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Master's Thesis
Academic Year 2017

FEEL IT: A Thermally Enhanced Environmental Perception System in VR

Keio University Graduate School of Media Design

Zikun Chen

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

Zikun Chen

Thesis Committee:

Associate Professor Kouta Minamizawa	(Supervisor)
Professor Masa Inakage	(Co-supervisor)
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Abstract of Master's Thesis of Academic Year 2017

FEEL IT: A Thermally Enhanced Environmental Perception System in VR

Category: Science / Engineering

Summary

How do we normally check weather? Through the phone, on television or Internet? Do we check the image of weather type, number of temperature, humidity and wind speed on the screen?

Are these the same ways we check weather in Virtual Reality(VR)? In this project, by combining thermal feedback with VR and utilizing thermal stimuli to present temperature data of weather, I attempted to use thermal haptic feedback to enhance users' perception of environment in virtual space. By integrating thermal modules with the current VR head mounted display to provide thermal feedback directly on the face, and by setting thermal stimulus to provide similar feeling towards real air temperature and the combination of multi-sensory feedback, I developed an application in which users are able to perceive the weather in VR environment to explore the possibility to enhance information perception in Virtual Reality.

A user experiment was also conducted to evaluate the design of this project, through which I verified that the thermal feedback can improve users' experience of perceiving environment in virtual space. The results also show the potential of utilizing thermal feedback in VR experience.

Keywords:

Haptic, Thermal, Environmental Information, Virtual Reality, VR

Keio University Graduate School of Media Design

Zikun Chen

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I want to thank to my family too, my father and mother and sister, although we are always far apart from each other, I really feel grateful for your unconditional support no matter what stupid decision I made.

Without you all I would not be able to go this far.

And I appreciate my LORD who holds tomorrow for what he has given and will give me.

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Chapter 1
Introduction

1.1 Background

By putting the users' view fully inside the environment without disturbing from surroundings in real life, Virtual Reality (VR) technology makes users feel they are actually in the space and enhances the immersive feeling of users in the virtual environment.

Through this technology, such as in games, like The Lab [3] and Rec Room [5] , users are able to be really immersed in the entire experience of the characters. With less disturbing from the real world, no matter how real or unreal the game space is, through VR technology the feeling of being placed into the virtual world is much more "real" than when sitting in front of the screen.

Not only in the entertainment experience, currently VR technology is also widely utilized in training processes, such as some professional sports, driving, construction, surgery, military, mining, etc. which provide trainees with precise, realistic simulations of what they may experience in some fields, at the same time lower the barrier for people who lack of access to enter some particular situations.

(a) (b) (c)

Figure 1.1: Examples of VR Experience

(a) Game The Lab [3]. (b) Game Rec Room [5]. (c) VR Mining [12].

It is possible to share immersive experience in remote place through VR technology as well. As shown in Figure 1.2, at present, some Japanese companies, such as Sync Travel [7] , a remote overseas travel service provided by KDDI Corporation, in which the costumers experience real-time local sightseeing guiding on the VR vision with a VR goggle in Japan and a 360 degrees camera in a local tourist spot connected.

(a) (b)

Figure 1.2: Sync Travel Provided by KDDI Corporation

However, although the main goal of VR technology is to provide a 360 degree view of the simulated environment in virtual space to provide real perception for users, compared with the way we sense the world around us in the real life, current VR is still lack of more complete multiple sensory experience.

As we usually perceive our surroundings through the multi-sensory system of our body, it is clear that our senses of touch, smell, taste, etc are also crucial components to complete the illusion. To simulate these senses, various studies have focused on increasing haptic feedback, such as adding vibration, force simulation, electrical stimulation, thermal stimulation, smell, taste, etc., into the experience in virtual space.

However in general, there are only few examples in which these kinds of technologies are applied into VR experience, and the proper methods to improve and enhance user experience in VR through adding multi-sensory feedback still remain to be discussed.

1.2 Motivation

1.2.1 Senses of Physical Environment

In real life, the physical environment (natural environment) around us includes includes all the purely physical factors, such as soil, water supply, climate, weather, and natural resources that affect human survival and economic activity. They are factors occurring naturally rather than artificially. This environment encompasses the interaction of all living species [22].

When human beings sense the physical environment, the ways in which we perceive and evaluate the environment are far more various [36], even look at the same thing, no two persons see the same reality. However, even human beings always have this uniqueness in their perception of things, in general as our process of sensing proceeded by similar sense organs, for example, we see things through our eyes, hear sounds through our ears, and feel touch through our skin. A theory suggested by Aristotle which describes how we perceive the environment (Figure 1.3) is through the five senses, the sense of seeing, hearing, smelling, tasting and touching [33] is still widely accepted, especially in environment understanding education [26]), as a conventional theory to explain how we perceive the world around us.

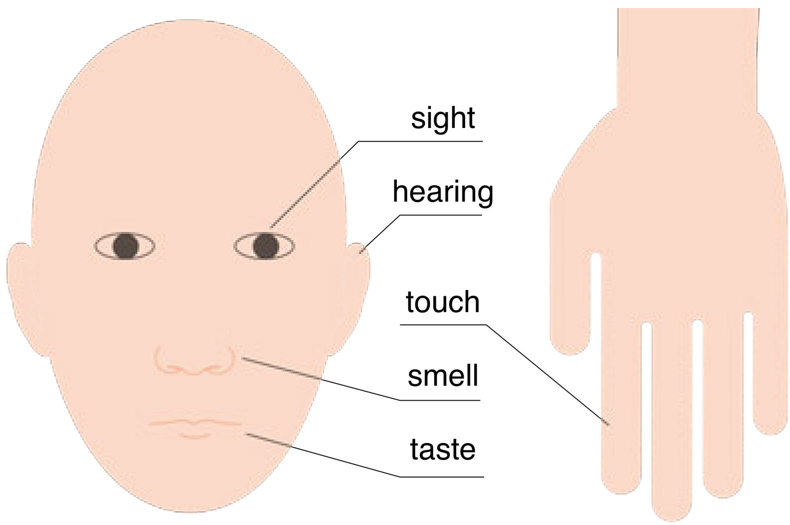


Figure 1.3: Aristotle's Five Senses Theory

As in current VR experience, visual and auditory sensations are the main aspects provided for generating the environment and main methods for perceiving the environment. Compared with our experience of sensing environment in real life, our d perception in virtual space are not yet complete. Some early researches on multi-sensory feedback in virtual environment [19] also suggested that the addition of tactile, olfactory and auditory cues to a virtual environment increased the user's sense of presence and memory of the environment. Therefor by adding more types of multi-sensory feedback to current VR technology, it is possible to enhance users' perception of environment. This methods can be applied in not only games or 360 degree movies, but also training, travelling and some information presenting process in virtual space.

And based on my previous works in a team which has been working on adding thermal haptic feedback into VR experience, and as my role in the team is to explore how to use the hardware our team has developed for providing information and improve the experience of users in vr, I gradually realized it's important and worthwhile to discuss how to provide haptic feedback can help users understand the environmental information better in virtual space.

Therefore in this project, what I intended to do is to explore the possibility for enhancing users' perception of environment in virtual space by adding haptic feedback into their experience.

1.2.2 Weather and Weather Information in VR

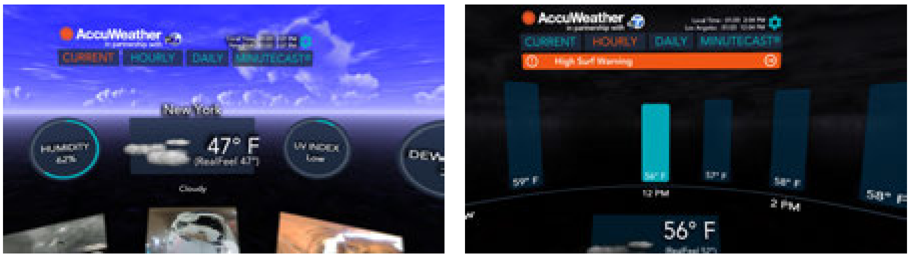
As a starting point of this topic, I chose weather as the aspect which represents environment at current stage of this project. As one of the most important types of information about physical environment, weather is as same as food, everyday we talk about it, we check it. There is no exaggeration to say that weather affects everything we do in our lives, it influences how we dress, whether we go out or whether we should bring an umbrella while we go out, it influences from our current activities to our future plans. Weather improve our life quality and s it cause inconvenience as well, and sometimes extreme weather destroy our towns or cities [27].

So how do we know weather in our daily life? Normally we have two approaches, first is the way we understand it by our own experience, we describe the space where we are from visual information by which we have comments like "it is wide space" "it is beautiful". And by our ears we know it is quite or noisy. By our skin, we know the temperature, also we feel the air flow passing by us. The other approach is not constrained by where we are - by checking the information from some weather stations. When we search for weather forecast or information about current weather, no matter through applications in smart phone, television or website, we have image, icons, animations or videos which tell us the weather types and temperature range within a day, and other information such as humidity, wind, pressure, etc.

In real life, people check weather data through the methods which are most efficient and convenient for them. Results of a survey conducted before (Ref. Table 3.1(a)) show that the most common way we search information about weather is on our smart phone, which is the easiest way for users to check both current data and future prediction about weather nowadays.

However, grabbing a smart phone when we are in VR environment sounds not convenient. A tool through which we can unfold weather news directly in VR environment sounds better.

Now AccuWeather [13] has taken the lead in attempting to launch a VR version of their weather news in which users can be refreshed to explore different types of weather phenomena through the 360 degree videos added to the application weekly, and can check all the information about weather, which include data of weather condition, like weather type, temperature, wind speed, dew point, wind direction, precipitation, etc. which are presented in almost the same way with their normal version (Figure 1.4).



(a) (b)

Figure 1.4: Interface of AccuWeather VR Application

However, if we directly import the same methods to give information about weather into VR, the current experience in inquiring weather information is actually not sufficient for users to have comprehensive understanding of the information efficiently.

First, our understanding about environment is more about our feeling rather than data. In AccuWeather we have the data presented in the conventional way we check weather, but people who are from different places with different perception, may have different understanding with the data. Like my friends from Hong Kong, last time they could not understand how cold 0°C could be until we travelled to Kawaguchi-ko during a winter. When we were there, my friends felt so excited for being in a environment has temperature below 0°C for the first time in their life. Meanwhile for people who come from cold places, it may be very hard for them to understand how hot the weather can be. Or for people from rainy area, they may not be able to imagine their skin will feel a little pain in very dry air.

Second, even we have visual and auditory feedback when we detect the environment information, without actual feeling, only through these methods doesn't mean users can have proper understanding on it. For instance, compare with picture of sunny day and rainy day, intuitively people feels the sunny day should be warmer than the rainy day, And compare sound of breeze and storm, it's likely that people feel the storm sound feels colder. Therefore by seeing and hearing, we cannot ensure users have right feeling towards the environment.

Third, mostly the space provided by virtual reality technology is full with visual scene and audio (sound effects and vocal guidance) which enhanced the immersive experience for users, in which it may be hard for users to focus when there are specific information provided by text, mark or sound, therefore in VR these types of information would be easy to be missed, or it require users to read the information more consciously.

Therefore, I intended to add haptic sensation in VR for help users understand the environment better than in current VR experience.

1.2.3 Main Goal of This Project

The main goal of this project is to design and develop a system through which users are able to inquiry the current weather in VR, and their experience is enhanced by haptic feedback which may enhance their understanding of the environmental information. In this system users can not only see and hear the environment as in normal VR system, but also feel the environment through the haptic feedback. And the focus of the evaluation of this design is on the performance of the key concept of the combination of haptic feedback and visual, auditory feedback in current VR system. Therefore the design of this project is trying to discuss the questions below:

1. *Does the proposed system make it easier for users to acquire environmental*

information?

2. *Does the proposed system allow users to perceive the environment more accurately in VR?*

Thesis Structure

CHAPTER 1: Introduction

Clarify the background, motivation and goal of this project.

CHAPTER 2: Related Works

Literature review. Presents the related work on environmental information presenting in current VR space, and how haptic feedback help people perceive the virtual space

CHAPTER 3: Concept and Method

Overview of this project. Presents the core concept and main methods utilized in the design process to achieve the goal of this project

CHAPTER 4: Design and Implementation

Presents design of the whole system (both hardware and software parts) and the studies which the design is based on.

CHAPTER 5: Evaluation

This chapter presents the design of the experiment and discussion on the results to evaluate the core concept for enhancing the environmental information presenting efficiency in VR by importing thermal feedback as information presenting method.

CHAPTER 6: Conclusion and Future Work

Conclusion of evaluation of this design, and discusses limitation and future possibilities.

Chapter 2

Related Works

2.1 Environmental Simulation in VR

At present, VR technology has made it easier for people to immerse themselves in the virtual environment than in the past, and the benefits of the user experience in games and movies are obvious, for entertainment no one would refuse to have a more immersive experience.

(a) (b)

Figure 2.1: VR Games

(a) Game Superhot [6]. (b) Immersive Horror Room Hospital Escape Terror in VR Zone in Shinjuku, Tokyo, Japan [2].

And with its high potential of simulating dangerous or risky situations within a controlled environment, and lower the cost of training, this technology has also got its utilization within a range of training scenarios, such as such as Osso VR, a surgical training platform which offers highly realistic hand-based interactions in an immersive training environment [4], and In Flight Emergency Simulation, with high-quality graphics and terrifying soundtrack, it is hoped to make people aware of the correct processes to follow for a landing on water [9].

In current VR technology, visual and auditory feedback have been fully considered, thereby in most existing VR experience the design and development team

(a) (b) (c)

Figure 2.2: VR Training

(a) A surgical training platform Osso VR [4]. (b) VR Inflight Emergency [9]. (c) VR Driving School [11].

always paid a lot of effort in the visual scene to make it realistic or fancy enough, with 360 degree view there is no limit of the users' view, which make a strong feeling for the users that they are actually in the virtual space. Meanwhile with utilizing proper sound effects these VR experience can greatly enhance users sense of immersion.

2.2 Haptic Feedback For Enhancing Sensing of Environment

Although through providing 360 degree view with high quality sound effect, as mentioned before, in real life human's perception is a complex process through which we sense the physical environment not only by sight and hearing, but also by the tactile sense, olfactory sense and taste sense. Those sensations are now sometimes all included into haptic sensation in haptic researches.

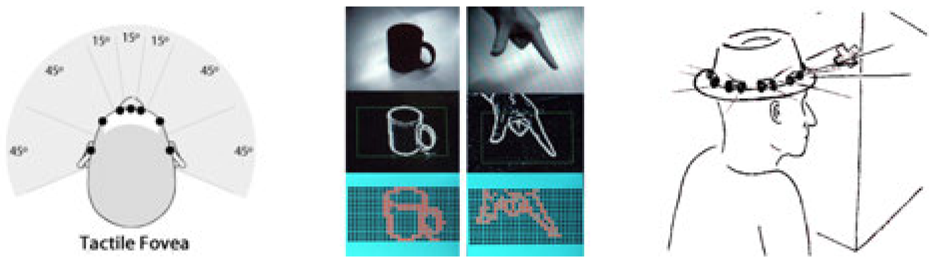
2.2.1 Kinesthetic and Tactile Feedback for Enhancing Perception of Environment

Previous research studies have shown that touch is a good mode of communication. In order to provide more compelling and complete experience, many related studies have been exploring a number of opportunities afforded by the tactile modality to enrich users' connection with the environment.

Vibrotactile feedback has been widely used in various researches on providing spacial awareness for users in both virtual and real environment. In the study of Cristy Ho et al., by designing two experiments to investigate the potential use of vibrotactile warning signals to present spatial information to car drivers, their research highlights the potential utility of vibrotactile warning signals in automobile interface design for directing a drivers visual attention to time-critical events or information. [20].

Forehead is a popular position on human body for investigating the use of vibrotactile feedback for providing spatial awareness. Alvaro Cassinelli et al added infrared proximity sensor and miniature off-axis vibration motors to forehead, with a tactile cues that created by simultaneously varying the amplitude and speed of the rotation, they made a haptic radar for detecting range of distance of even unseen objects, their work reduced blind angle for detection, and has potential for providing spatial awareness for blind people, or in virtual space [15].

Steve Mann et al explored the combination of Kinect range camera with vibrotactile helmet for navigation, though which Kinect on the user can observe the users environment and provide helpful spacial cues for collision avoidance especially for visual impaired individuals [28].



(a) (b) (c)

Figure 2.3: Use of Vibrotactile Feedback for Providing Spacial Awareness

(a) Tactile Fovea [18]. (b) Forehead Electro-tactile Display [25]. (c) ProximityHat [14].

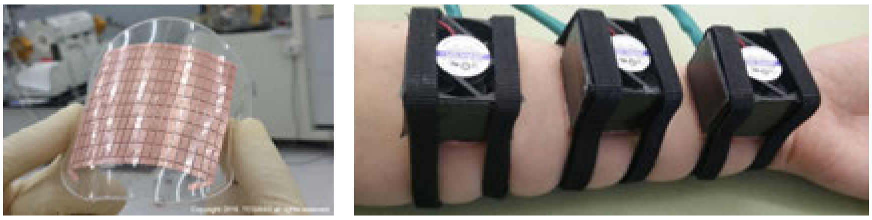
A different approach to help visual impaired people "see" the surroundings, is provided by Hiroyuki Kajimoto et al's work in adding electro-tactile display to the forehead as a vision substitution system by capturing and extracting outlines from the view in front, and converts the outlines to tactile sensation by electrical stimulation to provide rich and dynamic 2D information to the blinds [25].

To improve the precision and accuracy of vibrotactile feedback on the forehead, Victor Adriel de Jesus Oliveira et al has explored the way to create higher performance in using vibrotactile as directional cue on humans forehead, different from conventional ways like duplicating the number of actuators, by adding just two more motors on the forehead their design could increase precision and accuracy of users spacial perception [18].

Matthias Berning et al's study ProximityHat a wearable that detects the distance to the environment with ultrasonic sensors and displays this information to the user via tactile pressure actuators. In this design, the system determines the distance to surrounding objects with ultrasonic sensors and maps this information to an inward pressure, in this manner can give users information about their spacial relation with surroundings [14].

2.2.2 Thermal Haptic Feedback and Its Use in VR

As audio and vibrotactile feedback are not always suitable or desirable, as noise and/or movement may mask them, another aspect of haptic, thermal feedback may provide a salient alternative.



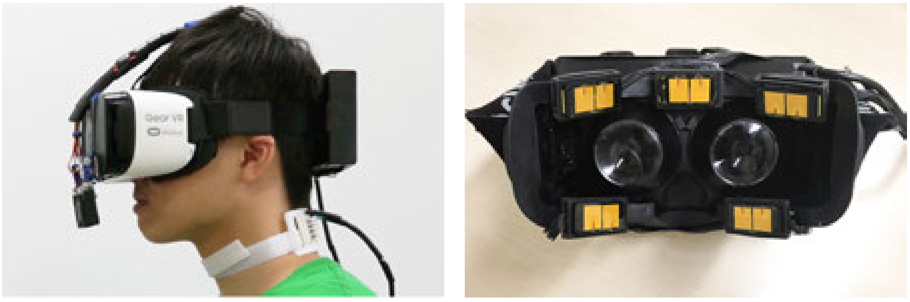
(a) (b)

Figure 2.4: Examples of Use of Thermal Haptic Feedback I

(a) ThermoReal [10]. (b) Heat Nav [35].

A recent example is ThermoReal, an interaction, flexible thermoelectric device which is designed by a Korean developer and manufacturer TEGway and demonstrated at HTC VIVE X Demo Day in Shanghai in July, 2017 [10]. By simulating heat, chill and pain in users' hands, this thermal module is able to bring sense of temperature into VR/AR and gaming experience. (Figure 2.4(a))

And Jordan Tewell, Jon Bird and George R. Buchanan designed a Thermal Array Display (TAD) called Heat Nav [35], which consists of three stimulator units, one positioned on the wrist, one under the elbow and the other between them, and in contrast of the pulsed thermal feedback provided in most thermal modules, their work explored the possibility to use continuous thermal feedback which does not require returning to neutral state before a new signal for navigational tasks (Figure 2.4(b)). The results of their study shows this continuous thermal feedback significantly improving performance in a 2D maze navigation task, and has potential to be used for real world navigational tasks.



(a) (b)

Figure 2.5: Examples of Use of Thermal Haptic Feedback II

(a) Ambiotherm [30]. (b) Our previous work of ThermoReality HMD [29].

As one new approach to enhance users' experience in VR, thermal feedback has draw some attentions in design of human-computer interaction. However this methods is yet to be fully investigated, only few researches made attempts to applied thermal feedback for providing better awareness of virtual environment.

In the work of Johann Citerin et al, they designed a haptic device that has been conceived to render both kinesthetic and thermal sensations computed from operator interaction with a 3D virtual environment. This device is able to render both kinesthetic and thermal properties when touching virtual objects and simulate flat and smooth surfaces of objects with different properties in virtual reality. [17]

Nimesha Ranasinghe et al designed Ambiotherm, a wearable accessory for current VR head mounted display that that consists of a ambient temperature module attached to the users neck and a wind simulation module focused towards the users face, and able to provide thermal and wind stimuli to simulate real-world environmental conditions, such as ambient temperatures and wind conditions [30].

And our team has been working on thermal feedback for VR experience as well. By integrating thermal modules to the facial side of current VR head mounted display, we intended to provide safe thermal feedback directly on users faces [16, 29]. As co-researcher and content designer in our team which work on importing thermal feedback to VR experience, my focus is how to present thermal feedback in VR. Based on our work on the exploration on the thermal feedbacks use as feedback in virtual environment including when combined with other types of feedback, our initial experiments reflected that the use of thermal feedback enhances the immersive feeling for the user. We believe that in addition to the text, visual and auditory information, the co-located thermal feedback on the faces, may provide a more enhanced way to immersively perceive the environment in virtual space.

Chapter 3
Concept and Method

3.1 Concept

Based on the idea of "adding haptic sensation in VR for enhancing users' perception of weather" in this project, several decisions have been made for clarifying the core concept, such as:

1. Identifying the most important information for users when they check the weather.
2. Determine the type of haptic feedback that is best for enhancing users perception of weather in VR.
3. Determine the right technology to utilize for the system.

3.1.1 Core Information and Haptic Feedback

When viewing information about weather, there are usually many factors listed in the report, such as weather type, humidity, air temperature, atmospheric pressure, wind, etc. However, for everyday use, not all these factors are necessary for users. Therefore, I first conducted a survey on people's experience when they check the weather in their daily life in order to select most important information to provide in the VR weather system.

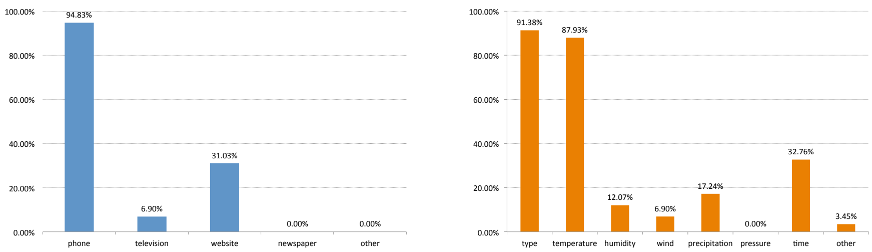
User Study 1: How do people check weather?

This study is an online survey conducted on Google which mainly focused on people's behavior and needs towards weather information. In this questionnaire, at beginning, I asked whether people check weather in their daily life, and participants who check weather are asked about their habits on methods and preference of information. The methods listed in the questionnaire were phone, television, website, newspaper and other (required specification), and the factors of the weather information included weather type, temperature, humidity, wind, precipitation, pressure, time, and other (require specification).

65 results were collected through an online Google survey, 53.2% are female, 46.8% are male, and aged from 18 to 35.

5 participants in this survey who were from San Diego, southern California, etc. said they did not check weather since the weather there were too stable (no rains) or too easy to predict.

The other 60 answers significantly show people's preference of information when they check weather.



(a) (b)

Figure 3.1: Results of User Study 1

(a) Main methods people use when checking weather. (b) The information people usually care about when checking weather.

As shown in Figure 3.1(a), when being asked where they checked the weather information, the results show that nowadays the most common method for checking weather is phone, 94.83% of the participants chose this options, And 31.03% of the participants check on website. With 6.90% and less percentage, obviously television and newspaper are not main methods for users to check weather any more.

Figure 3.1(b) shows that when asked what information people mostly care about when checking weather, 91.38% of the participants chose weather type and 87.93% of the participants chose temperature. 32.76% chose time, after time there were precipitation and humidity, got 17.24% and 12.07% respectively. Answers of "other" include: UV index, and percentage of rain forecast.

Therefore according to the results of User Study 1, the significantly essential information for users when checking weather are:

- Weather Type
- Temperature

Haptic Feedback

Compare with our perception of weather in real world, normally we know the weather type by seeing our surroundings and the sky, we see the sun, the clouds, lighterning, etc. and by hearing the sound of the wind, the rain, the thunder as well. And we perceive temperature by feeling on our skin.

Therefore in this project, information of weather type is provided by visual and auditory (if needed) feedback, include 360 degree full view scene corresponding to different weather types and sound effect such as sound of drizzle, rain, wind, etc.

And in terms of information of temperature, providing thermal sensation is more natural than conventional ways like by data, thus I decided to use thermal haptic feedback to simulate the air temperature in this system.

And as a position which is relatively the most sensitive part on the body to temperature change [21,23], human's face seems to be a good part on human body to feel weather. Besides, normally face, especially the area around eyes, is where on human body that never been covered by clothes through all seasons, while we have gloves for hands, scarfs for necks during the cold seasons. Hence face seems to be a natural choice as a part of human body for perceiving environment, in virtual space as well. Therefore in this project, face is chosen as the position of human body for receiving thermal haptic feedback.

3.1.2 Technology

Since in this project, thermal haptic feedback is going to be provided directly on users' faces in order to improve users' perception of weather in VR, the Thermo-Reality HMD our team has developed seems to be the best choice for immersing users in a virtual space through providing 360 degree visual scenes at the same time enhancing their experience in perceiving the environment by providing safe thermal stimuli on their face.

3.1.3 Core Concept

A thermally enhanced weather application for VR environment. In this design, users can check current weather in VR and the information they get is not only provided by visual scene, sound effects of the weather, they also feel the temperature through the thermal modules on the HMD which provide thermal feedback directly on their skin.

3.2 User Experience

3.2.1 Target Users

The ideal target users of this design is considered to be people who use VR environment for multiple purpose such as entertainment, remote communication, remote work, immersive information sharing, etc. which is built on the premise of higher social acceptance of Virtual Reality Technology that when it is more commonly accepted as an environment for game and work in the future which seems not too far. For such group of people, using of VR has less obstacles, which allow them have higher expectation in diversity and quality of information presented in virtual space.

3.2.2 User Experience

The goal of this project is to provide the user with a current weather checking system that can be more intuitive and more effective. In this system, as the environment is in VR, it allows users to check the weather while being in the space. And through the combination of Virtual Reality and thermal feedback, the main feature of this system is providing users a space to feel the environment.

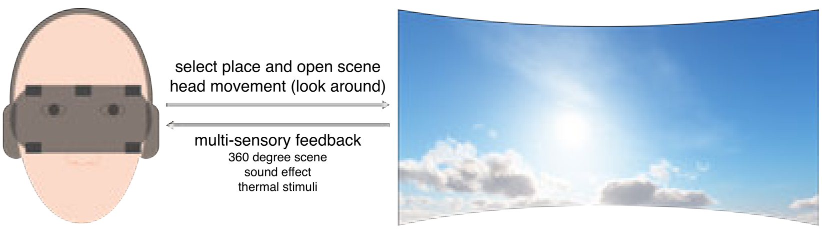


Figure 3.2: Interaction Between User and Feel It System

Users do not have too many operations in this application, because the main purpose of the system is to allow users to obtain and read information. Once the users launch the application, they start from the home scene where they can select place and open corresponding weather scene, and experience the multi-sensory feedback while checking the current weather there.

For instance, as shown in Figure 3.3, the Figure 3.3(a) and Figure 3.3(b) give examples of the scenes when users receive different weather data in *Feel It* application. In both scenes the user have 360 degree view of the environment, and receives sound effect of wind based on the weather data, in the example shown in Figure 3.3(a), the wind speed is 13 km/h, according to the setting in this project, this condition has sound effect of breeze (Ref. Table 4.2 and 4.6). As auxiliary information in this system, there is optional text on the screen shows the name of the city and the number of current temperature in corresponding place near the city name in order to ensure the best experience in information reading. Since this application provide classified thermal stimuli on users' skin according to real temperature the first one has temperature data as 296.15 °K (23 °C) and the second one has data as 272.15 °K (-1 °C), thus the two examples provide thermal stimuli at different temperatures to users skins.

(a) (b) (c)

Figure 3.3: Basic Concept of User Experience in Feel It Project

(a) (b) Two examples of the scenes in Feel It application. (c) A user wearing ThermoReality head mounted display.

Therefore, through the combinations of visual, auditory and haptic feedback which are designed for corresponding to the information from the real world, this system is able to provide users an experience of feeling the environment in virtual space.

3.3 Method

3.3.1 Hardware Development

The main purpose of the hardware part of this project is to provide the multi-sensory feeback which combines visual, auditory and haptic feedback to the users, thus the whole components consists of three kinds of module:

- **A head mounted display**

  An Oculus Rift Developers Kit 1 was used in this project as the visual feedback display and head movement tracker in this project.

- **Five vibro-thermal feedback modules**

  Five 2 x 1.5cm size thermal-tactile modules [32] were utilized in the hardware development for providing thermal feedback. In this modules, change of temperature is based on the initial skin temperature which ensure users can notice the change in temperature.

- **A Headphone**

  This system provided sound effect corresponding to particular weather conditions such as wind and rain as auditory feedback.

In designing and developing ThermoReality head mounted display (HMD), the basic solution for providing temperature change as feedbak is to introduce the thermal feedback modules into the VR experience. Therefore when our team started designing and developing the HMD, first we considered what parts of the human body the thermal feedback should be provided to.

Considering that the face is a part with relatively high temperature sensitivity [21, 23] and one of the parts of human body where perceives the ambient temperature. And taking into account the complexity of the system as a whole, it is determined that the thermal modules are directly combined with the facial side of Oculus Rift DK1 and the thermal feedback is provided directly to the face at the area around the eyes.

In our previous work we discussed the number of components used in the equipment, taking into account the design of the available area on users' faces, the weight of the equipment and the distribution of the thermal modules, we decided to use in total five thermal modules in this system in which three thermal modules are in contact with the three locations on users' foreheads (indicated in standard EEG 10-20 system for standardization [8]), the remaining two are located at the area below the eyes (the bridge of the nose is not suitable for placing the thermal modules, therefore on ThermoReality HMD there is no modules set at this position).

Each thermal module is driven by a full bridge motor controller and all modules are controlled by an Arduino Mega microcontroller employing a closed loop PID (proportional, integral, derivative) temperature controller for accurate temperature control).

3.3.2 Software Development

- **Development environment**

  Unity 3D, version 5.4.1f1

  Mac Pro (Retina, 13-inch, Early 2015)

- **Design Process**

  Basically, the design of the software consists of several aspects including information setting, interface design and thermal feedback design, and multi-sensory feedback setting, as shown in Figure 3.4

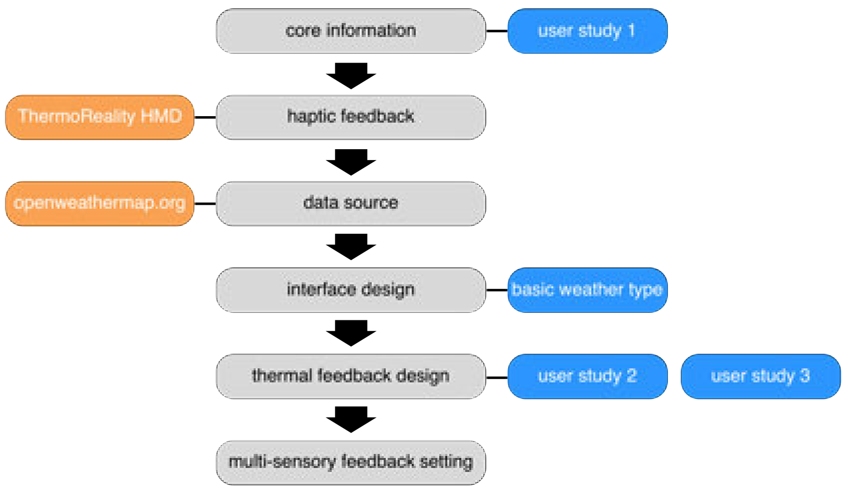


Figure 3.4: Design Process

Data Source

This project intended to provide real-time weather to users, and allow users to select cities by themselves to unfold information of the corresponding weather in VR environment. In this project I chose *openweathermap.org* as my source of data. In this website, there is free real-time weather application programmers interface(API) which provides limited yet sufficient information for this project. The Current Weather API allows access to current weather data for any location including over 200,000 cities, and there are various methods available for access to the data, such as by city name, by city ID, by geographic coordinates, etc. In this project, I chose city name as the method for searching locations.

The current weather is frequently updated based on global models and data from more than 40,000 weather stations which ensures the data is fresh enough. Data of weather which I access from Unity 3D are in Javascript Object Notation(JSON) format, an example is shown in Figure 3.5, and the example of data is of London.


```
{"coord":{"lon":-0.13,"lat":51.51},"weather":
[{"id":300,"main":"Drizzle","description":"light intensity
drizzle","icon":"09d"}],"base":"stations","main":
{"temp":280.32,"pressure":1012,"humidity":81,"temp_min":279.15,"temp_max":281.15},"visibili
ty":10000,"wind":{"speed":4.1,"deg":80},"clouds":{"all":90},"dt":1485789600,"sys":
{"type":1,"id":5091,"message":0.0103,"country":"GB","sunrise":1485762037,"sunset":148579487
5},"id":2643743,"name":"London","cod":200}
```


Figure 3.5: Weather Data from Openweathermap.org in JSON Format.

In this project, according to the discussion based on User Study 1, the essential data needed in this system are weather type ("main" in Figure 3.5, and temperature ("temp" in Figure 3.5). However, since human's perception about air temperature (which is normally dry bulb temperature) gets impact from humidity [31, 34], in this project, thermal feedback is set according to the apparent temperature (the feels-like temperature), rather than the air temperature which provided in the data, thus as the most important factor which has impact on human perception of temperature, humidity ("humidity" in Figure 3.5) is taken into account when calculating and setting thermal stimuli provided on the HMD.

And for setting of the sound effect, wind speed ("speed" in "wind" in Figure 3.5) is used in this system as well.

Weather Type and Interface Design

The *Feel It* application consists of two types of scene, first is the home scene from which users can select a city to open the scene with corresponding information of current weather.

This part of design focuses on the conventional types of feedback users usually get in VR environment - visual and audio, which were designed according to the basic types of weather. Therefore this part of design requires research on weather information.

According to the basic weather types divided by cloud condition, precipitation and wind speed, since wind is not a directly visible factor of weather, its conditions are presented as sound effect in this application. Another main sound effect utilized in this system is rain sounds. Therefore except the conditions manifested by auditory feedback, there are 12 basic scenes designed for presenting the types of weather in the application (Ref Figure 4.3 and 4.4).

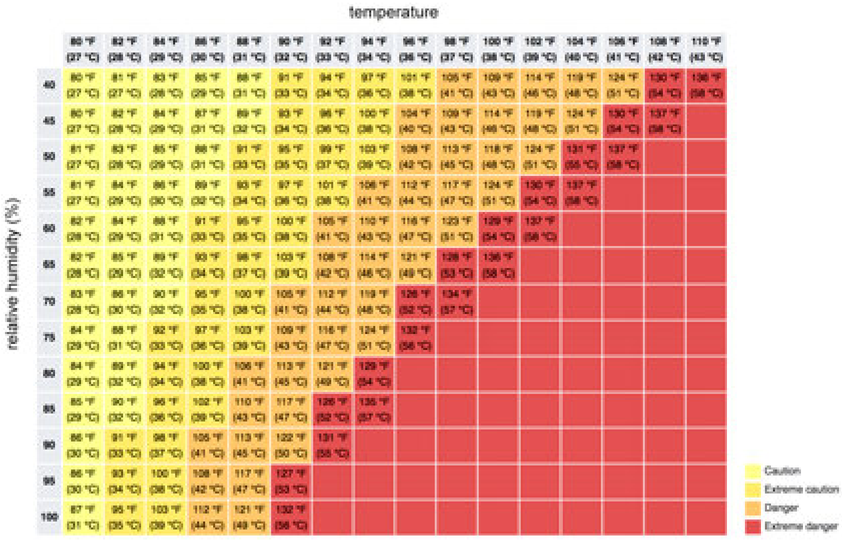
Thermal Feedback Design

Even in a same setting of environment, different materials give different tactile feedback while touching, for instance, in a room with temperature at 26°C, the glass or metal object in the same environment normally feels cooler than the ambient temperature when touching. This phenomenon reminds me that it would be not appropriate if we directly use the thermal modules to present the exact level of temperature.

And for the sake of information presenting, directly setting exact temperature on the thermal modules is also not a good idea for the reasons below:

First ,when people perceive the environment, what they care about is not the exact data of the environment, but their own feelings, which are more intuitive for them when sensing the surroundings. We usually hear people say "it's hot" or "it's cold" but hardly hear "it's 37°C" without checking the data. Therefore in the presentation of temperature feedback, the accuracy of the temperature data itself is not that essential goal of the design is trying to pursue, the goal of the thermal feedback is to generate the "(almost) same sensation" users have towards corresponding ambient temperature in the real world.

To this end, since humidity plays a critical role for human perception of temperature, it is important to calculate the apparent temperature (feels-like temperature) to improve the users' experience. A commonly used method for calculate the "feels like" temperature is Heat Index [1], according to which the system calculates the temperature for adjusting the thermal stimulus setting in this project as well. An example of heat index table from U.S. National Oceanic and Atmospheric Administration (NOAA) is shown in Figure 3.6.



	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Figure 3.6: Heat Index Table from NOAA

Besides, the temperature of thermal stimuli provided by ThermoReality HMD requires proper setting to represent the corresponding temperature towards users' thermal perception. Taking into account the safe temperature range for directly provided to skin through thermal modules [24, 29], the available range is much narrower than the real air temperature range, which is normally from -25°C to 45°C. However, based on the mechanism of ThermoReality HMD on which the thermal modules change temperature based on users' skin temperature, for the safety and comfort of skins, in this project the range of temperature change is -3°C and + 3°C based on the skin temperature, in other word, roughly between 34°C and 40°C. Thus the range of temperature the thermal modules provide is not the same with the range of real air temperature. In this case, I have to combine these different temperature into one system. My idea is to set the stimulus based on human feeling towards different type of temperatures (Figure 3.7).

Therefore, in order to explore a proper setting of the thermal stimuli provided by the thermal modules in this project, I conducted two studies (User Study 2 and User Study 3) for defining the matching pair of stimuli setting and the range of air temperature.

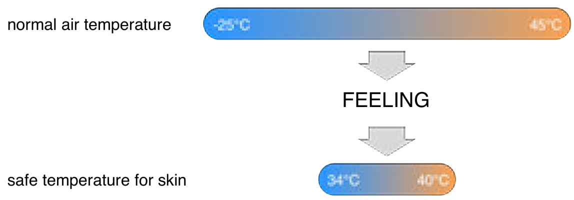


Figure 3.7: Idea for Categorizing Air Temperature

Through User Study 2 I intended to understand the relation between user's perception of temperature range with the air temperature they read from weather information. Subjects choose range of temperature corresponding to the keywords of feeling based their own perception. According to the results of this study, I could clarify the relation between feeling and air temperature.

User Study 3 was conducted to know how I can set the thermal stimuli for users to have corresponding feeling they have towards different air temperature. I provided different setting of the stimuli provided by ThermoReality HMD, and in this study asked subjects to rate their feeling towards the stimuli.

Later by matching subjects' feelings from User Study 3 to the results of User Study 2, I could set the thermal stimuli for generating corresponding feeling that users have towards different temperatures.

Multi-sensory Feedback Design

Based on the scene design and thermal haptic feedback settings, for each scene I set the multi-sensory feedback combination which consists of visual, auditory and thermal feedback for different weather types and different temperatures.

3.3.3 Evaluation Method

Purpose of Evaluation

This evaluation part is designed for evaluating whether the design of this project reached the main goal described in Chapter 1. Therefore the test is designed to compare under different conditions how users' perception of weather performs, and whether or not the idea of importing thermal feedback to the users can improve users' understanding of environmental information in VR experience.

Based on the purpose, the evaluation should be able to answers the hypotheses below:

1. *Without temperature information, people's perception of weather is inaccurate.*
2. *Thermal feedback allows people to perceive the environmental information more correctly.*
3. *The combination of thermal feedback with VR makes it easier for users to understand the virtual environment .*

Experiment

To verify the hypotheses on whether or not thermal feedback may improve the process users understand the environmental information when they are in virtual space, in this experiment I intended to compare under different conditions, which means different approaches for presenting the core environmental information, the users' performance in perceiving the environment and remembering the information.

Data Collection and Analysis

In this experiment during which subjects wore our HMD with thermal modules, the data of users' operation was automatically collected into files while they were doing the test. All data are saved into CSV file format and was analyzed in Microsoft Excel.

Chapter 4
Design and Implementation

The design of the whole system consists of hardware and software parts.

- **Hardware** ThermoReality head mounted display (HMD)
- **Software** Feel It application

4.1 ThermoReality HMD

As shown in Figure 4.1(b) the ThermoReality HMD is a device consists of five 2 x 1.5cm size thermal modules [32] mounted on the facial side (inside) of the head mounted display with a custom 3D printed rig, which are in direct contact with the users' face and are distributed to the left, center and right parts of the forehead and the left and right side of the parts under eyes on the user's face respectively(Figure 4.1(d)).

(a) (b) (c) (d)

Figure 4.1: ThermoReality Head Mounted Display

(a) The structure of the thermal modules used in this project. (b) The facial side of ThermoReality head mounted display. (c) ThermoReality head mounted display from the main view. (d) Locations of thermal modules when the user wearing the head mounted display

Figure 4.1(a) shows that each module consists of four peltier modules of which two diagonal peltier modules are used for heating and the other two diagonal modules are used for cooling. In this manner, using the thermal summation principle [37] , the modules are able to deliver fast thermal cues to the users and are able to increase or decrease (heat or cool) the temperature with relatively high speeds. Each peltier module is driven by a full bridge motor controller and all modules are controlled by an Arduino Mega microcontroller employing a closed loop PID (proportional, integral, derivative) temperature controller for accurate temperature control(Figure 4.1(c)). The T1, T2, T3 temperature sensors are used for the closed loop control where T1 directly measures the skin temperature. Therefore as shown in Figure 4.2, in each module, the temperature change is based on the skin temperature.

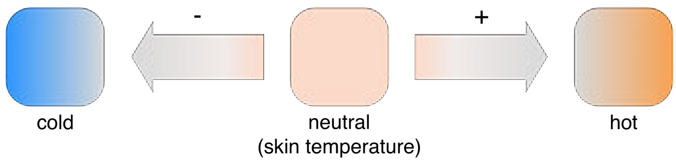


Figure 4.2: Temperature Change in Each Thermal Module on ThermoReality HMD

And according to the previous works of the ThermoReality team and some related researches, for the sake of skin safety and comfort, at current stage, the range of temperature change I uses in this project is -3°C and + 3°C based on the skin temperature.

In this system, while using the application, besides ThermoReality HMD, a headphone is required for ensure that users can hear the sound effects of different weather provided by the application, which ensure the immersion of users' experience in the application.

4.2 Feel It application

This *Feel It* application is designed to provide a immersive environment for users to understand the environment when checking current weather in VR with combination of visual, audio and thermal feedback.

The whole design of this application consists of several aspects below:

- **Interface** Design of the interface of the application in which I designed scenes corresponding to all basic weather types with Unity 3D.

- **Thermal Feedback for Presenting Temperature Data** Setting of thermal feedback for different temperatures which is based on two user studies on human perception of temperature and thermao stimuli.
- **Multi-sensory feedback** Based on the interface and thermal feedback setting, for each scene I set the combination of different types of feedback provided in this system to achieve multi-sensory experience in this VR weather application.

4.2.1 Interface

Basically the application consists of two types of scene, the home scene which shows the city list and the weather scenes which generate the immersive environment of corresponding weather.

Design of these scenes is based on the basic types of weather, and for each weather, there is one scene consists of 360 degree view of the environment and corresponding sound effects to present weather, which combined with thermal feedback for providing thermally enhanced immersive experience for users in VR environment.

Basic Weather Types

Weather is the state of the atmosphere, mainly with respect to its effects upon life and human activities [27]. As distinguished from climate, weather consists of the short-term (minutes to days) variations in the atmosphere, refers to day-to-day temperature , cloud condition and precipitation activity. Weather condition means the atmospheric conditions that comprise the state of the atmosphere in terms of temperature and wind and clouds and precipitation.

Types of weather is a brief description of different weather condition which, in most weather forecast on our television or websites, types of weather mainly describes the cloud conditions (or sky condition), the precipitation activity and wind, combined these three information, types of weather varies from sunny and clear to rainy and snowy weather. Since these descriptions are consistent with the description in the weather data at the *openweathermap.org* website, the category was used in this project based on which I designed and setthe visual and audio feedback for the main weather scenes in *Feel It* application. Table 4.1 shows the basic category of weather according to the data sources this project refers to.

Weather	Cloud Condition
Sunny/Clear	0/8 opaque clouds
Mostly Sunny/Clear	1/8 - 2/8 opaque clouds
Partly Sunny/Cloudy	3/8 - 5/8 opaque clouds
Mostly Cloudy	6/8 - 7/8 opaque clouds
Cloudy	8/8 opaque clouds
	Precipitation
Drizzle	liquid, small and slow
Rain	liquid, big and slightly fast
Heavy Rain	liquid, big and fast
Thunderstorm	liquid, huge and very fast
Freezing Rain	freezing, surface temperature blow freezing
Sleet	freezing, mix of rain and snow
Hail	frozen, balls or irregular lumps of ice
Snow	frozen, light, ice crystals, slow
	Wind Speed (km/h)
Light Wind	< 11
Gentle Moderate	12 - 28
Fresh Wind	29 - 38
Strong Wind	39 - 61
Gale	62 - 88
Whole Gale	89 - 117
Hurricane	>117

Table 4.1: Basic Weather Types

Design of the scenes in the application is based on those weather types. Since Wind is not what can be seen directly, and sometimes the direction of wind we feel is depends on the space we are located rather than the wind reported in weather information, thus in this project, wind is expressed by sound effect(Ref. Table 4.2).

Scene Design

The application *Feel It* consists of two types of scene, first is the home scene from where users can select a city to open the scene of its weather(Figure 4.3(a)), the other type is the scenes which present the weather(Figure 4.3, 4.4).

This part of design focuses on the conventional types of feedback users usually get in VR environment - visual and auditory feedback, which were designed according to the basic types of weather.

Weather Type	Skybox	Elements to Manipulate
Sunny/Clear	Sunny	
Mostly Sunny/Clear		particle system
Partly Sunny/Cloudy	partly Cloudy	particle system
Mostly Cloudy		
Cloudy	Cloudy	particle system
Drizzle	Cloudy	particle system, audio
Rain	Rainy	particle System, audio
Heavy Rain		
Thunderstorm	Storm	particle system, audio
Freezing Rain	Rainy	particle system, audio
Sleet	Rainy	particle system, audio
Hail	Rainy	particle system, audio
Snow	Rainy	audio
Light Wind		-
Gentle Moderate		audio
Fresh Wind		audio
Strong Wind	-	audio
Gale		audio
Whole Gale		audio
Hurricane		alert, audio

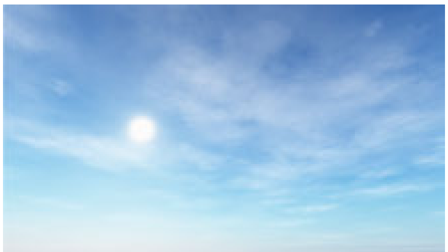
Table 4.2: Weather Scene Setting

Table 4.2 shows the basic setting of these scenes. According to the basic weather type divided by cloud condition, precipitation and wind speed, except since wind is not a directly visible factor of weather, its conditions are presented as sound effect in this application, each weather type has one corresponding scene (Figure 4.3, 4.4). The visual scene is developed in Unity 3D, by adding 6-sided skybox and set the particle system according to the weather types, the scenes provide a vivid 360 degree view of each weather type.

Beside wind sounds, another main sound effect utilized in this system is rain sounds, based on the type of weather, there are 4 types of rain sound effect utilized in this system. Thereby except the conditions manifested by auditory feedback, there are 12 basic scenes for presenting the types of weather in the application (the scene freezing rain is the same with rain).

(a)

(b)



(c)

(d)

(e)

(f)

Figure 4.3: Scene Design for Feel It Application I

(a) The home scene of Feel It App. (b)(c)(d)(e)(f) Five weather scenes: sunny, mostly sunny, partly sunny/cloudy, mostly cloudy, cloudy.

4.2.2 Thermal Feedback for Presenting Temperature Data

In this project, the main function of thermal feedback is for presenting the data of temperature. However, when setting the thermal stimuli provided by the Ther-

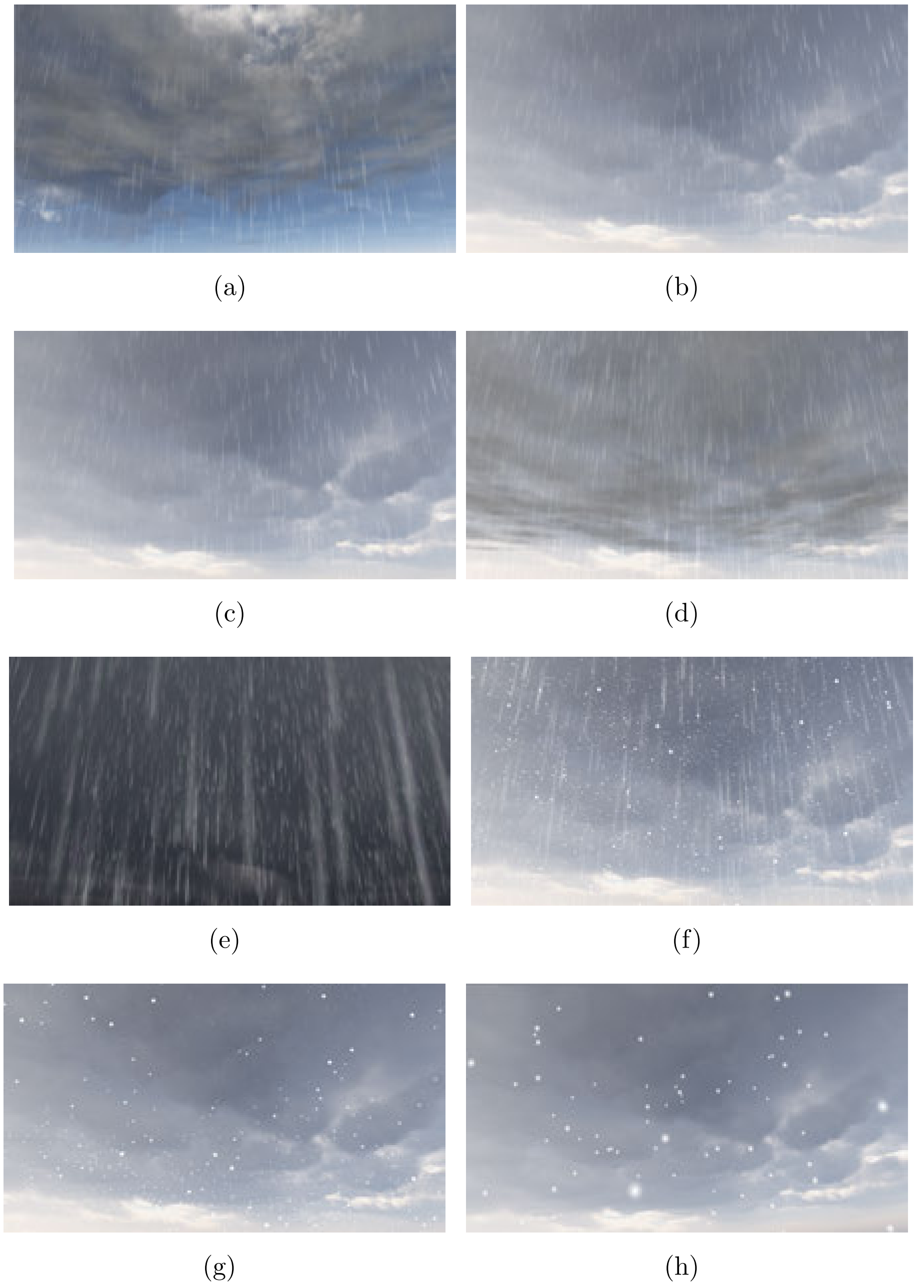


Figure 4.4: Scene Design for Feel It Application II

(a)(b)(c)(d)(e)(f)(g) seven weather scenes: drizzle, rain, freezing rain, heavy rain, thunderstorm, sleet, hail, snow.

moReality system, several aspects have to be discussed.

Based on our previous study, we have the range of thermal feedback setting for safe and non-uncomfortable feeling of the users in ThermoReality System, which is -3°C and + 3°C based on the skin temperature [24, 29]. However, the real air temperature range, which is normally from -25°C to 45°C, is much more wider than the range of temperature we actually present on users' skin.

Besides, normally when we talk about our feeling of cold or hot weather, we do not have exactly different feeling towards every specific temperature, when other conditions are the same, one person in general has almost same feeling towards a narrow range of temperature. therefore in this system, it is necessary to group the real temperature according to the range of thermal feedback when setting the thermal stimuli.

Therefore I intended to combine users' feeling towards air temperature and thermal stimuli, to assign stimuli to provide thermal feedback for generating temperature perception of the users towards corresponding range of air temperature. To this end, I conducted two studies (User Study 2 and User Study 3) to discuss the setting of thermal stimuli in ThermoReality system.

User Study 2: People's perception of range of temperature when they have different feeling towards the environment

This study is an online survey conducted on Google form about how subjects perceived the range of temperature when they had different level of cold or hot feeling to the environment.

In this study, I provided 9 different description of the temperature from "too cold" to "too hot" when asking subjects about their perception of air temperature. At the beginning, this study set a "default/neutral state" described as "If the neutral/comfortable temperature is when you only need to wear one t-shirt with jeans" and then asked the participants to give corresponding range of temperature towards different descriptions of feeling according to their perception.

11 healthy participants were involved in both User Study 2 and User Study 3, 6 males and 5 females with an average age of 25.

According to the results of User Study 2, subjects have relatively clear perception of the temperature range corresponding to their feelings, Figure 4.5 shows the average range of temperature people have the 9 different feelings from too cold to too hot defined in this study, which shows the rough corresponding temperature ranges for the 9 descriptions provided in this study.

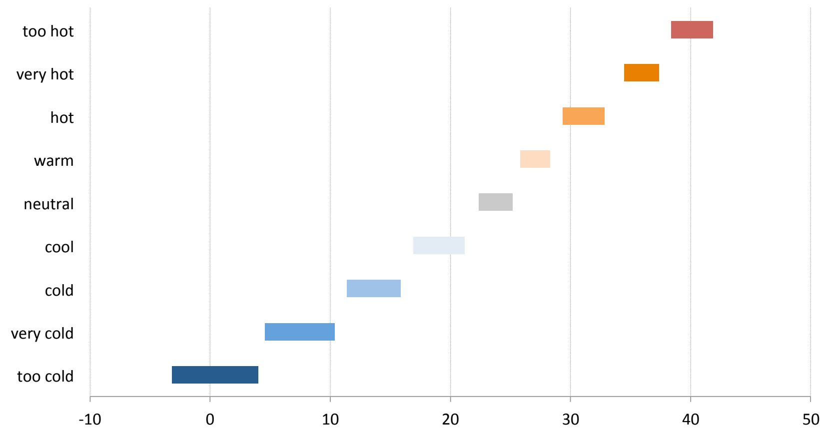


Figure 4.5: Results of User Study 2

Human perception of temperature range when having different extent of cold and hot feelings according to results from User Study2.

Previous Demo and Control of Thermal Stimulus

How does the system provide thermal stimuli at different temperatures? Basically in this system, there are mainly two ways to set temperature the stimulus reaches while working, one is setting length of the stimulus (millisecond), the other is setting the speed.

Our team has been working on providing thermal feedback on VR HMD users' faces by integrating thermal modules to the display's facial side, and according to our previous studies, this system has high potential in enhancing immersion of users [29]. Based on these studies I can explore the use of thermal feedback and related contents design in this team, and developed the first version of *Feel It* app in Unity.

In this previous demo, we followed our setting in previous user study [16, 29], thus the Speed of Change of the temperature was fixed as 3°C/s, we controlled the temperature through setting the length, the stimulus setting for each scene in this demo is shown in Table 4.3.

The previous version contains the core function of presenting thermal feedback corresponding to the weather, which is shown in Figure 4.6, besides the similar home scene with final version of Feel It application, from which users can unfold weather information of four different cities by clicking corresponding floating

City	Scene	Temperature (°C)	SOC(°C/s)	Length(ms)
Shanghai	Rainy	31	+3	600
Tokyo	Rainy	21	-3	600
Vienna	Partly Cloudy	15	-3	1000
California	Sunny	37	+3	1000

Table 4.3: Thermal Stimulus Setting for Previous Demo

crystal balls, this version only contains 4 scenes for four preset cities: Shanghai, Tokyo, Vienna and California. Each scene of weather information presents the visual and auditory simulation corresponding to the weather. Once the user enters a weather scene, every 3 second, all the thermal modules in this system will simultaneously provide a preset stimulus to their skin. On each scene, there is also text information about the basic weather data, including a icon of weather type, temperature, chance of rain, humidity, wind and its feels-like temperature.

This previous version of *Feel It* application was presented as invited demo at AsiaHaptics2016 and ACM CHI2017(Figure 4.7), and during the demonstration, we used preset weather data instead of real-time weather data to ensure people experienced different conditions, this version includes two types of cold stimuli, and two types of hot stimuli, as well as different thermal sensation under same weather (Shanghai and Tokyo).

And during the demonstration we could collect more feedback and got some interesting findings.

1. With different setting of the length of the stimuli, what people felt on their face was rather than the difference in length, mostly people regarded it as the difference of speed of the temperature change.

2. The cold stimuli cause a illusion of wetness sensation. Especially when combined with the rainy scene, many users asked if this system sprayed water on their face. But with warm stimuli, even in rainy scene, users hardly had wetness feeling.

3. After trying the demo, we asked people whether they had different level of cold and hot sensation, many people could described the scene with their feeling correctly. For example, "Vienna is cold place." or "It's so hot. That is California, that is, that is." etc. However, if we asked whether they saw

(a)

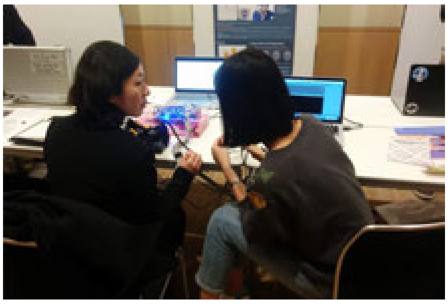
(b)

(c)

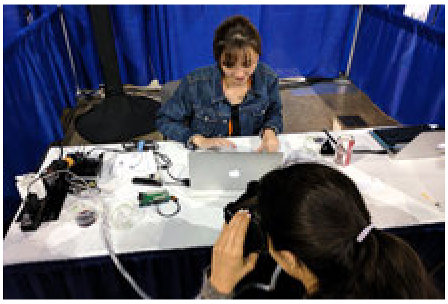
(d)

Figure 4.6: Interface of Previous Demo

(a)(b)(c)(d) Four basic weather scenes for "What Is The Weather" demo.



(a)



(b)

Figure 4.7: Demonstration at AsiaHaptics2016 and ACM CHI2017

the text in the scene, many people reported they didn't notice it, or they didn't want to read it.

Thus, the demonstration and its feedback reflects that the use of thermal feedback enhances the immersive feeling for the user, and shows the potential of utilizing thermal feedback as one new approach for information presenting. At the same time, however, setting the length of stimulus to reach different level of temperatures seems not good enough for this situation, setting of stimuli should be combined with the purpose and contents.

Therefore in *Feel It* application, in order to use same pattern for providing thermal stimuli on users' faces, I determined to change the way for controlling temperature into by setting the speed of change (SOC) in the temperature in the modules.

User Study 3: Feeling and Temperature

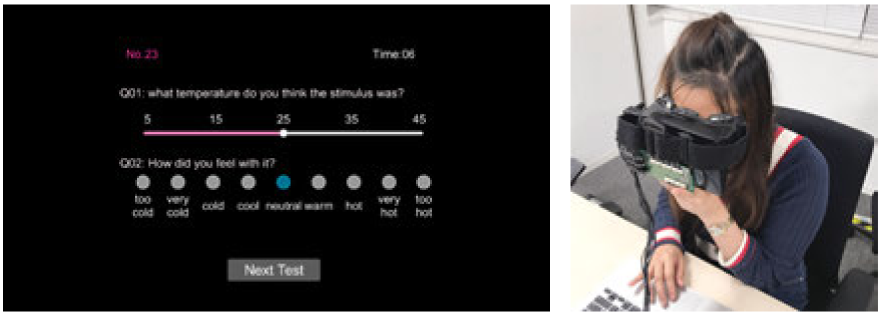
This is a study on users perception of thermal stimuli provided by ThermoReality HMD. Subjects who participated in User study 2 participated in this study after they finished the previous one.

In this study, as the length of thermal stimuli are fixed as 1 second for providing same pattern of thermal feedback for presenting information of air temperature in the whole system, for presenting the different level of temperature, the thermal feedback is set by controlling the speed of temperature change (SOC) in the module. Taking into account the safety and comfort of skin, the range of the speed used in this system is from 0°C/s to 3°C/s, in which for cold stimuli, the speed is from 0-3°C/s, while for hot stimuli, in order to avoid pain feeling, the speed is set within 0-1.8°C/s. And as shown in Table 4.4, 4 different speed settings for both cold and hot stimuli respectively are chosen for providing thermal sensations. This study also contains a "stimulus" with speed = 0 setting. Therefore in total 9 types of stimuli are provided in this experiment to explore users' perception of cold and hot feeling under different conditions.

In this study, I developed an interface (Ref. Figure 4.8(a)) for conducting the experiment and collecting data. All procedures were conducted in VR environment where subjects wore our HMD with Peltier modules during the training and experiment, and subjects were sitting in a room with stable ambient temperature at 24°C, subjects were ensured to find a resting comfortable sitting posture,and they are allowed to pause the study at anytime they want during the experiment during the study.

Type	Stimulus No.	Length(s)	SOC(°C/s)
Hot	h4	1.00	+1.80
	h3	1.00	+1.35
	h2	1.00	+0.90
	h1	1.00	+0.45
Neutral	neutral	-	0
Cold	c1	1.00	-0.75
	c2	1.00	-1.50
	c3	1.00	-2.25
	c4	1.00	-3.00

Table 4.4: Thermal Stimulus Setting in User Study 3



(a) (b)

Figure 4.8: User Study 3

(a) Interface of application for conducting User Study 3. (b) A participant doing the user experiment.

For each experiment, at the beginning, the subject was explained on the system and the concept. Next, during the training phase, the subjects were allowed to familiarize with the user interface, and the procedure operation method (filling out the questionnaire by mouse click), and to experienced all types of temperature stimuli. After the training, the experiment was commenced. During the experiment, subjects receive one stimulus in each task, each type of stimulus is given 5 times and all types of stimulus are provided in random order, so each subject receive in total 45 times of the thermal stimuli in the experiment. Between each task there was a 10-second interval for ensuring subjects skin adjust to the original temperature.

In each task, after perceiving the thermal stimulus, subjects are asked to immediately answer two questions on the screen, the first is choosing the number on a slider from 5°C to 45°C to describe the temperature of the stimulus they feel. The second question require them choose the sensation description mostly matched their feeling towards the stimulus from a list of buttons (too cold, very cold, cold, cool, neutral, warm, hot, very hot, too hot, which is corresponding to the study 2). All the answers are automatically collected and saved in CSV file.

The 11 healthy participants who took part in User Study 2 participated in User Study 3.

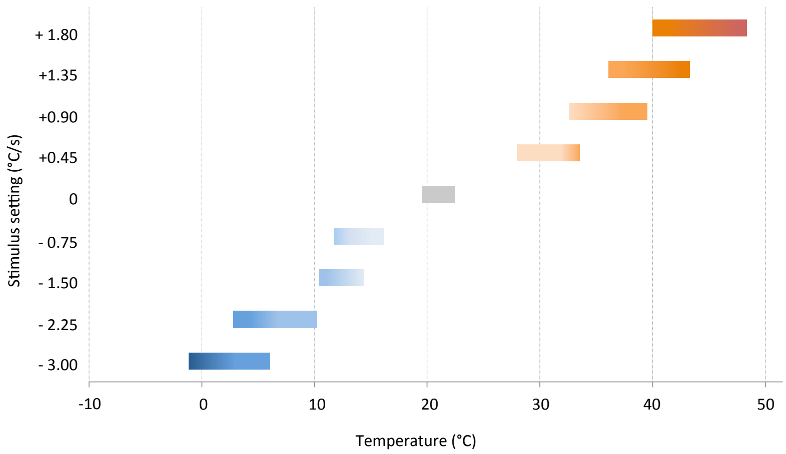


Figure 4.9: Results of User Study 3

Subjects' rating of different settings of stimuli in User Study 3, the numbers of rating represents description of feeling from too cold to too hot.

The results of User Study 3 show the hot and cold sensation of the subject for different thermal stimuli. By matching this result with the results of User Study 2, the results roughly show the range of real temperature and its corresponding setting of thermal stimuli. The results after matching is shown in Figure 4.9, which indicate the range of real temperature the different setting of thermal stimuli can manifest. And on the chart, the colours of the bars show the degree subjects feel cold or hot when they were given different thermal stimuli during the study.

The results shows even temperature change speed setting for the hot stimuli were chosen from a narrower range than for cold stimuli, the distinction of the hot stimuli was more significant than the distinction of the cold stimuli for the users.

During the experiment there were several times subjects reported pain feeling on their face. According to the results and observation during experiments, overall there are over 20 times that subjects reported "too hot" and had pain feeling when perceived the hottest stimulus h4 (SOC = 1.80°C/s), while for cold stimuli there were 6 times subjects reported as "too cold" and felt bit painful on their faces when subjects perceived stimulus c4 (SOC = 3°C/s).

As shown in the Figure 4.9, the results of User Study 3 are consistent with those described in User Study 2. For example, when the subjects felt neutral, the corresponding temperature range was around 20°C/s, and the corresponding setting of thermal stimulus is 0, which means there was no temperature change in the thermal modules, the temperature subjects detected was the temperature on the surface of the thermal modules. And in accord with User Study 2, when subjects feel "too cold" and "too hot", the temperature the corresponding thermal stimuli represented were roughly 3-4°C/s and over 40°C/s respectively.

Thermal Feedback Setting

Setting of the thermal stimulus provided by the thermal modules requires grouping of the air temperature based on users' description of feeling, matching same feeling to temperature and corresponding stimuli to get the group of temperature presented by thermal stimuli provided by ThermoReality System. In this project, based on the results from User Study 2 and User Study 3, I could set thermal stimuli corresponding to different ranges of temperature. The thermal stimulus setting is shown in Table 4.5

Stimulus Type	Length(s)	SOC(°C/s)	Feelings	Temperature(°C))
Hot	1.00	+1.35	Too Hot	≥ 38
	1.00	+1.35	Very Hot	34 - 37
	1.00	+0.90	Hot	29 - 33
	1.00	+0.45	Warm	26 - 28
Neutral	-	0	Neutral	22 - 25
Cold	1.00	-0.75	Cool	16 - 21
	1.00	-1.50	Cold	11 - 15
	1.00	-2.25	Very Cold	5 - 10
	1.00	-3.00	Too Cold	≤4

Table 4.5: Temperature Group for Thermal Stimulus Setting

In the weather scene, every 3 second, all the thermal modules in this system will simultaneously provide the 1-second long thermal stimuli to the user's face.

4.2.3 Multi-sensory Feedback

After setting up different types of feedback, in order to enhance users' perception of environment in this VR weather application, for each weather scene I set the combination of visual, auditory and thermal feedback, among which he thermal feedback is set for multiple purpose. In this system is used not only as expression of temperature, but also used for simulate particular weather in this system.

1. For providing the information of temperature, the thermal stimuli which represent the apparent temperature is set according to Table 4.5 and Heat Index theory (Ref. Figure 3.6). When users in the weather scene, the thermal stimuli for presenting temperature is provided every 3 seconds, and the length of each stimulus is 1 second.

2. During the interval of the first thermal feedback, I used different setting for simulating particular weather such as rain and snow to enhance users' perception of weather in this system. For instance, in rainy scene, during the 3s interval between the thermal stimuli for presenting temperature, by giving 100ms-length cold stimuli (SOC = -3.00°C/s) on random module (one module each time), users will have a feeling of rain dropping down on their face. Similarly in snowy scene, with lower frequency, a longer cold stimuli which length is 200 milliseconds is randomly given when users open the scene which intends to snowflakes fall down on users' faces.

The visual feedback setting and audio feedback setting are in accord with the settings shown in Table 4.2. And The settings for multi-sensory feedback are briefly indicated in Table 4.6.

Weather Type	Visual	Sound Effect	Thermal
Sunny	Sunny Scene	None/Wind	Temperature
Mostly Sunny	Sunny Scene + Cloud Particle	None/Wind	Temperature
Partly Sunny	Partly Sunny Scene + Cloud Particle	None/Wind	Temperature
Mostly Cloudy	Mostly Cloudy Scene + Cloud Particle	None/Wind	Temperature
Cloudy	Cloudy Scene + Cloud Particle	None/Wind	Temperature
Drizzle	Cloudy Scene + Rain Particle	Rain/Wind	Temperature + Rain Simulation
Rain	Rainy Scene + Rain Particle	Rain/Thunder/ Lightening	Temperature + Rain Simulation
Heavy Rain	Rainy Scene + Cloud Particle + Rain Particle	Rain/Thunder/ Lightening	Temperature + Rain Simulation
Thunderstorm	Storm Scene + Cloud particle + Rain Particle	Storm	Temperature + Rain Simulation
Freezing Rain	Rainy Scene + Rain Particle	Rain/Wind	Temperature + Rain Simulation
Sleet	Rainy Scene + Rain Particle + Hail Particle	Sleet/Wind	Temperature + Rain Simulation
Hail	Rainy Scene + Hail Particle	Hail/Wind	Temperature + Rain Simulation
Snow	Rainy Scene + Snow Particle	None/Wind	Temperature + Snow Simulation

Table 4.6: Multi-sensory Feedback Setting

Chapter 5
Evaluation

To evaluate whether this design achieves the main goal of this project, the evaluation needs to verify three hypothesis:

1. *Without temperature information, people's perception of weather is inaccurate.*
2. *Thermal feedback allows people to perceive the environmental information more correctly.*
3. *The combination of thermal feedback with VR makes it easier for users to understand the virtual environment .*

Based on these hypotheses I set the experiment to compare through different ways to provide temperature, how users will perceive environment under different conditions.

5.1 Experiment Design

The main comparison in the experiment is the influence of the way to present temperature data on users' perception of environment. According to the way we query weather in our daily life, when searching information, the temperature is normally presented in text or vocal information. So this experiment included conditions as shown in Table 5.1.

In each experiment, there was one non-thermal condition test and one thermal-condition test, this two parts were conducted in random order. Under non-thermal condition test, each subject would get one condition randomly from non-feedback, text only, vocal only conditions, in which non-feedback mean what subjects would only go through all the scenes with place name (A, B, C, D, E) and without any feedback of the temperature information. This condition is set for compare

Non-thermal Condition			Thermal Condition
None	Text Information	Vocal Information	Thermal Feedback
Length 10s	3 times	-	Length 1s, 3 times
Scene Only	Scene + Text	Scene + Vocal	Scene + Thermal Stimuli

Table 5.1: Non-thermal and Thermal Conditions for Evaluation

people's perception for the visual scene. Thermal condition test gives subjects thermal stimuli represented the same temperature which were presented in other ways under non-thermal condition as well during the test. And the temperature I used in this test is: 5°C, 13°C, 18°C, 24°C, 27°C, 31°C, 37°C.

And except text condition there is additional text on the screen shows the temperature data, under other conditions subjects would only see the scene and city name (Figure 5.1). And Table

(a)

(b)

Figure 5.1: Scene Setting for Evaluation

(a) Non-text scene under Vocal, None and Thermal condition. (b) Scenes under Text condition.

As shown in Figure 5.1, under each condition, there are five scenes for subjects to go through during each part of the experiment, the scenes show five different weather types, sunny, partly cloudy, cloudy, thunderstorm, and snowy. In each test, subjects will see the five scenes in random orders with random temperatures (as shown in Table 5.2, except snowy scene always has the coldest temperature 5°C, all other scenes got temperature randomly from 13°C, 18°C, 24°C, 27°C, 31°C, 37°C), every scene last for only 10 seconds, the length or frequency of each type of feedback is shown in Table 5.1. After each test, subjects were asked to do

Scene	Temperature Value (°C)
Sunny	13, 18, 24, 27, 31, 37
Partly Cloudy	13, 18, 24, 27, 31, 37
Cloudy	13, 18, 24, 27, 31, 37
Thunderstorm	13, 18, 24, 27, 31, 37
Snowy	5

Table 5.2: Thermal Stimulus Setting for Evaluation

a sequence quiz - they were asked to sort the five places they just went through from coldest to hottest according to their perception. Table 5.3 shows the example of the test for one subject during the experiment.

Condition	Scene (A, B, C, D, E)	Temperature (°C)	Correct Order
Vocal	Thunderstorm, Sunny, Cloudy, Partly Cloudy, Snowy	37, 31, 13, 27, 5	E C D B A
Thermal	Sunny, Snowy, Cloudy, Partly Cloudy, Thunderstorm	37, 5, 18, 27, 31	B C D E A
None	Snowy, Thunderstorm, Sunny, Cloudy, Partly Cloudy	5, 24, 31, 27, 13	-
Text	Snowy, Sunny, Thunderstorm, Cloudy, Partly Cloudy	5, 13, 21, 24, 37	A B C D E

Table 5.3: An Example of The Experiment of One Subject

5.2 Results and Discussions

15 healthy participants were involved in this evaluation, 10 males and 5 females age 22-29, all of them are from Asia and have been staying in Japan over 1 year, and can speak English.

Under the condition without information of temperature, there is no correct or incorrect answers, but subjects answers shows the visual have some common influence on them. 93% of them chose snow scene as the coldest scene. 67% felt sunny scene was the hottest scene. And once there was a sun in the scenes, all subjects felt they should be warm or hot.

When given information of temperature, when the data was given by text, audio and thermal feedback, the percentages of the correct order were 20%, 27%, 60% respectively. This results significantly shows that thermal feedback makes it easier for users to correctly remember the information of temperature.

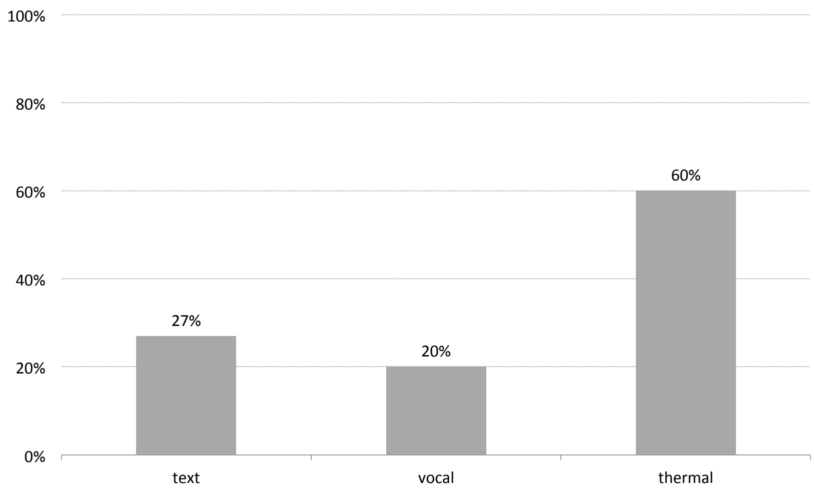
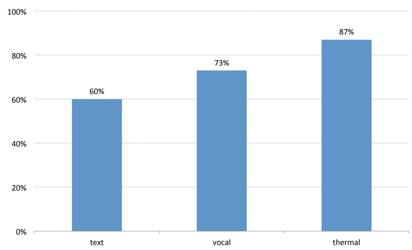
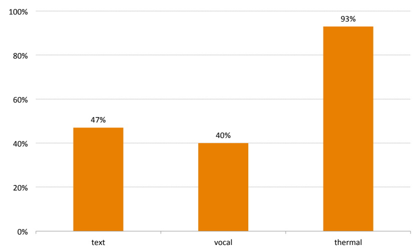


Figure 5.2: Results of Evaluation I



(a)



(b)

Figure 5.3: Results of Evaluation II

(a) Percentage of subjects who detected the coldest scene. (b) Percentage of subjects who detected the hottest scene.

Not only the entirely correct answers are taken into the comparison, in this evaluation, I also compared that under different conditions, whether people can roughly distinguish the information of cold and hot temperature. Therefore I compared the percentage that subjects could detect the coldest and hottest scenes in this experiment. According to the results, the percentages that subjects found the coldest scene were 73%, 27%, 87% and for the hottest scene were 40%, 47%, 93% respectively, which indicated that thermal feedback improves people's understanding of the environmental information in VR

After each experiment, I also collected their feedback on these different ways for presenting weather information. Some feedback are as below:

"The thermal feedback make me directly understand how the weather feel."

"This test reminds me even sunny day can be very cold."

"In this test, the temperature on my face is most impressive and the feeling is much easier to remember."

"When the temperature changed on my face, it was easy to recognize."

"Without glasses i can see the scene, but cannot read the text so thermal feedback better for me."

"To remember the number is challenging, while to remember the feelings is not hard."

"Thermal feedback seems more natural."

"I was sweating during the test, this may had impact to my feeling towards the stimuli."

Therefore the results of this experiment indicated the significant advantage of thermal stimuli for helping users understand the weather more correctly in this situation, and with the combination with thermal feedback, the VR weather system make users able perceive the environmental information less consciously and more naturally.

Chapter 6
Conclusion and Future Work

6.1 Conclusion

In this project, as a starting point of my exploration on enhancing users' perception of environment in VR by adding haptic feedback, I designed and developed a thermally enhanced weather application in which users can check current weather in VR and the information they get is not only provided by visual scene, sound effects of the weather, they can feel the temperature on their face through the thermal modules on ThermoReality HMD developed by our team.

By integrating thermal modules with the current VR head mounted display to provide thermal feedback directly on the face. the ThermoReality HMD is a device consists of five 2 x 1.5cm size thermal modules [16, 29, 32] mounted on the facial side (inside) of the head mounted display with a custom 3D printed rig, which are in direct contact with the users' face and are distributed to the left, center and right parts of the forehead and the left and right side of the parts under eyes on the user's face respectively.

Based on two user studies on human perception towards air temperature and thermal stimuli, I could set the thermal stimuli provided by the modules on ThermoReality HMD to represent the real air temperature which provide similar feelings on human skins.

And through the combination of visual, auditory and thermal feedback, this project intended to design and develop an application in which users are able to "feel" environment when checking weather in VR.

As one preliminary exploration on adding thermal haptic feedback into VR to enhance enhance users' perception of virtual environment, the main goals of this project is to discuss:

1. *Does the proposed system make it easier for users to acquire environmental information?*

2. *Does the proposed system allow users to perceive the environment more accurately in VR?*

Based on these two questions, three hypotheses were determined for evaluating the core concept of this project.

1. Temperature is crucial factor for understanding weather.
2. Thermal feedback makes users perceive the environment more correctly.
3. Thermal feedback makes it easier for users to understand the environment in VR

The evaluation was conducted in this project. The results of the experiment verified the three hypotheses, and indicated that thermal feedback significantly improve people's understanding of the environmental information in VR.

Therefore, this project shows the high potential of utilizing thermal feedback as a method for presenting information and enhancing users perception of the environment in VR, and provides a new approach for setting thermal feedback for presenting environmental information in virtual space, which also shows the potential for extending the use of thermal feedback in various type of experience in virtual space.

6.2 Limitation

This system still have some limitations in both hardware and software aspects.

First, taking into account safety of skin, the range of the temperature available for presenting in this system is constrained.

Second, current Feel It application doesn't contains all types of weather, only basic weather types available in this system and no extreme weather conditions. Therefore further classification of weather and design for corresponding scenes are taken into account to improve users' experience in this application. And impact of other factors of weather also worth discussing

Third, to keep this system fit for any place's weather information, when designing the scene I keep the view in the sky. If in future it's available to import 360 degree photos into this design may make the scene more realistic as a weather news system.

And now individual difference is not fully taken into account in this system, a further discuss can be much more about the different skin condition of the users.

6.3 Future Work and Extension

Therefore in the future, this work's improvement includes exploration and investigation on not only impact but also simulation of other environmental factors, such as humidity, wind, windchill, dew point etc. And the improvement in customizing of setting according to individual difference including skin conditions is a worthwhile direction as well.

It's not hard to apply the methods for setting multi-sensory feedback into other applications such as games, movies, and information sharing, etc. In this project I discussed about weather because weather is one of the most important aspects of environmental information and it is objective. If applying the settings I used in this project into movies, games, in which the environment can be very extreme condition, like super cold in the universe, or super hot near volcano according to the context, even some other type of information such as emotion. In these applications there are less constrains in combination of multi-sensory feedback with environmental information, therefore once there is a proper way to set the thermal stimulus for manifesting the information, thermal haptic feedback would has more potential to be manifestation of various type of information, thus this project can be not only a system for presenting real life weather, also possible for providing new approach for presenting other types of information for enhancing users' experience in VR in the future.

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Appendix

A User Study 1 Questionnaire: How do you check weather forecast?

User Study 1: How do people check weather? (An online survey conducted which mainly focused on peoples behavior and needs towards weather information)

Section 1

1. Your age?

   ☐ - 17 ☐ 18 - 25 ☐ 26 - 35 ☐ 36 -

2. Your gender?

   ☐ Male ☐ Female

3. Do you check weather forecast?

   ☐ Yes ☐ No

   (Yes - go to section 2, No - go to section 3)

Section 2

1. Why do you check weather forecast?

   ____

2. How do you check it?

   ☐ Phone ☐ Television ☐ Website ☐ Newspaper

   ☐ Other __________

3. What information do you usually check?

   ☐ Weather type

☐ Temperature

☐ Humidity

☐ Wind

☐ Precipitation

☐ Pressure

☐ Time

☐ Other __________

Section 3

1. Why do you think no need to check weather forecast?

   ____

B User Study 2 Questionnaire: Cold or Hot?

User Study 2: Peoples perception of range of temperature when they have different feeling towards the environment.

1. Where are you from?

   ____

2. Your age?

   ____

3. Your gender?

   ☐ Male ☐ Female

4. Select the temperature unit you are using

   ☐ Celsius (°C) ☐ Fahrenheit (°F)

If the neutral/comfortable temperature is when you only need to wear one T-shirt with jeans, what range of temperature do you perceive when you have the feelings described below? (please insert a range of temperature, ex. 0-40)

1. Too Cold

   ____

2. Very Cold

   ____

3. Cold

   ____

4. Cool/ Slightly Cold

   ____

5. Neutral/ Comfortable

   ____

6. Warm/ Slightly Hot

____

7. Hot

____

8. Very Hot

____

9. Too Hot

____