that asked them to answer the following questions:

> How easily did you perceive the rocks?
>
> How large did you feel the avoidance of the rocks was?
>
> How did you feel about the system situation awareness of the rocks?
>
> What is the comfort level of the interaction?

The questionnaire used in the experiment is shown in Appendix A.

5) Experience the next scene

Participants were required to go through a total of six different virtual driving experiences, repeating steps (3) and (4) for each scene under different conditions. In Figure 4.20, the participant puts on the VR headset again after completing the questionnaire.The order of conditions for each participant will be random to reduce potential ordering effects. Each participant engaged in three identical 2 scenes, and each participant experienced a total of six virtual autonomous driving experiences. The participants experienced the two scenes a total of three times under three different conditions. The three conditions are: no thermal feedback, with hot thermal feedback, and with cold thermal feedback. The order of the conditions was randomized, and the scenes in each condition block were randomly ordered for each participant. At the beginning of each session, participants were not informed whether the scenario involved thermal feedback or not.

6) Post-experiment interview

After all six virtual autonomous driving experiences were completed, participants were asked to share their overall opinions and comments on the entire experience, including their comments on the performance of the autonomous car in different scenes, the information they perceived through thermal feedback, as well as their comments on the hot thermal feedback and the cold thermal feedback, etc.

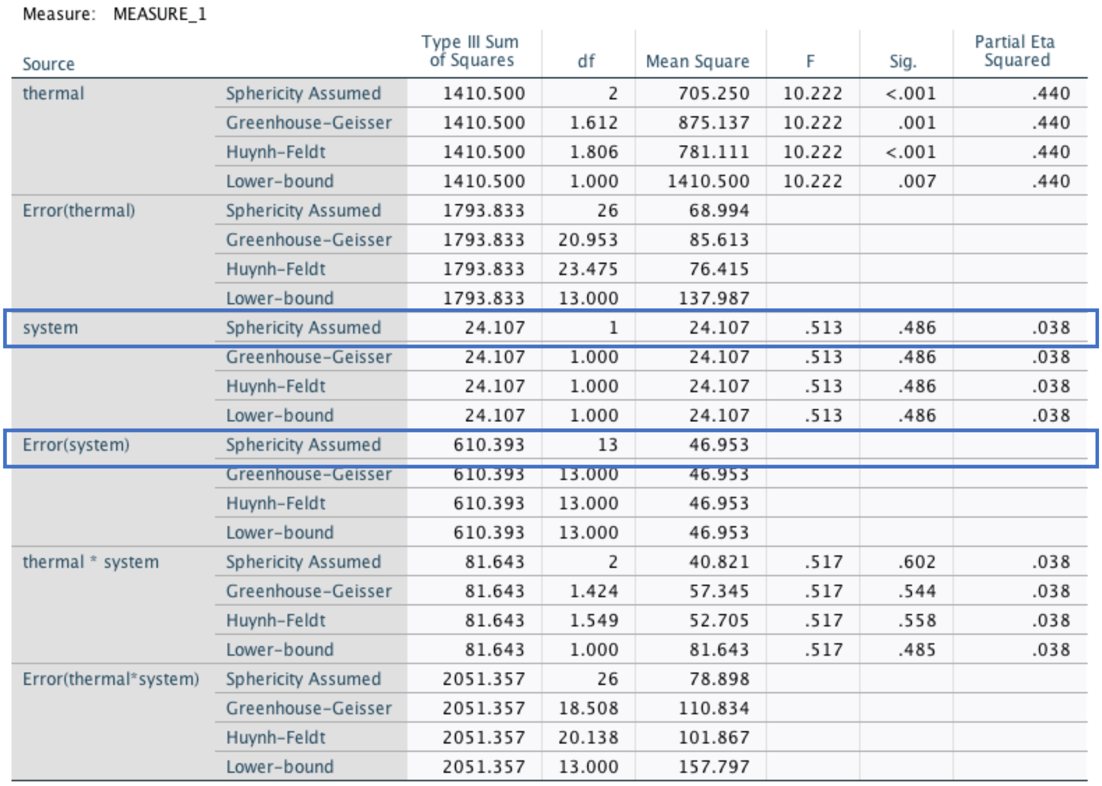
Figure 4.20 The participant puts on the VR headset again

4.3.3 Results

A total of 16 participants (8 male, 8 female, age 22 to 31) have taken part in the experiment. Two of the questionnaires were invalid. Repeated measures factorial analyses of variance (ANOVAs), with thermal feedback (non-thermal feedback, hot thermal feedback and cold thermal feedback) and system type (system1 and system2) as the independent variables were used to determine the statistical significance of the independent variables on the dependent variable (participants' trust in automated driving systems).

The effect of system type

As shown in Figure 4.21, the main effect of system on trust was not statistically significant, F(1, 13) = 0.513, p = 0.486.

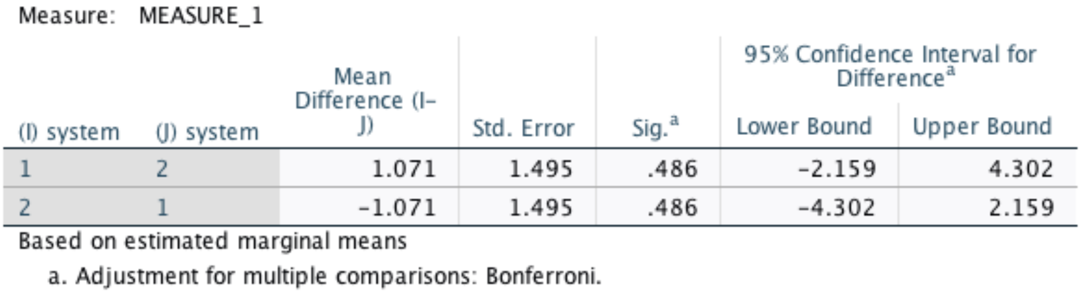


Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
thermal	Sphericity Assumed	1410.500	2	705.250	10.222	<.001	.440
	Greenhouse-Geisser	1410.500	1.612	875.137	10.222	.001	.440
	Huynh-Feldt	1410.500	1.806	781.111	10.222	<.001	.440
	Lower-bound	1410.500	1.000	1410.500	10.222	.007	.440
Error(thermal)	Sphericity Assumed	1793.833	26	68.994			
	Greenhouse-Geisser	1793.833	20.953	85.613			
	Huynh-Feldt	1793.833	23.475	76.415			
	Lower-bound	1793.833	13.000	137.987			
system	Sphericity Assumed	24.107	1	24.107	.513	.486	.038
	Greenhouse-Geisser	24.107	1.000	24.107	.513	.486	.038
	Huynh-Feldt	24.107	1.000	24.107	.513	.486	.038
	Lower-bound	24.107	1.000	24.107	.513	.486	.038
Error(system)	Sphericity Assumed	610.393	13	46.953			
	Greenhouse-Geisser	610.393	13.000	46.953			
	Huynh-Feldt	610.393	13.000	46.953			
	Lower-bound	610.393	13.000	46.953			
thermal * system	Sphericity Assumed	81.643	2	40.821	.517	.602	.038
	Greenhouse-Geisser	81.643	1.424	57.345	.517	.544	.038
	Huynh-Feldt	81.643	1.549	52.705	.517	.558	.038
	Lower-bound	81.643	1.000	81.643	.517	.485	.038
Error(thermal*system)	Sphericity Assumed	2051.357	26	78.898			
	Greenhouse-Geisser	2051.357	18.508	110.834			
	Huynh-Feldt	2051.357	20.138	101.867			
	Lower-bound	2051.357	13.000	157.797			

Figure 4.21 Tests of within-subjects effects

As shown in Figure 4.22 below, the trust value of the study subjects in the intervention trial was 1.071 (95% confidence interval: -2.159 -4.302) lower than that of the control trial, and the difference was not statistically significant, p=0.486.



Measure: MEASURE_1

(I) system	(J) system	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	Upper Bound
1	2	1.071	1.495	.486	-2.159	4.302
2	1	-1.071	1.495	.486	-4.302	2.159

Based on estimated marginal means

a. Adjustment for multiple comparisons: Bonferroni.

Figure 4.22 Pairwise Comparisons

The effect of thermal feedback

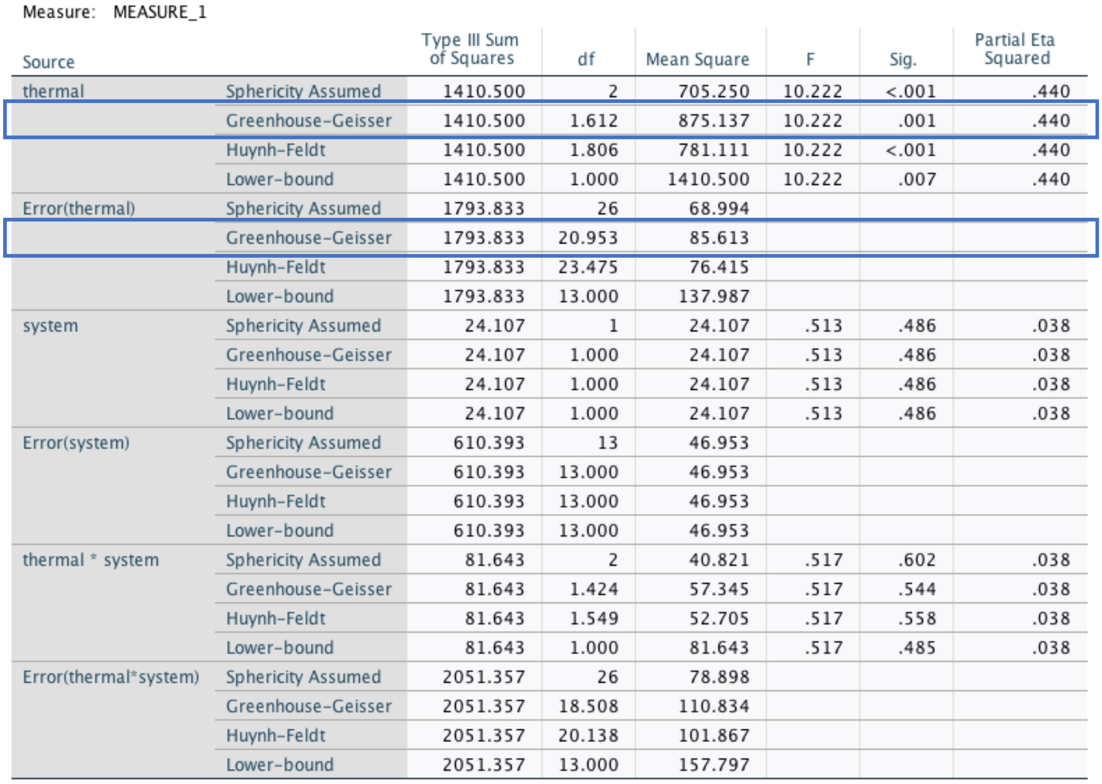
As seen in Figure 4.23, the effect of Thermal feedback on the trust value was statistically significant, F(1.612, 20.953) =10.222, p=0.01.

As shown in Figure 4.24, The difference in trust under the influence of non-thermal feedback(thermal1) and cold thermal feedback(thermal3) is statistically significant (P=0.006) with a mean difference of 10.036 (95% confidence interval: 2.846 - 17.225), and the difference in trust under the influence of hot thermal feedback(thermal2) and cold thermal feedback(thermal3) is statistically significant (P = 0.033) with a mean difference of 4.857 (95% confidence interval: 0.346 - 9.368).

Under the influence of non-thermal feedback (thermal1) and cold thermal feedback (thermal3), the mean values of the participants' trust in the autonomous driving system are shown in Figure 4.25.

Comparison of trust values under the influence of independent variables

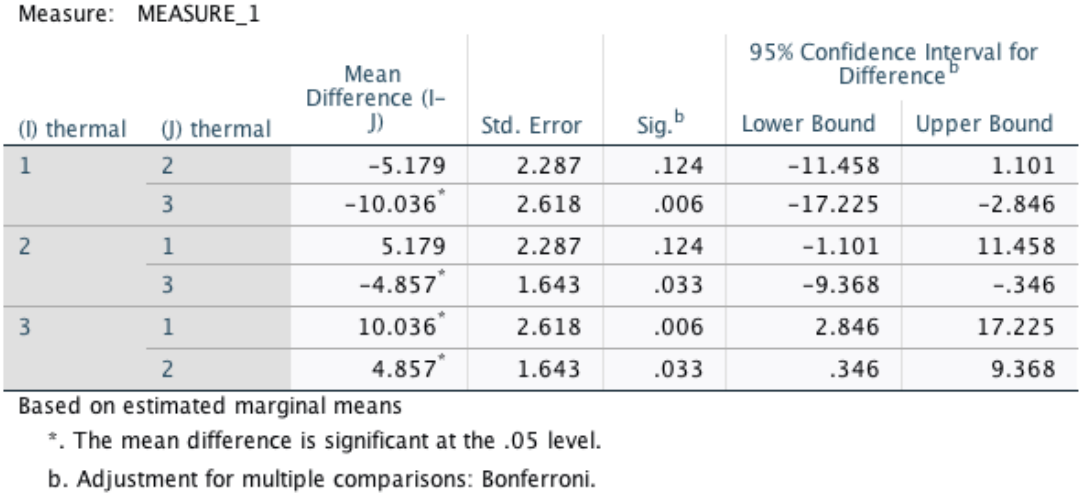
The comparison of participants' trust values in the automated driving system under the influence of different independent variables in the experimental conditions is shown in Figure 4.26 and Figure 4.27.



Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
thermal	Sphericity Assumed	1410.500	2	705.250	10.222	<.001	.440
	Greenhouse-Geisser	1410.500	1.612	875.137	10.222	.001	.440
	Huynh-Feldt	1410.500	1.806	781.111	10.222	<.001	.440
	Lower-bound	1410.500	1.000	1410.500	10.222	.007	.440
Error(thermal)	Sphericity Assumed	1793.833	26	68.994			
	Greenhouse-Geisser	1793.833	20.953	85.613			
	Huynh-Feldt	1793.833	23.475	76.415			
	Lower-bound	1793.833	13.000	137.987			
system	Sphericity Assumed	24.107	1	24.107	.513	.486	.038
	Greenhouse-Geisser	24.107	1.000	24.107	.513	.486	.038
	Huynh-Feldt	24.107	1.000	24.107	.513	.486	.038
	Lower-bound	24.107	1.000	24.107	.513	.486	.038
Error(system)	Sphericity Assumed	610.393	13	46.953			
	Greenhouse-Geisser	610.393	13.000	46.953			
	Huynh-Feldt	610.393	13.000	46.953			
	Lower-bound	610.393	13.000	46.953			
thermal * system	Sphericity Assumed	81.643	2	40.821	.517	.602	.038
	Greenhouse-Geisser	81.643	1.424	57.345	.517	.544	.038
	Huynh-Feldt	81.643	1.549	52.705	.517	.558	.038
	Lower-bound	81.643	1.000	81.643	.517	.485	.038
Error(thermal*system)	Sphericity Assumed	2051.357	26	78.898			
	Greenhouse-Geisser	2051.357	18.508	110.834			
	Huynh-Feldt	2051.357	20.138	101.867			
	Lower-bound	2051.357	13.000	157.797			

Figure 4.23 Tests of within-subjects effects 2



Measure: MEASURE_1

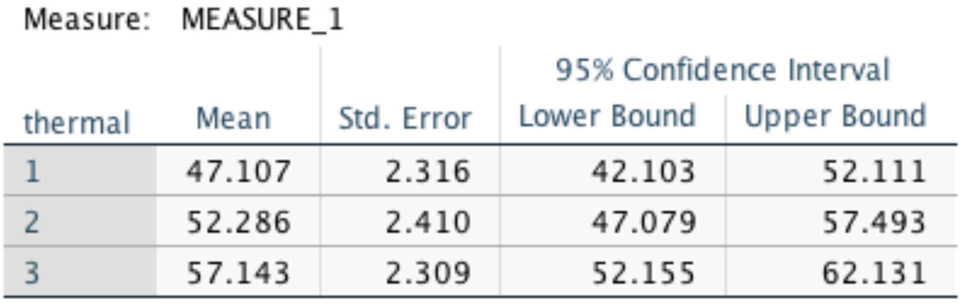
(I) thermal	(J) thermal	Mean Difference (I–J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	Upper Bound
1	2	-5.179	2.287	.124	-11.458	1.101
	3	-10.036*	2.618	.006	-17.225	-2.846
2	1	5.179	2.287	.124	-1.101	11.458
	3	-4.857*	1.643	.033	-9.368	-.346
3	1	10.036*	2.618	.006	2.846	17.225
	2	4.857*	1.643	.033	.346	9.368

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

b. Adjustment for multiple comparisons: Bonferroni.

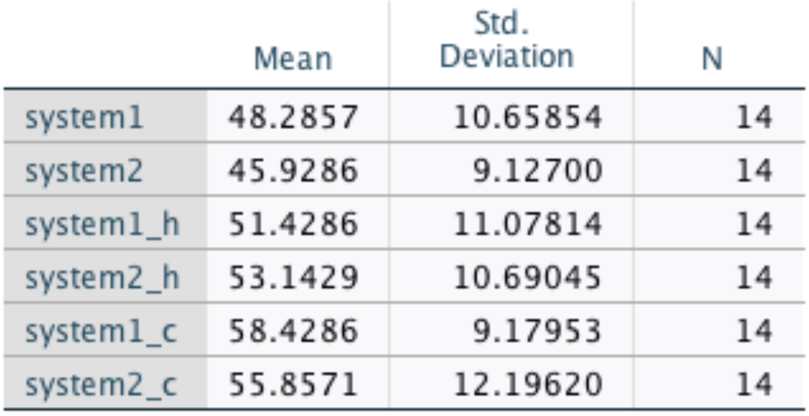
Figure 4.24 Pairwise Comparisons 2



Measure: MEASURE_1

thermal	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
1	47.107	2.316	42.103	52.111
2	52.286	2.410	47.079	57.493
3	57.143	2.309	52.155	62.131

Figure 4.25 Estimates



	Mean	Std. Deviation	N
system1	48.2857	10.65854	14
system2	45.9286	9.12700	14
system1_h	51.4286	11.07814	14
system2_h	53.1429	10.69045	14
system1_c	58.4286	9.17953	14
system2_c	55.8571	12.19620	14

Figure 4.26 Descriptive Statistics

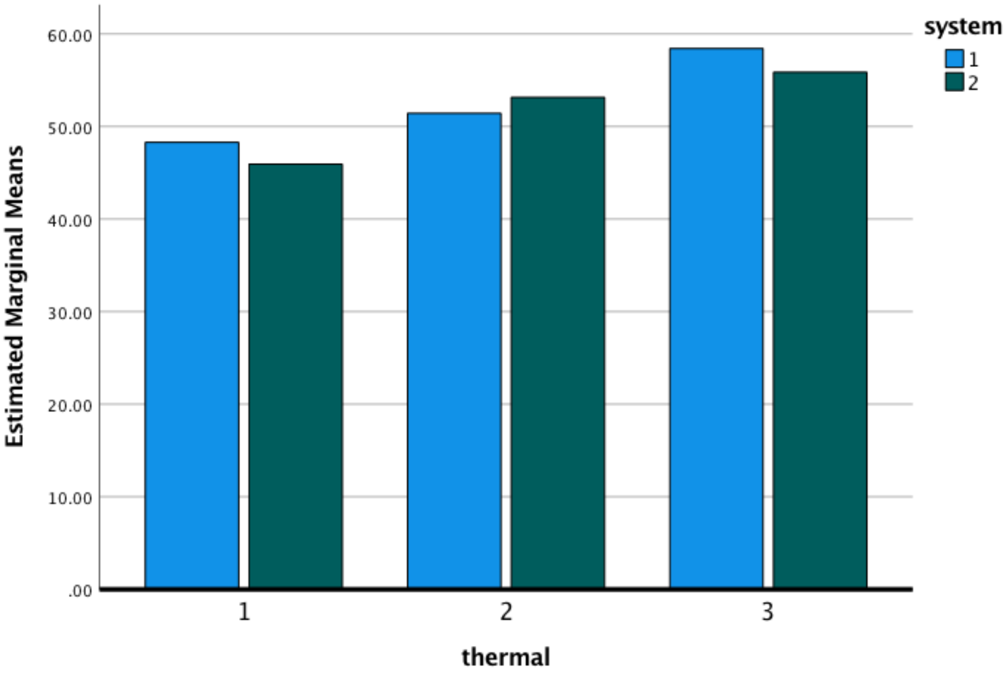


Figure 4.27 Estimated Marginal Means of MEASURE 1

4.3.4 Discussion

Analysis of questionnaire results

From the analysis of the above data, it is clear that participants trust the autonomous driving system with cold thermal feedback more than the autonomous driving system without thermal feedback. It can be said that under the experimental conditions, cold thermal feedback did enhance people's trust in the autonomous driving system.

According to the results of the data analysis, participants had higher trust in the autonomous driving system with cold thermal feedback than in the autonomous driving system with hot thermal feedback. However, this is based on the results of the current temperature setting under experimental conditions. Since there are large individual differences in people's perceptions of temperature, it is difficult to say that there is a correspondence between the temperature of hot thermal feedback and cold thermal feedback under the experimental conditions. In fact, in the interviews, some participants indicated that the hot thermal feedback was too hot. Thus the possibility exists that the hot thermal feedback temperature was set too high and affected the results. In addition, although the temperature of the thermal element on the thermal interface is constant when it is heated or cooled, the temperature changes significantly when the thermal element is in contact with the skin of the face. In addition, different people can feel the same temperature differently.

In conclusion, the effect of thermal feedback on human trust in automated driving systems needs to be further explored, especially the effect of hot thermal feedback.

Analysis of interview results

1) Preference for cold thermal feedback

In the post-experiment interviews, 11 of the 14 participants mentioned their preference for cold feedback. They said they prefer cold feedback, they like cold feedback, they think cold feedback is better than hot feedback, or they feel more comfortable with cold feedback. Interestingly, one participant mentioned in the interview that he thought hot feedback was better, but the results of the questionnaire analysis showed that he trusted the system with cold thermal feedback more than the system with hot feedback.

Participants mentioned the following reasons for their preference for cold thermal feedback in their interviews.

- In a driving environment where participants tend to feel anxious and also a bit carsick, cold thermal feedback can calm them down.
- Cold thermal feedback makes participants feel more comfortable, and the temperature is set appropriately.
- Participants feel they like cold thermal feedback. This is a subjective feeling or personal preference that they have.
- Cold thermal feedback brings a sense of security.
- Cold thermal feedback makes participants feel more confident in the autonomous system.
- The cool temperature gives a sense of the rock itself, and this temperature feedback matches the impression people have of the object.
- The Cold thermal feedback can be distinguished from natural temperature changes such as sunlight.

It is evident that participants prefer cold feedback for two main reasons. The first reason is that the participants felt good about the stimulus of cold thermal feedback applied directly to their skin surface. This is a direct response to cold stimulus for them. They found this physiological perception from the colder temperature to be comfortable and pleasant. The second reason is that cold thermal feedback conveys just the right level of warning when delivering information. The cold temperature stimuli fit the subject of the delivered message, making the participants feel that the design is reasonable. This is the participants' recognition of the rationality of the methodological settings for conveying the system's situation awareness.

In addition, the experiment was conducted indoors with air conditioning, so the ambient temperature should have little effect on the participants' preference for cold feedback. However, the effect of seasonal temperature on participants' subjective feelings and moods could not be completely excluded.

2) Negative effects of hot thermal feedback

From the results of the data analysis, it is clear that hot thermal feedback and cold thermal feedback provide the same information but do not achieve the same effect of enhancing trust. This is possibly due to the fact that while providing information, hot thermal stimuli also bring some negative effects. In the interviews, the participants mostly recognized the warning effect of hot thermal feedback. They mentioned that hot thermal feedback is not easy to ignore, that hot thermal feedback does remind them, and that hot thermal feedback has a warning effect.

However, participants also mentioned various disadvantages of hot thermal feedback. The main reasons why they disliked hot feedback are the following.

- Hot thermal feedback is disturbing and annoying.
- Hot thermal feedback is too hot.
- Do not like the feeling of heat.
- Hot thermal feedback makes them feel dangerous, feel anxious and panic, feel nervous.
- The participant does not know how far it will heat up before stopping, worried about the hot thermal feedback is not safe.

Participants felt that the hot thermal feedback was too hot, and that the temperature may have been set too high. The effect of gentler hot thermal feedback on trust needs to be further explored. Participants frequently mentioned words related to negative emotions such as danger and anxiety, suggesting that the hot thermal stimulus brought them negative emotions, which apparently had a negative effect on their trust in the autonomous system.

3) User experience enhancement

All participants reported that the thermal feedback had a reminder effect and was effective in capturing their attention. Participants can understand the information conveyed by the thermal feedback and the correspondence between the thermal feedback pattern and the position of the rocks.

From the interviews, it is clear that the thermal feedback provided reminders to the participants on two levels. The first level is to alert the participant that there is a change around them, which is enhancing the driver's situational awareness. The second level is to remind the driver that the system perceives a change in the surroundings, which is to help the participant understand the system's situation awareness.

Participants had the following suggestions for improving the conveying of system situation awareness information through thermal feedback.

- Temperature Setting Three participants mentioned in the interviews that they wanted the thermal feedback to slowly get colder or warmer as the distance to the stone decreased. It was also mentioned that one prefers slow warming over sudden warming of the thermal interface.
- Reminder timing settings There was a great deal of individual variation in participants' evaluations of the timing of the delivery of information. Some people think the timing of the hot feedback prompt is too late and should be earlier. Some people think the prompt is too early and want the thermal interface to heat up as the car passes over the rock and disappear when the car is completely over the rock. One would expect thermal feedback to be activated just a little earlier than when the car passes the rock, not much earlier. Some feel that the current time setting for the appearance of thermal feedback is appropriate.
- Information content setting Two participants expressed a preference for the system to indicate the car's next direction of movement rather than the location of the rocks.

4) Evaluation of two systems

Participants could all feel the difference between system 1 and system 2. Among them, those who have a lot of driving experience will care a lot about the distance between the car and the surrounding objects, and they can easily see how far the car is from the rocks. People without a driving license or those with a license but little driving experience tend to observe the movement of the steering wheel, the angle of the car's steering, etc.

From the data, it is clear that in the absence of thermal feedback, participants were able to distinguish between the different performances of the two systems, and most of them had more trust in system 1. In the interviews they mentioned that the cars controlled by system 1 were further away from the rocks, which made them feel safe. With the addition of cold thermal feedback, 11 out of 14 people maintained their judgment on both systems. Specifically, people who trust system 1 more than system 2 still trust system 1, which with cold thermal feedback, more than system 2, which with cold thermal feedback. And in the presence of hot thermal feedback, the participants' ratings of the two systems in terms of trust changed significantly when comparing the two systems. Hot thermal feedback interfered to some extent with the participants' evaluation of the system.

Chapter 5
Conclusion

5.1. General discussion

This research focuses on solving the problem of lack of human trust in automated driving systems during the transition period due to complex human-vehicle interaction processes, lack of understanding of automated systems, and complex traffic environments.

The goal of this study is to increase user trust in highly automated driving during the transition period and to provide an in-vehicle user interface that is easy to accept, effective to use, and provides an enjoyable driving experience.

From the literature review, it is clear that in order to improve user trust in autonomous driving, system transparency and efficient information transfer should be achieved. According to previous studies in this area of driver trust in autonomous driving, presenting system situation awareness to the driver is an effective way to enhance human trust in the automated system and improve the user experience. Presenting system situation awareness to the driver can be done through various channels such as visual, auditory, and haptic. In this study, thermal feedback from haptic feedback is introduced during highly automated driving to investigate how the presentation of system situation awareness information through different types of thermal feedbacks affects the driver's trust in the automated driving system.

This study chose to provide participants with system situation perception information in a virtual autonomous driving simulator through wearable devices that provide thermal feedback corresponding to specific driving scenarios, and to measure participants' trust in the autonomous driving system through a standard psychological questionnaire. First, feasibility experiments were conducted using a prototype consisting of a VR headset with thermal elements. After that, this study experimentally investigates the effect of hot thermal feedback and cold thermal feedback on human trust in highly automated driving systems. According to the experimental results, under experimental conditions, presenting system situation awareness by cold thermal feedback can enhance human trust in highly autonomous driving systems. In addition, under the experimental conditions, people have higher trust in the autonomous driving system with cold thermal feedback than in the autonomous driving system with hot thermal feedback.

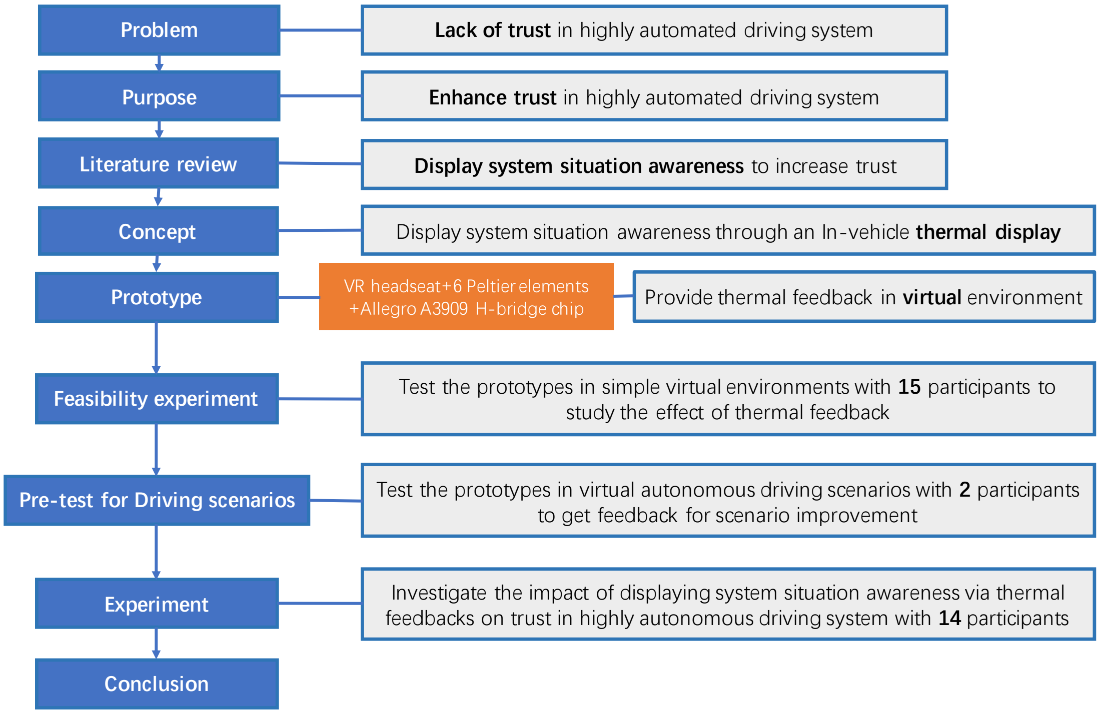


Figure 5.1 General Structure

5.2. Limitation

Limitations of thermal feedback

First, some participants responded that the thermal feedback hardware had unstable performance during the experiment. In addition, the pulsating feedback selected due to technical limitations is restricted, and further enhancement of the hardware settings to provide thermal feedback with smoother temperature changes should be considered.

Since there are individual differences in human perception of temperature, even if the temperature is set at the same level, each individual may feel differently. In order to provide a better user experience, the temperature range should be debugged in advance to find the right temperature range for each individual. The temperature sensor should be considered to monitor the temperature change curve in real time, but it must be noted that when the thermal element is in contact with the skin of different people, the temperature of the contact surface will be very different.

In this study, the thermal feedback device was combined with the VR headset, which would result in the effect of thermal feedback in a real driving environment being different from the experimental results. In addition, the effect of thermal feedback when acting on other parts of human skin should also be further investigated.

Limitations of VR driving simulation

Obviously there will be differences between an autonomous driving simulation in a virtual environment and a realistic autonomous driving.

The weight and tactility of the VR headset has an impact on the overall experience. There are limitations to studying human-machine interaction in autonomous driving through VR. In addition, Oculus Quest supports limited image quality, which also affects the realism of the autonomous driving experience.

Limitations of scene setting

The simulated driving scenarios set in this study are simple and the information is direct, while the real driving environment and interaction process are more complex. Therefore, the virtual driving experience process is not close enough to the actual driving experience process, and there are non-negligible differences. Next time, long driving routes and setting secondary tasks can be considered.

Limitations of the measurement method

Only subjective measures were used to measure human trust in automated driving systems in this study, and subjective data were collected without building a dynamic model based on real-time trust values. Advanced physiological measuring techniques, such as the electrocardiogram (ECG) and electroencephalogram (EEG) could be conducted to detect user trust dynamically during human-vehicle interaction.

5.3. Future work

Further enhancement of pattern design

In future research, the possibility of providing thermal patterns corresponding to more specific contexts can be explored. In driving scenarios, the thermal patterns for guiding or warning drivers could be designed according to external traffic conditions. Low temperature can be designed to guide the driver in normal driving scenarios, and high temperature can be designed to warn the driver about the emergency situation in which the automated system tends to have bad performances. The application of tactile patterns to automated driving can lead to the enhancement of driver situational awareness during the take-over process.

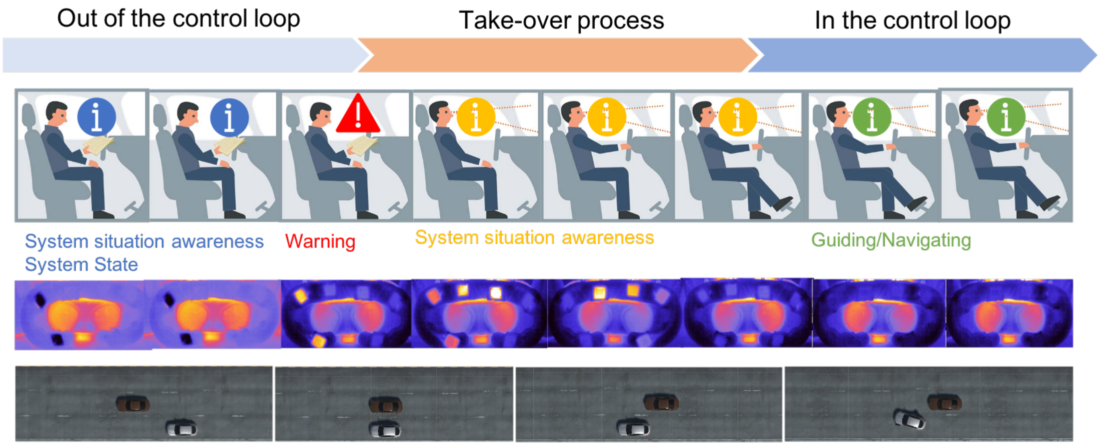


Figure 5.2 A sketch of the application of thermal feedback in different driving phases

For example, when it comes to driver take-over events, different types of thermal feedback can provide different types of information during the corresponding driving phase, as shown in Figure 5.2. When the driver is out of the control loop, the thermal interface can increase the driver's trust in the automated driving system by providing information about the system's situational awareness. When the system reaches its functional limit, the automated system sends a takeover request and switches the control generator from the automation to the driver. The thermal interface will become hotter to warn the driver and help prepare the driver to take control effectively. It also needs to guide or warn the driver when he enters the control loop.

In addition, the possibility of turning simple "on" or "off" feedback switches into a reliable range like "nothing, a little bit cold, mildly cold, or very cold" to create a much stronger sense of presence. Various temperature strengths corresponding to different conditions can be applied in pattern design, such as temperature becoming progressively stronger or weaker with distance, to convey more accurate information.

Transformation of single-sensory interaction to multi-sensory interaction

mainly work on technologies to create multiple sensory stimuli to the human somatosensory subsystem (i.e., pressure, temperature, texture, pain, and body position) to encode, model, and deliver information from automated systems in a minimally obtrusive way.

Providing haptic and temperature feedback to enhance human trust in the automated driving system based on an understanding of human information processing will be the main exploration. Users' responses to each modality can be recorded in experiments and the effect of different feedback on their trust can be compared by psychophysiological measures. How cross-modal and multi-modal signals cooperate to provide information to humans in an appropriate way and enhance the interaction experience in autonomous driving scenarios can also be clarified through experiments.

Establishment of human-vehicle interaction system based on haptic feedback

In the future, further research can be conducted on how multi-sensory modalities can be constructed and utilized in autonomous driving scenarios. Different ways of interaction will be explored through the process of designing, implementing and evaluating multi-sensory prototypes in specific driving scenarios. A central feature of the research will be haptic feedback such as thermal feedback and vibration feedback to avoid affecting non-driving tasks. Based on previous research on thermal feedback, the plan is to build a multi-sensory display consisting of temperature haptic, visual, and auditory elements, explore it in specific situations, and then figure out the mechanisms by which it cooperates with other kinds of feedback, such as pressure tactile feedback.

References

[1] Daniel Watzenig and Martin Horn. *Automated driving: safer and more efficient future driving.* Springer, 2016.

[2] Eshed Ohn-Bar and Mohan Manubhai Trivedi. Looking at humans in the age of self-driving and highly automated vehicles. *IEEE Transactions on Intelligent Vehicles*, 1(1):90–104, 2016.

[3] Kristin E Schaefer, Jessie YC Chen, James L Szalma, and Peter A Hancock. A meta-analysis of factors influencing the development of trust in automation: Implications for understanding autonomy in future systems. *Human factors*, 58(3):377–400, 2016.

[4] John D Lee and Katrina A See. Trust in automation: Designing for appropriate reliance. *Human factors*, 46(1):50–80, 2004.

[5] Robert R Hoffman, Matthew Johnson, Jeffrey M Bradshaw, and Al Underbrink. Trust in automation. *IEEE Intelligent Systems*, 28(1):84–88, 2013.

[6] Kevin Anthony Hoff and Masooda Bashir. Trust in automation: Integrating empirical evidence on factors that influence trust. *Human factors*, 57(3):407–434, 2015.

[7] Kumar Akash, Wan-Lin Hu, Tahira Reid, and Neera Jain. Dynamic modeling of trust in human-machine interactions. In *2017 American Control Conference (ACC)*, pages 1542–1548. IEEE, 2017.

[8] Cynthia L Corritore, Beverly Kracher, and Susan Wiedenbeck. On-line trust: concepts, evolving themes, a model. *International journal of human-computer studies*, 58(6):737–758, 2003.

[9] Bonnie M Muir and Neville Moray. Trust in automation. part ii. experimental studies of trust and human intervention in a process control simulation. *Ergonomics*, 39(3):429–460, 1996.

[10] John Lee and Neville Moray. Trust, control strategies and allocation of function in human-machine systems. *Ergonomics*, 35(10):1243–1270, 1992.

[11] Kunal Gupta, Ryo Hajika, Yun Suen Pai, Andreas Duenser, Martin Lochner, and Mark Billinghurst. Measuring human trust in a virtual assistant using physiological sensing in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 756–765. IEEE, 2020.

[12] Wan-Lin Hu, Kumar Akash, Neera Jain, and Tahira Reid. Real-time sensing of trust in human-machine interactions. *IFAC-PapersOnLine*, 49(32):48–53, 2016.

[13] Kumar Akash, Wan-Lin Hu, Neera Jain, and Tahira Reid. A classification model for sensing human trust in machines using eeg and gsr. *ACM Transactions on Interactive Intelligent Systems (TiiS)*, 8(4):1–20, 2018.

[14] Ahmad Khawaji, Jianlong Zhou, Fang Chen, and Nadine Marcus. Using galvanic skin response (gsr) to measure trust and cognitive load in the text-chat environment. In *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*, pages 1989–1994, 2015.

[15] Jiun-Yin Jian, Ann M Bisantz, and Colin G Drury. Foundations for an empirically determined scale of trust in automated systems. *International journal of cognitive ergonomics*, 4(1):53–71, 2000.

[16] Maria Madsen and Shirley Gregor. Measuring human-computer trust. In *11th australasian conference on information systems*, volume 53, pages 6–8. Citeseer, 2000.

[17] P Goillau, C Kelly, M Boardman, and E Jeannot. Guidelines for trust in future atm systems-measures. 2003.

[18] Randall D Spain, Ernesto A Bustamante, and James P Bliss. Towards an empirically developed scale for system trust: Take two. In *Proceedings of*

the human factors and ergonomics society annual meeting, volume 52, pages 1335–1339. SAGE Publications Sage CA: Los Angeles, CA, 2008.

[19] Reena Master, Xiaochun Jiang, Mohammad T Khasawneh, Shannon R Bowling, Larry Grimes, Anand K Gramopadhye, and Brian J Melloy. Measurement of trust over time in hybrid inspection systems. *Human Factors and Ergonomics in Manufacturing & Service Industries*, 15(2):177–196, 2005.

[20] Maria Luz. *Validation of a Trust survey on example of MTCD in real time simulation with Irish controllers.* PhD thesis, PhD thesis, thesis final report. The European Organisation for the Safety of . . . , 2009.

[21] Lisa Buckley, Sherrie-Anne Kaye, and Anuj K Pradhan. Psychosocial factors associated with intended use of automated vehicles: A simulated driving study. *Accident Analysis & Prevention*, 115:202–208, 2018.

[22] Jessie Y Chen, Katelyn Procci, Michael Boyce, Julia Wright, Andre Garcia, and Michael Barnes. Situation awareness-based agent transparency. Technical report, Army research lab aberdeen proving ground md human research and engineering . . . , 2014.

[23] Edward Tufte. The visual display of quantitative information, 2001.

[24] Heather F Neyedli, Justin G Hollands, and Greg A Jamieson. Beyond identity: Incorporating system reliability information into an automated combat identification system. *Human factors*, 53(4):338–355, 2011.

[25] Younho Seong and Ann M Bisantz. The impact of cognitive feedback on judgment performance and trust with decision aids. *International Journal of Industrial Ergonomics*, 38(7-8):608–625, 2008.

[26] Lu Wang, Greg A Jamieson, and Justin G Hollands. Trust and reliance on an automated combat identification system. *Human factors*, 51(3):281–291, 2009.

[27] Nastaran Dadashi, Alex W Stedmon, and Tony P Pridmore. Semi-automated cctv surveillance: The effects of system confidence, system accuracy and task

complexity on operator vigilance, reliance and workload. *Applied ergonomics*, 44(5):730–738, 2013.

[28] Richard Pak, Nicole Fink, Margaux Price, Brock Bass, and Lindsay Sturre. Decision support aids with anthropomorphic characteristics influence trust and performance in younger and older adults. *Ergonomics*, 55(9):1059–1072, 2012.

[29] Brian Daniel Green. *Applying human characteristics of trust to animated anthropomorphic software agents.* State University of New York at Buffalo, 2010.

[30] J Ewart. de visser, frank krueger, patrick mcknight, steven scheid, melissa smith, stephanie chalk, and raja parasuraman. 2012. the world is not enough: Trust in cognitive agents. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 56, pages 263–267, 2012.

[31] George F Loewenstein, Elke U Weber, Christopher K Hsee, and Ned Welch. Risk as feelings. *Psychological bulletin*, 127(2):267, 2001.

[32] Dinesh K Pai. Multisensory interaction: Real and virtual. In *Robotics Research. The Eleventh International Symposium*, pages 489–498. Springer, 2005.

[33] Marianna Obrist, Elia Gatti, Emanuela Maggioni, Chi Thanh Vi, and Carlos Velasco. Multisensory experiences in hci. *IEEE MultiMedia*, 24(2):9–13, 2017.

[34] Eugene C Adam. Fighter cockpits of the future. In *[1993 Proceedings] AIAA/IEEE Digital Avionics Systems Conference*, pages 318–323. IEEE, 1993.

[35] Kohei Sonoda and Takahiro Wada. Displaying system situation awareness increases driver trust in automated driving. *IEEE Transactions on Intelligent Vehicles*, 2(3):185–193, 2017.

[36] Luke Petersen, Lionel Robert, Jessie Yang, and Dawn Tilbury. Situational awareness, driver's trust in automated driving systems and secondary task

performance. *SAE International Journal of Connected and Autonomous Vehicles, Forthcoming*, 2019.

[37] Alexander Kunze, Stephen J Summerskill, Russell Marshall, and Ashleigh J Filtness. Augmented reality displays for communicating uncertainty information in automated driving. In *Proceedings of the 10th international conference on automotive user interfaces and interactive vehicular applications*, pages 164–175, 2018.

[38] Johannes Beller, Matthias Heesen, and Mark Vollrath. Improving the driver–automation interaction: An approach using automation uncertainty. *Human factors*, 55(6):1130–1141, 2013.

[39] Zhuoluo Ma, Yue Liu, Dejiang Ye, and Lu Zhao. Vibrotactile wristband for warning and guiding in automated vehicles. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–6, 2019.

[40] Sunyoung Oh and Jeha Ryu. Preliminary evaluation of multi-vibration haptic feedback on a steering wheel spinner. In *2013 13th International Conference on Control, Automation and Systems (ICCAS 2013)*, pages 1079–1082. IEEE, 2013.

[41] Ariel Telpaz, Brian Rhindress, Ido Zelman, and Omer Tsimhoni. Haptic seat for automated driving: preparing the driver to take control effectively. In *Proceedings of the 7th international conference on automotive user interfaces and interactive vehicular applications*, pages 23–30, 2015.

[42] Jingyan Wan and Changxu Wu. The effects of vibration patterns of take-over request and non-driving tasks on taking-over control of automated vehicles. *International Journal of Human–Computer Interaction*, 34(11):987–998, 2018.

[43] Marine Capallera, Peïo Barbé-Labarthe, Leonardo Angelini, Omar Abou Khaled, and Elena Mugellini. Convey situation awareness in conditionally

automated driving with a haptic seat. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings*, pages 161–165, 2019.

[44] Anke Brock, Slim Kammoun, Marc Macé, and Christophe Jouffrais. Using wrist vibrations to guide hand movement and whole body navigation. *i-com*, 13(3):19–28, 2014.

[45] Jose Salazar, Keisuke Okabe, and Yasuhisa Hirata. Path-following guidance using phantom sensation based vibrotactile cues around the wrist. *IEEE Robotics and Automation Letters*, 3(3):2485–2492, 2018.

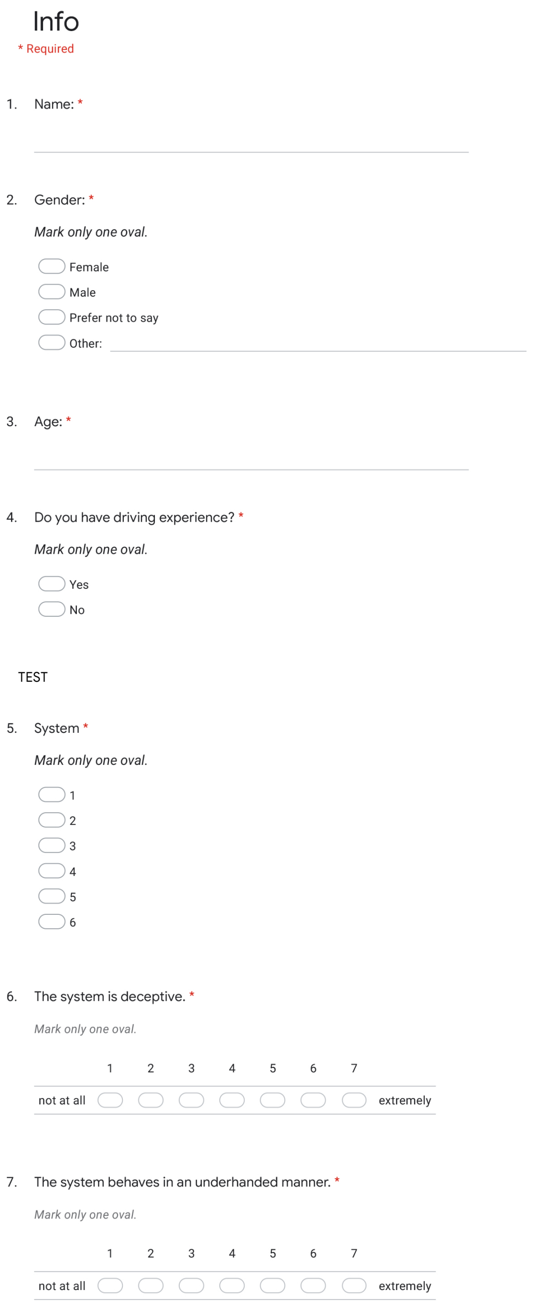
[46] Zikun Chen, Roshan Lalintha Peiris, and Kouta Minamizawa. A thermal pattern design for providing dynamic thermal feedback on the face with head mounted displays. In *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*, pages 381–388, 2017.

[47] Nimesha Ranasinghe, Pravar Jain, Shienny Karwita, David Tolley, and Ellen Yi-Luen Do. Ambiotherm: enhancing sense of presence in virtual reality by simulating real-world environmental conditions. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 1731–1742, 2017.

Appendices

A. The ED questionnaire

The ED (Empirically Determined) questionnaire used in this study is a 7-point Likert scale consisting of 12 items that can be used to measure human trust in automation [15].



Info

* Required

1. Name: *

2. Gender: *

Mark only one oval.

○ Female
○ Male
○ Prefer not to say
○ Other:

3. Age: *

4. Do you have driving experience? *

Mark only one oval.

○ Yes
○ No

TEST

5. System *

Mark only one oval.

○ 1
○ 2
○ 3
○ 4
○ 5
○ 6

6. The system is deceptive. *

Mark only one oval.

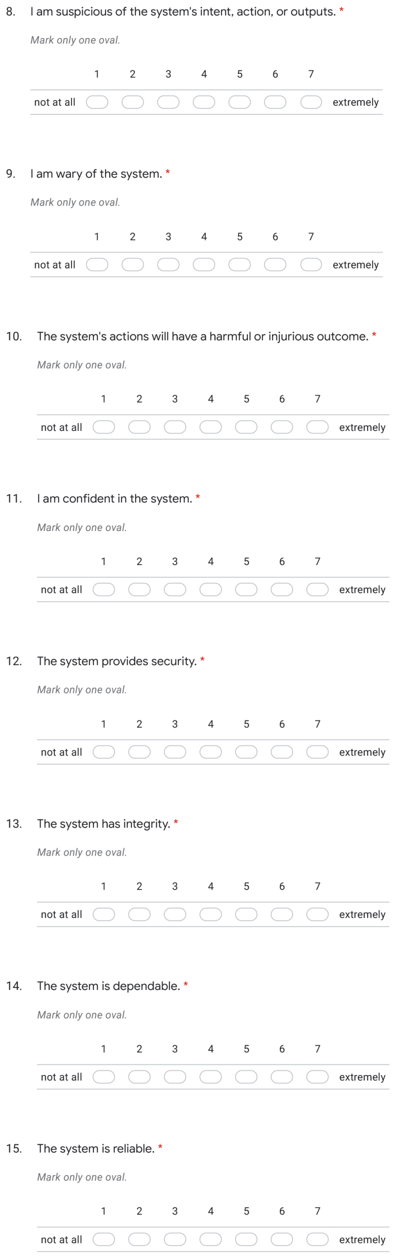
	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

7. The system behaves in an underhanded manner. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

Figure A.1 Part 1 of the questionnaire



8. I am suspicious of the system's intent, action, or outputs. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

9. I am wary of the system. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

10. The system's actions will have a harmful or injurious outcome. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

11. I am confident in the system. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

12. The system provides security. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

13. The system has integrity. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

14. The system is dependable. *

Mark only one oval.

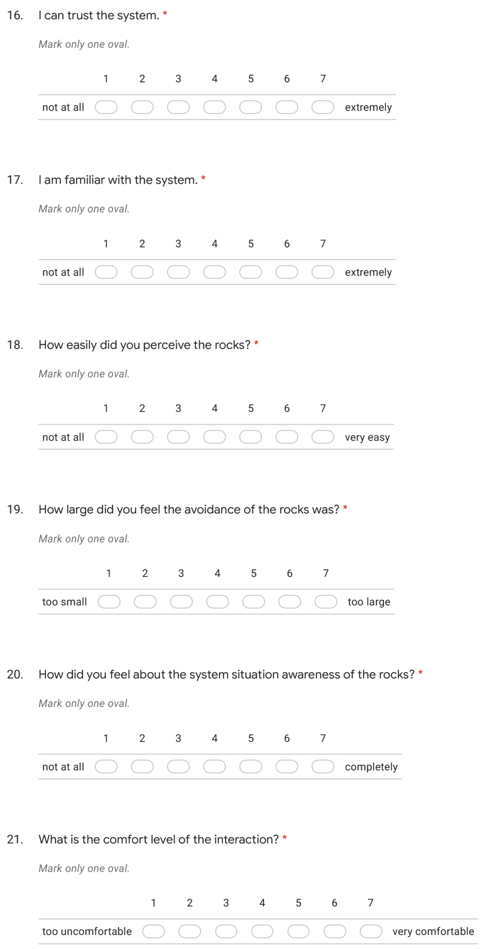
	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

15. The system is reliable. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

Figure A.2 Part 2 of the questionnaire



16. I can trust the system. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

17. I am familiar with the system. *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	extremely

18. How easily did you perceive the rocks? *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	very easy

19. How large did you feel the avoidance of the rocks was? *

Mark only one oval.

	1	2	3	4	5	6	7	
too small	○	○	○	○	○	○	○	too large

20. How did you feel about the system situation awareness of the rocks? *

Mark only one oval.

	1	2	3	4	5	6	7	
not at all	○	○	○	○	○	○	○	completely

21. What is the comfort level of the interaction? *

Mark only one oval.

	1	2	3	4	5	6	7	
too uncomfortable	○	○	○	○	○	○	○	very comfortable

Figure A.3 Part 3 of the questionnaire