Exploring Reaction Time in an actual whole-body Jump'n Run Game

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Declaration of Authorship

I, Wenjie ZHAO, declare that this thesis titled, "Exploring Reaction Time in an actual whole-body Jump'n Run Game" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly conducted while in candidature for a degree at Technical University of Applied Sciences Lübeck.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"*Stay hungry.*
Stay foolish."

Steve Jobs

TECHNICAL UNIVERSITY OF APPLIED SCIENCES LÜBECK

Abstract

Department of Electrical Engineering and Computer Science

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by Wenjie ZHAO

Reaction time has become an important indicator in kinematics and psychology research. Human reaction times are generally in the region of 200ms. However, this applies to tactile and visual stimulus. It is unclear that how fast the human haptic response of foot, especially in response to changes in terrain. To explore this, we develop a VR game in which players will respond to terrain changes simulated by smart shoes. We tested participants under different sound conditions and observed their reaction times to terrain changes. We also performed simple response tests on participants' eye-hand reaction times to validate the results of previous studies. Finally we find that most participants have a much slower tactile response time to the foot than the eye-hand response. Moreover, the different sound conditions bring about a greater effect on the tactile response of the foot than the eye-hand response. We hope that this study will make a small academic contribution to future research, particularly in the areas of psychology, kinesiology and VR technology.

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LIST OF ABBREVIATIONS

RT	**R**eaction **T**ime
VR	**V**irtual **R**eality
HMD	**H**ead **M**ounted **D**isplay

Dedicated to my someone,
who is not being intelligent but always trying your best
to persevere, to love and to stay positive.

1 INTRODUCTION

1.1 Motivation

FIGURE 1.1: Football goalkeepers need extremely fast reflexes to judge the direction of the ball when making a save Denver (2018)

Humans undergo constant self-learning during the course of their evolution. Learning is an integral part of the human experience and can occur explicitly, actively, or outside of our awareness, also known as passively(Abrahamse et al., 2010). Since the last century, explicit and implicit learning has been at the forefront of anthropological research, and the parameter of reaction time (RT) has been widely used in various studies(Craddock, Molet, and Miller, 2012). For example, Jack Nissan argues that intelligent people tend to have shorter reaction times, thus demonstrating the relationship between RT and intelligence(Nissan, Liewald, and Deary, 2013). In some basic tasks, people with shorter RTs, who perform at higher processing speeds, show better complex reasoning abilities(Schneider and McGrew, 2012). Furthermore, in a couple of other research areas, including medical research, psychopharmacology and experimental psychology, RT has been widely used(Strachan et al., 2001).

As far as it seems, there have been many studies and experiments on human reaction times. However, most experiments at the current stage have been designed and conducted based on eye-hand response. Research on the human foot response is very limited(Eckner, Kutcher, and Richardson, 2010). In 2014, a study by Pfister et al. (2014) notes that human eye-hand response times are approximately 318.24ms ± 51.13 whereas eye-foot response times are approximately 328.69ms ± 48.70, which is approximately 10ms slower than the former. Vedel and Roll (1982) also indicate that human foot has fewer receptors and is slower to respond. However, the above studies still have limitations, as they do not accurately reflect the true extent of haptic responses of foot in a given task. It would also not be possible to point out the gap between human eye-hand and haptic response of foot in the course of daily life.

To achieve these goals, this paper aims to answer:

Question 1: How much correlation exists between human eye-hand reaction time and haptic foot reaction time?

Question 2: To what extent do factors affecting the human eye-hand response influence the haptic foot response?

1.2 Related work

1.2.1 Reaction time

Response time is the time lapse between the presentation of a stimulus and the onset of a response. The time required after the stimulus is applied to the organism until the onset of an apparent response(Teichner, 1954). RT is influenced by many factors including but not limited to age, gender, region, mental state, and environmental factors(Wu et al., 2009). Even within the same individual, reaction times vary over different time spans. Individuals are becoming less alike as a function of individual differences in change. For example, Hultsch, MacDonald, and Dixon (2002) found significant increases in variability over 6 years for seven of nine cognitive variables(Joanette and Brownell, 1993). In inconsistent cases, intra-individual variability is greater in older adults compared to younger adults, at least for some tasks. Several studies have shown that inconsistency increases with age in trials of RT tasks(Anstey, 1999), although some researchers have suggested this increase can be accounted for by individual differences in mean-level performance(Raz, 2000).

1.2.2 Sense of touch

Before this section, several proper terms haptic, kinesthetic, tactile and their relationship need to be explained. Haptic feedback is generally divided into two different classes: tactile and kinesthetic(Gallace and Spence, 2014). The difference between the two is quite complex. Simply put, kinesthetic is what you feel from the sensors in your muscles, joints and tendons. The weight, extension and joint angles felt by the arms, hands, wrists and fingers. Imagine you are holding a coffee cup in your hand. The kinesthetic feedback tells your brain the approximate size and weight of the cup and the relative position of the cup you are holding. Tactile is what you feel on the surface of the skin layer. Tissues (for example in your fingers) have many different sensors embedded in the skin and under the skin. They allow your brain to feel vibrations, pressure, touch, texture, etc. In summary, haptic feedback is a combination of tactile feedback and kinesthetic feedback(Paterson, 2007). In this project we focus on response of human foot to terrain changes, so most of the haptic feedback refers to tactile feedback.

As one of the channels through which humans learn about the outside world and provide feedback to themselves, haptic has played an important role in human evolution and learning. Unlike smell, sight and sound, it is intimate in that it requires direct contact with the skin, which is the sensory organ of touch. Humans constantly rely on tactile feedback to perform everyday tasks such as pulling keys out of cluttered pockets, as well as basic behaviors such as typing and fetching. Normal cognitive development in mammals also requires the sense of touch(Jenkins and Lumpkin, 2017).

Several major classes of mechanoreceptors have been identified in the human body. The principal touch receptors in the glabrous (hairless) skin of the lips, palm, fingers and sole of the foot are the Meissner corpuscle and the Merkel cell–neurite complex(Johansson and Flanagan, 2009). The human hand is richly endowed with these sensors. Each hand has approximately 150 000 mechanoreceptors which are connected to the central nervous system by 30 000 primary afferent fibers. The density of these receptors is highest on the fingertips (2500 per cm2). Each fingertip is innervated by 250–300 mechanoreceptive fibers. This large number of nerves confers fine tactual acuity to the fingertips, enabling human to read Braille and to discriminate surface texture(Johansson and Vallbo, 1983).

With the foot as the first and often only direct point of contact between the body and the external environment, sensory feedback from the skin receptors of the foot plays a role in the regulation of normal gait patterns. A correlation between the resultant changes in muscle activity following dermal nerve stimulation and gait kinematics has been demonstrated(Zehr, Komiyama, and Stein, 1997). Multisynaptic reflexes from skin receptors can alter motor output over a latency of 70 to 110 milliseconds(Duysens et al., 1990). However, there is a lack of specific research on how quickly the foot responds to terrain changes. That is, it is still unknown how soon humans respond to changes in terrain after they have sensed them.

As a result, due to the lack of research into the human haptic foot response, particularly to changes in terrain, this project will focus on the human haptic foot reaction time during normal walking. Visual and haptic changes will be simulated through a VR game and smart shoes.

1.2.3 Reaction time experiments

In the field of psychology, experiments studying human reaction times fall into three basic categories, simple reaction time experiment, choice reaction time experiment and recognition reaction time experiment(Kosinski, 2008).

Simple reaction time experiments are those in which humans respond to a single stimulus. In these types of experiments, participants are generally tested by pushing a button. When a visual change is produced, the participant presses the button and thus records the reaction time. For example, in a 2010 study of reaction times in football players, James T. Eckner and his colleagues conducted a simple reaction time experiment with 94 college athletes. The results showed that the average simple response is over 90% accurate and the average RT is 268 $\pm$ 44s(Eckner, Kutcher, and Richardson, 2010).

In the choice reaction time experiment, participants have to respond to different stimulus accordingly. When two or more stimulus are presented, participants are asked to respond differently to each of the different stimulus. In this case, the period of time between the presentation of the stimulus and the subject's choice response is called the choice response. There are usually several buttons with different functions in front of the participant and they correspond to different stimulus. For example, when the computer screen changes, which means humans visually receive a stimulus, they must quickly identify the type of stimulus in their brain and then press the corresponding button. This is a single choice reaction time experiment(Hultsch, MacDonald, and Dixon, 2002). The average time for the choice response is generally slower than the simple response time because in this experiment the human brain has an additional task of information processing(Eckner, Kutcher, and Richardson, 2010; Hultsch, MacDonald, and Dixon, 2002; Luce et al., 1986).

Recognition reaction time experiments are similar to choice reaction time experiments in that when two or more stimulus are presented, participants are asked to respond to a particular stimulus and not to the other stimulus. The time between the presentation of the stimulus and the response is the recognition reaction time(Hultsch, MacDonald, and Dixon, 2002). This further requires the brain to process different information in order to make a judgement. Thus, in general, the recognition response time is the slowest and the error rate is higher compared to the first two experiments(Luce et al., 1986).

In general studies, most experiments will only test simple reaction times and choice reaction times. This is sufficient for most data requirements and comparison needs. In this project, we focus only on the simple reaction time of eye-hand.

1.2.4 Hand response and foot response

Reaction time has been studied in great depth, from kinesiology to biology to psychology, and it has become a very important indicator. However, most research is still based on eye-hand reaction times(Montés-Micó et al., 2000). There are only a few studies on haptic foot reaction time. In almost all sports, RT represents an important component of psychomotor performance, which is influenced by: genetic characteristics related to the rate of transmission of nerve influx to the synapse, and the subject's experience of the sport(Woods et al., 2015). Sports and exercise practitioners are able to enhance the speed of response to a particular stimulus after a long period of training. In physical activity, understanding and mastering the use of the most appropriate stimulus embodied in physical exercise is a prerequisite for optimisistng motor behavior(Badau and Badau, 2022).

Sudirman et al. (2022) suggest that when discussing the eye-foot reaction, a distinction should be made between the reaction and the reflex. Reflexes are the body's unconscious responses to simple stimuli, such as the knee-jerk reflex. Reaction, on the other hand, is a conscious human response to one or more stimuli and is the result of judgement by the human brain. Pavlov's concept of classical conditioning is a similar unconditioned reflex that can be stimulated by a stimulus through training(Gormezano and Kehoe, 1975). The research of Montés-Micó et al. (2000) has shown that trained football players show superior performance compared to the general population, both in terms of eye-hand response and eye-foot response, and within each group, eye-foot reaction times are slower than eye-hand reaction times.

There are two main reasons why the foot response is slower than the hand response. One is that there are more sensors on the palms of the hands than on the feet, with a particularly high density of receptors on the fingertips(Johansson and Vallbo, 1979). In contrast, there are fewer mechanoreceptors on the foot, which are mainly used to maintain body balance(Nyland et al., 2018).

The other reason is that the distance from the foot to the nerve response center is longer than that of the hand. The stimulus passes through the skin sensors, through the spine, to the brain, where it is judged to send a signal that is eventually transmitted back to the end of the limb(Nyland et al., 2018). The eye-hand response and the latter part of the eye-foot response are identical, the difference being their distance from the spine, which gives the eye-hand response an advantage.

In general, the human foot response is generally slower than the hand response. Humans perform most of their activities through their hands, and therefore hands require a higher level of sensitivity. The main function of the feet is to maintain body balance and co-ordinate motor states, so high response is not required.

1.2.5 Factors influencing reaction time

There are many factors that determine human reaction time. Human reaction times depend not only on individual differences such as gender, age, trauma, perception, but also on ad hoc factors such as environment, type of stimulus, arousal state(Kosinski, 2008; Klapp, 1995).

Arousal is one of the main factors affecting reaction times(Adelman, 1997). However, rather than influencing reaction time, it is more likely to influence the outcome of the experiment. In other words, a person's RT in a relaxed state is not as fast as in a concentrated state. The more focused the participant is, the better he or she performs in the experiment. Etnyre and Kinugasa (2002) found that subjects had faster reaction times to stimulus if they warmed up their leg muscles for 3 seconds isometrically before the stimulus. Thus, in general, the more focused a human's attention is, the faster the experiment yields a reaction time. However, even with more concentration, the RT of each individual is close to a limiting value.

Unlike arousal, although people are able to concentrate on the test at hand, other distractions can still affect the outcome of the experiment. In studies of the effect of drivers playing with mobile phones on traffic accidents, it is shown that all phone use conditions proved to be the most important factor in reducing driving performance(Choudhary and Velaga, 2017; Haque and Washington, 2014). In the choice reaction time test, although in both males and females choice reaction time after mental fatigue is increased, the increased choice reaction time with distraction is due to interference with performance as a result of which reactions are delayed and smooth flow of continuous performance is interrupted(Welford, 1988).

Welford (1988) has shown that the fact that age has a negative effect on RT is widespread. David, Stuart and Roger examined three basic types of variability, variability between persons (diversity), variability within persons across tasks (dispersion), and variability within persons across time (inconsistency), for age differences. Shinde and Pazare (2014) showed that all three types of variability are greater in older adults compared to younger participants, even after statistically controlling for between-sample differences. Individual differences can vary over short periods of time depending on mood, environment, etc. For example, Rabbitt et al. (2001) measured inconsistencies in reaction times of elderly people in a letter recognition task. They found that greater intraindividual variability is associated with poorer performance on cultural intelligence tests, both trial-to-trial and week-to-week. However, putting aside these individual differences, reaction times did correlate positively with age. However, these individual differences aside, RT did correlate positively with age. The study of Pierson and Montoye (1958) showed for subjects under 60 years of age, movement time and reaction time are significantly related to chronological age.

In addition to these factors, there are many other factors that affect human reaction time. This depends on the experimental design, the testing environment and is also related to some non-quantifiable factors such as mental state, mechanical errors etc.

1.3 Conclusion

Research into reaction times has been going on for decades. With the development of new things such as cars and mobile phones, research in this area has continued. Nevertheless, very little research has been done on foot response, particularly on the response time of the foot to changes in terrain. Therefore, this project will test people's RT to terrain changes based on a VR game to explore how factors affecting the eye-hand response affect the tactile response of the foot.

2 METHODOLOGY

The main purpose of this chapter is to introduce the reader to the techniques and methods used in this study so that the reader can have a better understanding of the methodology used in this paper. In this chapter, we explain the research design of this study, the research steps, data collection, data analysis and why this methodology is used.

2.1 Introduction

The aim of this thesis is to investigate the speed of human response to simulated terrain changes. Obtaining effective data and information is of vital concern to build an accurate picture of the issue being studied. To a large extent, methodology determines the outcomes of any research. Therefore, it is crucial to choose appropriate research methods and conduct them effectively in order to answer the research question and meet the research objectives well.

2.2 Research design

2.2.1 Quantitative and Qualitative Approach

There are two main types of marketing research in terms of the two, essentially different types of data that are generated by fundamentally different research approaches-quantitative and qualitative methods(Adcock and Collier, 2001).

Quantitative research involves the collection of information that can be expressed in numbers (Brassington and Pettitt, 2003). However, it includes not only numerical data such as sales figures, market shares, market sizes and demographic information, but also numerical aspects of other data, often derived from primary research such as questionnaire-based surveys and interviews. The success of quantitative research therefore depends to a large extent on establishing a sufficiently large representative sample to ensure that the data collected is reliable and objective. Due to time and financial constraints, it is clearly not realistic to conduct a truly quantitative study in terms of the time and requirements of this research project. This is not to say that quantitative data will not be used in this project. In fact, it is important to obtain quantitative data from secondary sources in order to support arguments.

Qualitative research, on the other hand, usually involves the collection of interpretable non-numerical data, such as participants' opinions, where no statistical validity is intended to be established (Brassington and Pettitt, 2003). The nature of qualitative research is that it is 'diagnostic'; as such, it is particularly useful for investigating attitudes, motivations, beliefs and intentions. In practice, they are usually based on small samples; therefore, it cannot be generalized in numbers (Brassington and Pettitt, 2003). Chisnall (1997)further characterises this method as impressionistic rather than conclusive, and he also notes that it allows for a better understanding of certain factors that may influence decision-making. However, it is important to note that the results generalized from this process are often subjective. Typically, secondary data is obtained from both print sources (books, magazines, journals and trade newspapers) and electronic sources (CD-ROM encyclopaedias, software packages or online services such as the Internet). Books are general resources that provide relevant theoretical support for research. Journals are a useful resource for everyday information. They can provide up-to-date views and developments in specific areas of research. The Internet is also useful for data collection, especially specialist websites.

In this study, a mixture of quantitative and qualitative analysis methods will be used. For the analysis of objective experimental data quantitative analysis needs to be used. The variables in the experiment can be quantified, such as age, gender, profession, response time, error rate, deviation value, etc. of the participants. Therefore, quantitative research methods need to be used. In addition, quantitative analysis of the participants' experience is also important, e.g., ease of use, enjoyment, etc.

2.2.2 Strategy

The research strategy plays a crucial role in a study, which determines the experimental content (Schell, 1992)of a study. As shown in Figure 2.1, the research strategy explains to the reader the questions of where, who, how, why, etc. In order to provide the reader with a further understanding of this study, this section will detail the places, people, instruments, and research process involved in this study.

The experimental site for this research project is selected in the laboratory of the University of Applied Sciences Lübeck in Lübeck, Schleswig-Holstein, Germany. Since the main focus of this project is to test the human response to terrain changes using smart insoles, the site requirements for this project are not high. The general laboratory of the University of Applied Sciences Lübeck is sufficient for the experimental requirements.

In terms of participants, due to time and size constraints, 5-10 healthy subjects will be selected within the University of Applied Sciences Lübeck through the community for this project. Because of the small sample size, it is not really possible to do a quantitative study. Therefore secondary data provides some reference for this study.

Relevant situations for different research strategies

Strategy	*Form of research question*	*Requires control over behavioural events?*	*Focuses on contemporary events?*
Experiment	how, why	yes	yes
Survey	who what, where, how many, how much	no	yes
Archival analysis	who what, where, how many, how much	no	yes/no
History	how, why	no	no
Case study	how, why	no	yes

FIGURE 2.1: Relevant situations for different research strategies

In this study, the experimental tools are an important part. The tools used in this project include:

- Meta quest pro
- iphone12 pro
- air pods pro
- a pair of smart insoles
- Excel
- short UEQ

VR-HMD(Figure 2.2) will be used for the demonstration of VR games. The game is created and packaged into the head display through the unity engine, thanks to the advantages of the meta quest pro all-in-one.

IPhone12 pro(Figure 2.3) is really useful for its camera, as it is needed to record the images of the subject during the experiment and to assist in determining the reaction time data.

FIGURE 2.2: Meta quest pro

FIGURE 2.3: Iphone12 pro

The air pods pro(Figure 2.4) is used to create different sound environments for the purpose of controlling variables.

The smart insoles(Figure 2.5) are useful in two ways. The first is the ability to simulate changes in terrain, such as asphalt, grassy and sand. The second is to capture the subject's responses and record them via sensor transmission to a computer terminal.

FIGURE 2.4: Airpods pro

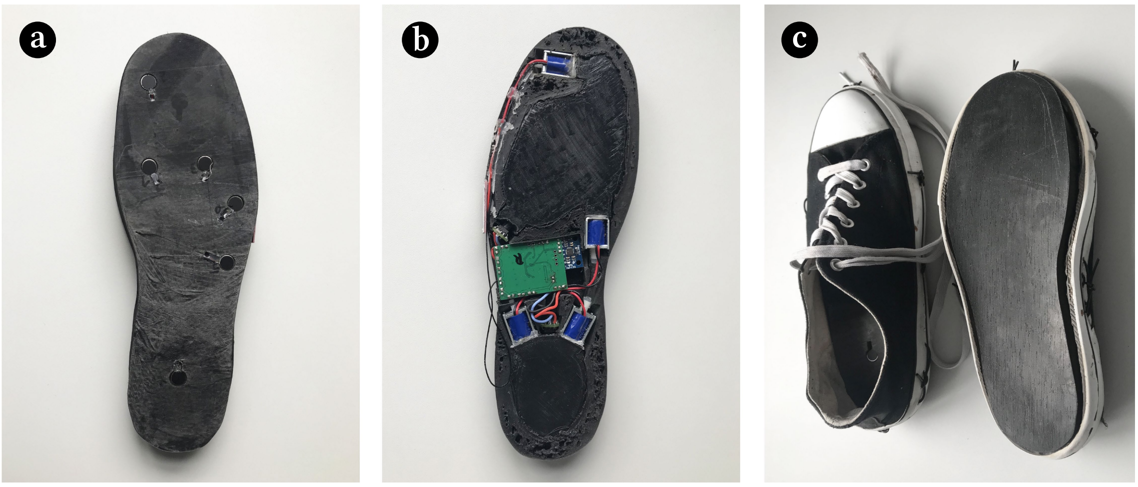

FIGURE 2.5: Smart insoles

Excel will be used to collect and analyze the above quantitative data.

The Short UEQ is used to collect the subjective feelings of the participants as a sourc e of qualitative data.

2.3 Research method

2.3.1 Data collection

Data collection is divided into two main parts, namely quantitative data of objective numbers and qualitative data of subjective perception.

The quantitative data includes the simple eye-hand reaction time test before the terrain change test, which is obtained and recorded through the Human Benchmark website. For the terrain change reaction test, a video of the experiment is taken with a camera and saved for playback, i.e., the participants' test process, which focused on the movements of the participants reacting to the terrain. In addition to this, there is data recorded by a computer terminal through a smart insole sensor, which gives a more precise indication of when the participants reacted to the terrain changes.

At the end of the experiment, participants are asked to fill out a questionnaire. The first half of the questionnaire contained basic information about the participants and served as a source of part of the quantitative data. This includes

- Gender
- Age
- height
- Body weight
- Job
- Hobbies

The qualitative data consisted of a questionnaire section completed by the participants. The short UEQ is used to ask about several aspects of

- Overall satisfaction with the test

  - Did you have fun, and are you entertained during the test. If so, which parts?
  - are you concerned about your reaction time?

- Questions about the test equipment
  - is the equipment in the test easy to use?
  - is the VR device comfortable to wear?
  - Did the VR device cause you some stress to the point that you are slow to react?
  - Did the scenes in the VR field of view distract you?
  - Are the shoe inserts comfortable to wear?
  - Is the environment simulated by the insoles realistic?

- Questions about the participants
  - Do you think your reactions are the same under different sound conditions?
  - Do you usually play sports that require fast reactions? For example, basketball, soccer, badminton, ping pong or video games like FPS (csgo, valorant, OW2, Apex, PUBG) or Moba (Dota2, LOL).

Participants are asked to fill in their level of satisfaction with these aspects.

2.3.2 Experimental steps

2.3.2.1 Simple reaction test

A simple eye-hand response test is administered to the participants prior to the start of the experiment on response to topographic changes. A single stimulus reaction time test is performed five times on the Human Benckmark website(https://humanbenchmark.com)using a mouse and monitor, resulting in an average reaction time for each participant. Participants should wear headphones and take the test once in a noise-reduced, soothing musical environment and once in a loud musical environment to obtain their simple eye-hand reaction times in different sound environments. The experimenter recorded the average reaction time for each participant in the three different states.

2.3.2.2 Preparation

Prior to the start of the terrain reaction time experiment, participants will wear shoes with smart insoles and adjust them to the most comfortable level. And wearing the meta quest pro head VR display device, adjust the elasticity, pupillary distance and angle to achieve the clearest visual image. After the participants put on the headphones, the experimenter should adjusts the phone camera view to ensure that the subject's lower body is clearly visible. In addition, the infinity sensor of the smart insole needs to be connected to the personal laptop to ensure that the experimental data can be recorded.

2.3.2.3 Testing Process

After the subject entered the game-like test scene in VR view(Figure 2.6), the experimenter first activated the cell phone camera and the sensor recording on the personal computer for image and waveform recording. During the test, the system simulates several terrain changes through the insoles with pre-set instructions. The subject should lift one foot after feeling the terrain change to indicate that he/she feels the terrain change. After the smart insoles simulated several changes, the test is over. The experimenter confirmed that the whole experiment is recorded as well as the sensor data is saved.

2.3.2.4 Questionnaire

At the end of the test, participants are also asked to fill out a simple user experience questionnaire a source of data for some of the quantitative analysis and all of the qualitative analysis. The questionnaire included aspects such as the

FIGURE 2.6: VR scene as participants' view

comfort level of the head-mounted VR device, the experience of the VR game, the comfort of the smart insole, and the overall experience of the test.

At the end of the user experience questionnaire, the experiment of this research project will be completely finished. The follow-up is to analyze the data for the experimental results, summarize and draw stage conclusions.

2.4 Data analysis

The analysis of the quantitative data will be conducted after the experimental data have been collected and organized, using Excel, and will focus on the research questions of whether there is a correlation between simple intra-individual eye-hand responses and responses to changes in simulated terrain, and the extent to which sounds affecting human eye-hand responses affect human responses to changes in simulated terrain.

2.4.1 Quantitative analysis

2.4.1.1 Intra-individual analysis

In the first place, for each individual, their eye-hand reaction times and reaction times to simulated terrain changes will be compared. From this, we can infer whether there is a correlation between individuals with different reaction speeds to changes in the simulated terrain.

2.4.1.2 Sound variable analysis

Secondly, whether the participants showed different reaction speeds in the simple eye-hand response test and the simulated terrain change test for different sound environments. That is, whether the sounds that affect human simple eye-hand responses have a similar effect on human responses to changes in simulated terrain.

2.4.2 Qualitative analysis

The qualitative data will complement the analysis of the quantitative data and to some extent will be able to correct the answers to the research questions. In the questionnaire, we will know how subjective the participants feel, whether the design and presence of the experimental site, tools, and personnel affect the mood and state of the participants, thus making the collected data lose some objectivity. Therefore, quantitative data are needed to assist in the analysis.

3 IMPLEMENTATION

In this chapter, the experiments of this project are described, including the pilot experiment and the formal experiment. The pilot experiment has a short process with only one participant. It aims to familiarize the experimenter with the experimental process, to verify the rationality of the experimental design, and to improve the experimental steps and process. The formal experiment has eight participants and takes more time. The purpose of the experiment is to collect the data needed to support the project and to draw preliminary conclusions from the analysis.

3.1 Pre-experiment

Before the formal experiment started, we conducted a pre-experiment. The main purpose of this experiment is to identify the deficiencies in the experimental design phase and also to strengthen the overall experimental design scheme to ensure the smooth running of the formal experiment afterwards.

3.1.1 Participants

The participants in this experiment are Zhao Wenjie, Marco Gabrecht and Huang Chenwei. Zhao Wenjie, as the experimental designer and the experimental conductor of the study, organizes the running of the experiment. Marco Gabrecht, as Zhao Wenjie's supervisor, provides the site and some of the tools for the experiment, including the insoles and the program to control the insoles. Huang Chenwei, as the participant of the experiment, the subject of the experiment, performs the corresponding actions under the guidance of the experimenter.

3.1.2 Preparation

The experiment is conducted in room 18-2.03 of the University of Applied Sciences in Lübeck and in the corridor outside. The experimental tools included a pair of Meta Quest Pro, an iPhone, a pair of airpods pro, a pair of smart insoles and their control program. Before the experiment started, the experimenter had to wear the VR device to mark the activity area in the corridor where the experiment would be conducted, which is roughly a rectangle of 1.5m*10m in length and width. The cushions are connected to the computer and controlled by a python program. Only Inflation and Deflation are able to work due to the cushion failure. The control panel is shown in the following figure.

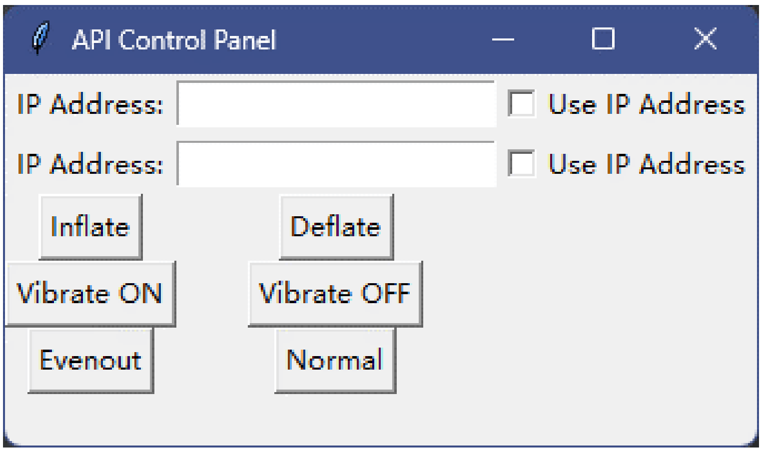

FIGURE 3.1: API Control Panel

Two of the lines of IP Address require the IP of the insole to be entered so as to communicate with the insole.The insoles can change the simulated terrain by pressing a button on the panel, thereby sending out a stimulus. After confirming that the insoles are properly connected, the experiment begins.

3.1.3 Simple reaction experiment

Before the experiment on the reaction time of the simulated terrain, according to the experimental design, participants will perform a simple eye-hand reaction experiment. The experiment is conducted on the Human Benchmark website (https://humanbenchmark.com). The experiment will be conducted five times and the final results will be averaged. Participants will be tested under three different sound conditions while wearing headphones, and the experimenter will record the results. The response speed of the participants is measured under noise reduction, soothing background sound and high background sound as follows.

Sound Type	Quiet	Soothing	High
Reaction Time	256ms	274ms	295ms

TABLE 3.1: Pre-experimental simple reaction test results

3.1.4 Simulated terrain change response experiment

Participants wear VR equipment and adjust the level of comfort and pupil distance to ensure they can clearly see the scene inside the helmet. Participants put on the insoles, wear the headset, and start walking back and forth along the corridor after the experimenter sets up the phone and starts recording. Instructions are given to the insoles via keystrokes on the computer, and the time it took for the participant to respond is recorded. From the frame in the program when the mouse is released to give the command, to the end of the frame when the subject gives the signal. The time in between will be used as the subject's reaction time to the simulated terrain change.It is worth mentioning that the vibration motor is not able to be used due to the failure of the insole itself. Therefore, only inflation and deflation are used as stimulus in this experiment.

3.1.5 Improvements

After the first terrain change response experiment, the experimenter examined the video and found that although the command is given at a specific time after the start of the video, this is not accurate enough and there is a considerable error for a millisecond response time, which is unacceptable. Therefore, after discussion with the tutor, it is decided that each click of the mouse when a command is given would be operated within the range that the camera could capture. Moreover, the action of asking the experimental subject to give feedback is changed from raising the hand to making a fist, which could further reduce the error. In this way, the commanding action and the subject's response signal are captured in the same shot, and the camera is able to capture both actions successively, allowing the experimenter to obtain relatively more accurate data through later analysis of the video.

3.1.6 Preliminary Analysis

The results of this pre-experiment are shown as table 3.2.

The Number column is the serial number of the stimulus. There are four types, Inflation, Deflation, Vibration on and Vibration off. The Sound column is the sound played in the participant's headphones, and there are three types: Quiet, which is the noise-canceling environment; Soothing, which plays soothing music; and High, which plays high music. The Start column refers to the frame where the stimulus start, that is, the frame where the experimenter released the mouse. The Respond column refers to whether the participant respond to the stimulus or not, the main purpose of this column is to calculate the error rate. The Reaction column refers to the frame where the participant start to respond. The RT column is calculated from the Start column and the Respond column. Since the video is captured at 60 frames, the reaction time is given by the following equation.

$$RT(ms) = (Reaction - Start) * 1000(ms)/60$$

Number	Type	Sound	Start	Respond	Reaction	RT/ms
1	Inflation	Quiet	889	N		None
2	Deflation	Quiet	1620	N		None
3	Inflation	Quiet	2283	N		None
4	Deflation	Quiet	3169	Y	3246	1283
5	Inflation	Quiet	4132	Y	4186	900
6	Deflation	Quiet	4970	Y	5017	783
7	Inflation	Quiet	5781	Y	5807	433
8	Deflation	Soothing	6389	Y	6456	1117
9	Inflation	Soothing	7289	Y	7319	500
10	Deflation	Soothing	7975	Y	8034	983
11	Inflation	Soothing	8454	Y	8511	950
12	Deflation	Soothing	9054	Y	9147	1550
13	Inflation	Soothing	9820	Y	9872	867
14	Deflation	Soothing	10459	Y	10513	900
15	Inflation	High	11162	Y	11201	650
16	Deflation	High	11686	Y	11824	2300
17	Inflation	High	12250	Y	12320	1167
18	Deflation	High	12898	Y	12992	1567
19	Inflation	High	13359	Y	13404	750
20	Deflation	High	13919	Y	14015	1600
21	Inflation	High	14398	Y	14429	517
22	Deflation	High	14892	Y	15094	3367
23	Inflation	High	15393	Y	15452	983

TABLE 3.2: Pre-experimental simulated terrain reaction time test

Based on the experimental data in table 3.2, we can derive the following table 3.3.

	Inflation	Deflation	Avergae
Quiet	666,667	1033,333	850,000
Soothing	772,222	1137,500	954,861
High	813,333	2208,333	1510,833

TABLE 3.3: Pre-experimental reaction time analysis table

With the following histogram 3.2, we are able to see more clearly how the reaction time changes under different stimuli and different sound conditions.

It is easy to see that participants respond more slowly to inflation than deflation in all three sound conditions. In a quiet environment and with soothing music,

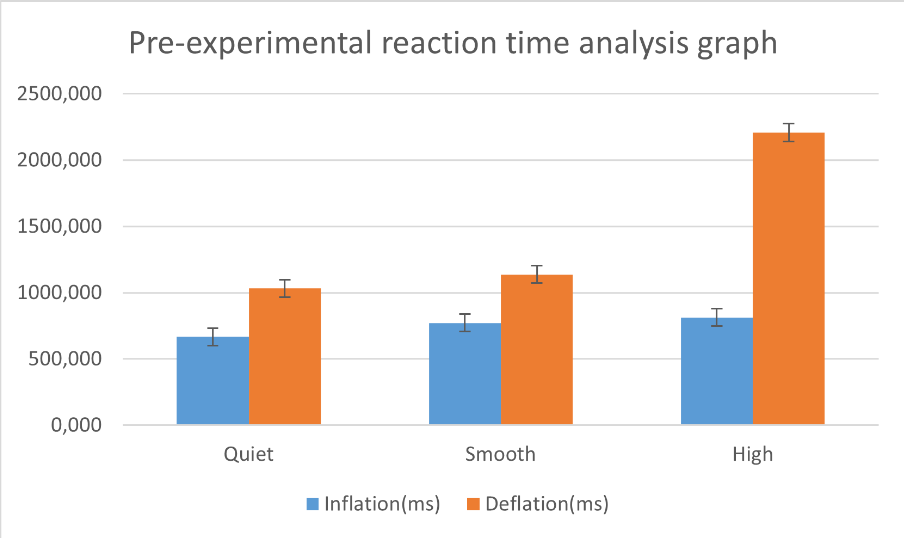

FIGURE 3.2: Pre-experimental reaction time analysis graph

participants respond to inflation about 100 ms faster than deflation. In the high music environment, this gap is widened even more, to about 1100ms. However, it is clear that this gap is too large. In the case that the participant respond too slowly, with a response time higher than 1500ms, this response should be considered a failure. There are many reasons for this result, including but not limited to the insole itself and the subject's slow response to a certain stimulus.

3.1.7 Conclusion

The main purpose of this pre-experiment is to ensure the smooth running of the formal experiment, so it is necessary to use this experiment to improve the previous design. Moreover, this experiment can help the experimenter to roughly estimate the time needed for each participant, so as to better arrange the experiment process and control the time of the experiment. There are many electronic devices used in the experiment, and the endurance is a factor that must be considered, so it is necessary to control the experiment time well.

3.2 Formal experiment

The experiment conducted in this project is broadly similar to the pre-experimental steps described in chapter 3.1, according to the experimental design. However, there are more participants, the duration is longer, and therefore more data are collected. Due to time and financial constraints, there are 8 participants in this experiment, and the cumulative duration of the experiment is approximately 3 h. A total of 8 valid data are collected, each containing 32-43 response times to each stimulus, for a total of 302 response times to each stimulus. Although this amount of data is not very sufficient, it is possible to analyze some superficial conclusions.

3.2.1 Preparation

As in the previous pilot experiment, this experiment is conducted in the university room 18-2.03 of Lübeck Applied Technology as well as in an external corridor.

Before the experiment starts, the experimenter networks the computer and opens the website (https://humanbenchmark.com) to ensure that the experiment with simple eye-hand reactions would run smoothly. The VR-HMD is then put on and a 1.5m*10m experimental area is delineated in the corridor outside the room. The application packaged into the VR headset is selected in the headset VR interface and enter into the virtual scene.

The experimenter calibrates the scene angle to ensure that the road displayed in the headset is in the same direction as the road in reality to avoid accidents during the subsequent experiment.

3.2.2 Experimental procedure

The experimental procedure for each participant is the same as the pre-experiment. A simple stimulus eye-hand response test is performed on the

Human Benchmark website (https://humanbenchmark.com) to find out the approximate response time of each participant. Then the participants wear the smart insoles and adjust the tightness.

Then they put on the VR headset and adjust the pupil distance and angle to ensure that the scene inside the headset is clearly visible. The next step is to familiarize themselves with the scene in the area delineated in the corridor to prevent safety accidents during the subsequent experiments. As in the pilot experiment, the experimenter is able to control the insole through the code written in the python program to give stimulation. The control panel is shown as the figure 3.3.

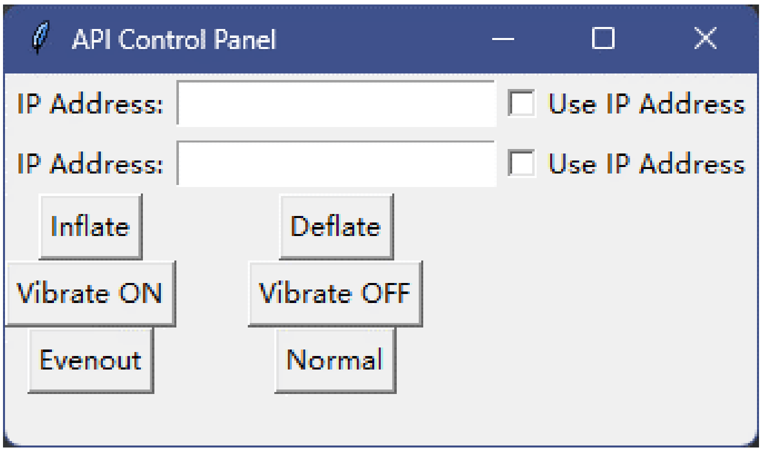

FIGURE 3.3: API Control Panel

The two lines of IP address communicate with the left and right insoles respectively. The button below allows you to send control commands to the insoles. Make sure both insoles are online and start experimenting.

3.2.3 Simple stimulus reaction experiment

As in the pilot experiment, participants are asked to perform only three response tests on the Human Benchmark website (https://humanbenchmark.com). These three tests are conducted under three different sound conditions. These are a noise-reducing environment, a soothing musical environment, and a high musical environment. In order to reduce the chance of the experiment, each participant can do the test once to get familiar with the testing process and environment, especially the strength of mouse clicks. This test will not be recorded and will only be used to familiarize participants with the experiment. The order of the sound played in each participant's headphones will be disrupted, which makes the experiment results more convincing.

3.2.4 Experiment on terrain change response in VR scene

The experimenter set up the camera to ensure that the subject's raised hand could be clearly visible before the experiment could begin. During the experiment, the subject walks freely in the area delineated in advance, and the experimenter sends out stimuli by manipulating the computer, and ensures that the whole process of clicking the mouse is in the same picture with the subject. In addition to this, the error time between each stimulus sent from the program and the real response of the insole should be recorded. Each time the experimenter clicked the mouse, the insole worn by the participant would send out one of the four stimuli to simulate the change in terrain. After sensing the change in terrain, participants should quickly clench their fists to give a signal that they perceive the change in terrain. The participant should release the fist in time rather than keeping it clenched in preparation for the next time. The camera captures the entire process of each stimulus from the experimenter to the participant giving feedback as a source of data.

3.3 Experimental results

The experimental results are shown in the appendix pages A.

4 EVALUATION

This chapter will be devoted to the evaluation of the experiment and the analysis of the experimental data. Several hypotheses will be presented and analysed. The data is mainly divided into quantitative and qualitative analysis. The data for the quantitative analysis are mainly derived from the response time data measured during the experiment. The data for the qualitative analysis are mainly derived from the questionnaires completed by the participants at the end of the experiment.

4.1 Hypotheses

To answer the research question, based on the previous theoretical basis and experimental design, we can propose several hypotheses as follows

H1 Different sound conditions affect participants' eye-hand responses as much as they affect the responses to terrain changes.

H2 Different sound conditions affect participants' responses to terrain changes more than eye-hand responses.

H3 Different sound conditions affect participants' responses to terrain changes less than eye-hand responses.

H4 Different sound conditions do not affect participants' eye-hand responses nor do they affect participants' responses to terrain changes.

H5 Different sound conditions do not affect participants' eye-hand responses, but affect participants' responses to terrain changes.

H6 Different sound conditions affect participants' eye-hand responses and did not affect participants' responses to terrain changes.

4.2 Data collection

4.2.1 Quantitative data

The quantitative data for this project are divided into the reaction times of participants in the simple response experiment and the reaction times of participants in the simulated terrain change test. The reaction times of participants in the simple reaction experiment are derived directly from the website and recorded by the experimenter.

The reaction times in the simulated terrain change are derived from the video taken. The frames in which the stimuli are emitted and the frames in which the participants perceived the stimuli are analyzed frame by frame by the experimenter at a later stage.

The participant's reaction time (RT) is the frame in which the participant felt the stimulus (Reaction) minus the frame in which the experimenter released the mouse and the stimulus is emitted (Start), and then multiplied by the time represented by each frame (1000ms/60). Then subtract the error time (Error) from the time the stimulus is sent to the time the insole starts to respond, this time can be obtained in real time through the manipulation panel in the experiment and recorded by the experimenter. This is shown in the following equation.

$$RT(ms) = (Reaction - Start) * 1000(ms)/60 - Error(ms)$$

The frame where the iconic clicking sound is clearly heard through the video when the mouse is released. This is used as the basis for determining when the experimenter releases the mouse(Figure 4.1). From the frame where the participant's fingers begin to flex, the initial frame of a fist clenching could be determined(Figure 4.2 and 4.3). This difference is seen very clearly when compared with the before and after frames. This minimizes errors in the data collection process.

FIGURE 4.1: The frame where the mouse is released

FIGURE 4.2: The previous frame of finger bending, 2046/11145 frames of the whole video

FIGURE 4.3: The first frame of finger bending, 2047/11145 frames of the whole video

Since the experimental data for this project are based on the analysis of the video taken and the video frame rate is 60 FPS, there will be unavoidable errors. Since the reaction time is calculated as the frame in which the participant reacts minus the frame in which the left mouse button is released, there will be 1-2 frames of error in both places. Therefore, the participant's reaction time should have a positive or negative floating value of about 4 frames. This error time is

$$4 * 1000(ms)/60 = 66.667(ms)$$

4.2.2 Qualitative data

Qualitative data are obtained through the questionnaire mentioned in chapter 2.3.1.

4.3 Quantitative analysis

This section is a quantitative analysis based on the data obtained from the experiments. The main focus is on analyzing the trends of the data and the differences under different conditions.

4.3.1 Eye-hand reaction experiment

As shown in the table 4.1, the eye-hand reaction time data for each participant are as follows.

Type	Eye-hand reaction			
Number	Quiet	Soothing	High	Average
Pre-test	256	274	295	275,000
1	234	242	297	257,667
2	232	255	284	257,000
3	238	258	250	248,667
4	237	239	240	238,667
5	239	238	260	245,667
6	265	291	264	273,333
7	329	264	363	318,667
8	241	257	288	262,000

TABLE 4.1: Eye-hand reaction data

With the data in the table, we can generate histogram as figure 4.4.

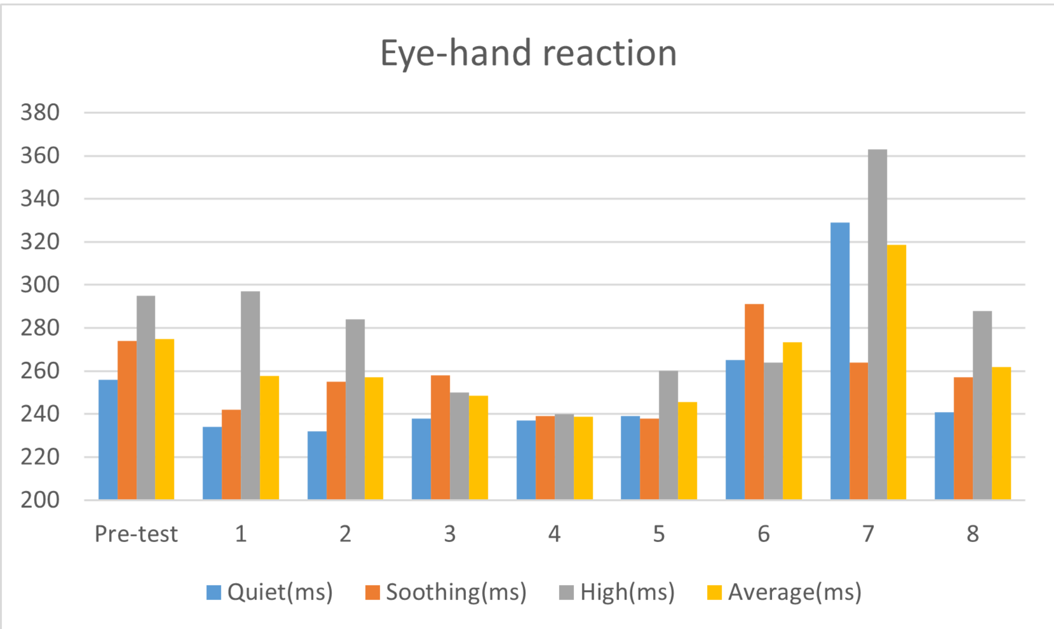

FIGURE 4.4: Eye-hand reaction graph

Obviously, for most of the participants, there are differences in their reaction speed under different sound conditions. The participants react fastest in the noise-reduced environment, followed by the soothing music condition, and the participants usually show the slowest reaction speed in the emotionally charged sound environment. This is the same as the pre-experimental conjecture, which means different sound conditions bring different effects to the subjects. As mentioned in Chapter 1.2.5, distraction, as one of the main factors affecting human response speed, can delay the time for humans to respond to a stimulus.

4.3.2 VR scene reaction experiment

In the VR scene response experiment, we had 8 participants in the experiment and measure the response time under 302 single stimuli. This part will be analyzed for the responses under different stimuli in different sound conditions.

4.3.2.1 Analysis of reaction time under inflatable stimulus

For the experimental data measured by the inflatable stimulus, we are able to derive the following histogram as figure 4.5.

It can be seen that the participants' responses to the inflatable stimuli varies. There is a large variation in response times both within individuals and between each individual. This may be due to the inflation stimulus themselves. One is that each person walks at a different frequency and has a different way of walking. Therefore, it may result in the insole being inflated with the foot still in the air and not being felt until the participant's foot is fully on the ground. Therefore, the time for the participant to give feedback should be added to the time for the foot to hit the ground.

Secondly, because of the difference in walking habits between individuals, some people are used to landing heel first, while others are used to landing toe first. Due to the design of the smart insole itself, the inflatable air cushion is designed to the forefoot. This resulted in some participants being insensitive to the inflation stimulus, thus producing feedback well beyond the normal response time.

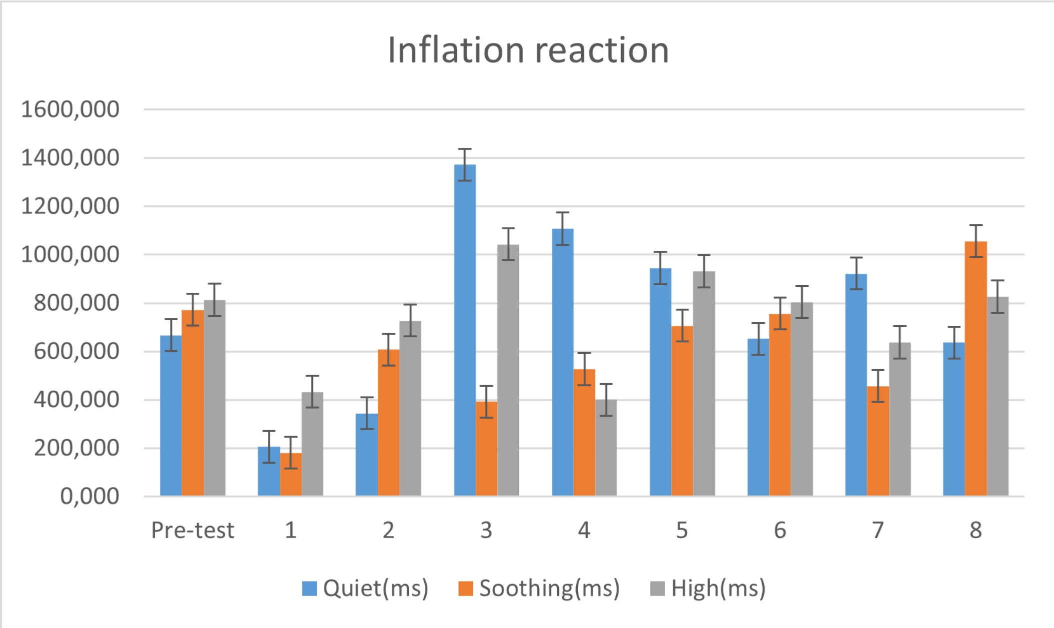

FIGURE 4.5: Inflation reaction graph

Nevertheless, we are still able to see that the minimum of the participants' reaction times in the three sound conditions,which means the fastest responses occur in the noise-reducing and soothing environments. With the exception of some specific data, the subjects showed longer reaction times, which means slower reaction speeds, in the high sound condition.

4.3.2.2 Analysis of reaction time under deflation stimulus

For the experimental data measured by the inflatable stimulus, we are able to derive the following histogram 4.6.

Similar to the inflation stimulus, the deflation stimulus is also delivered through the same air cushion. However, we found that the participants' response time to the discovery of the deflating stimulus is more stable, meaning that they are more sensitive to the deflating stimulus. This may be due to the fact that deflation causes a reduction in pressure under the feet compared to inflation, and humans are more sensitive to this sensation.

However, the participants' responses to the deflation stimulus are generally slow, mostly concentrated above 500 ms. This may be due to the fact that, as with the

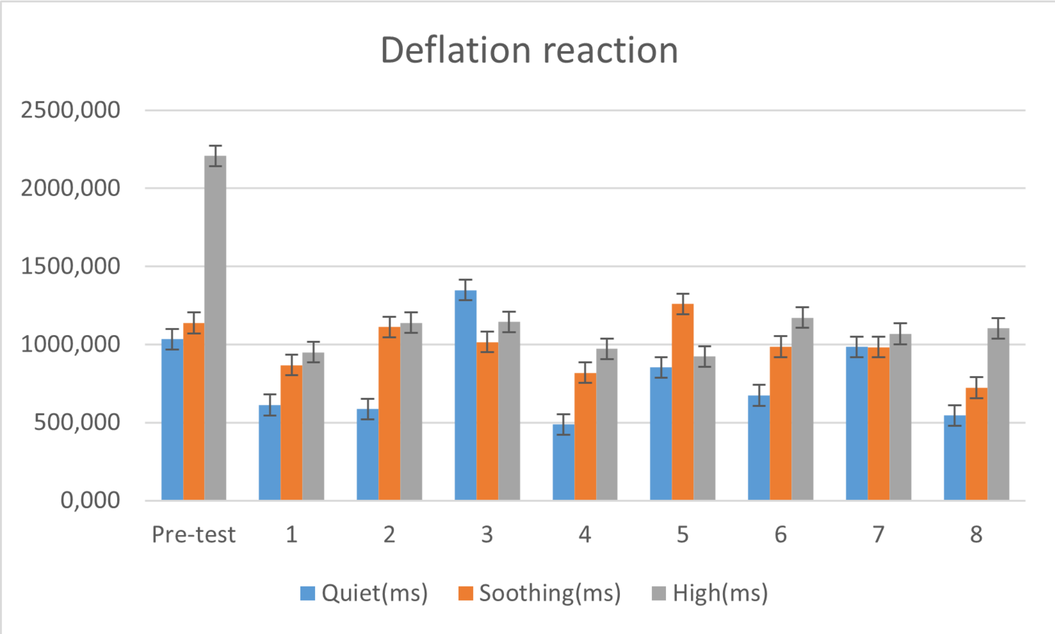

FIGURE 4.6: Deflation reaction graph

inflation stimulus, participants are less sensitive to changes in the state of the air cushion under their feet. In comparison, we found that the participants' response speed in the three different sound conditions is as expected. That is, participants responded fastest in the noise-reducing environment (quiet), had the longest response time in the high sound environment, and remained moderate in the soothing music environment.

4.3.2.3 Analysis of the reaction time under vibration onset stimulation

For the experimental data measured at the beginning of the vibration, we are able to statistically obtain the following histogram as figure 4.7.

From the above graph, it can be seen that most of the participants had a fast response to the vibration, with the average value fluctuating around 700ms. This is because the vibration of the motor in the insole is clearly felt by the participants regardless of the state they are in when walking, whether it is with one foot off the ground or with both feet on the ground, which is also reflected in the questionnaire. Except for the response of No. 2 in the high sound condition and the slow response shown by No. 6 and No. 8 experimental subjects,

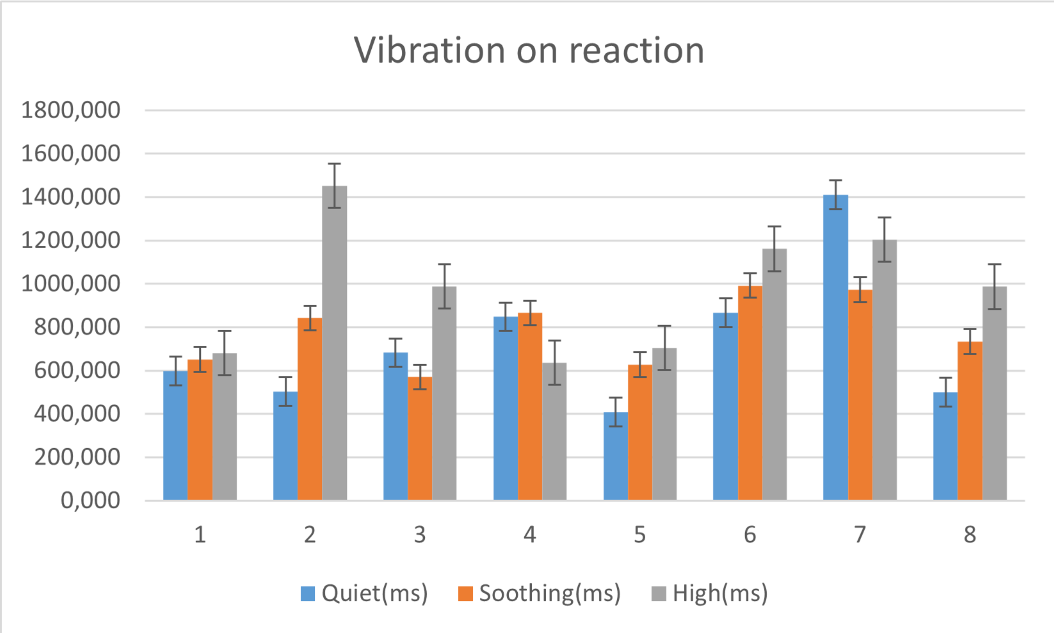

FIGURE 4.7: Vibration on reaction graph

the average response time of all other participants is excepted in the range of 500ms-800ms. Moreover, their responses are in the order of fastest in the noise-reducing environment, second in the soothing music environment, and slowest in the high music environment. Although numerous participants showed faster reaction times than inflation and deflation in the experiment, this reaction time is still much longer than their eye-hand reaction times.

4.3.2.4 Analysis of the reaction time under vibration off response time

Based on the experimental data measured by the participants in response to the vibration shutdown, we can obtain the following histogram as figure 4.8.

Firstly, it is clear from the figure that the effect of sound on participants' responses is still present and that the high sound condition has a strong effect on participants' responses. For subjects No.2-8, the high sound condition caused them to make slower responses than the other two sound conditions, which is the same as the previous three conditions and confirms again that the sound factors that affect human eye-hand reaction time also affect human reaction speed to terrain changes.

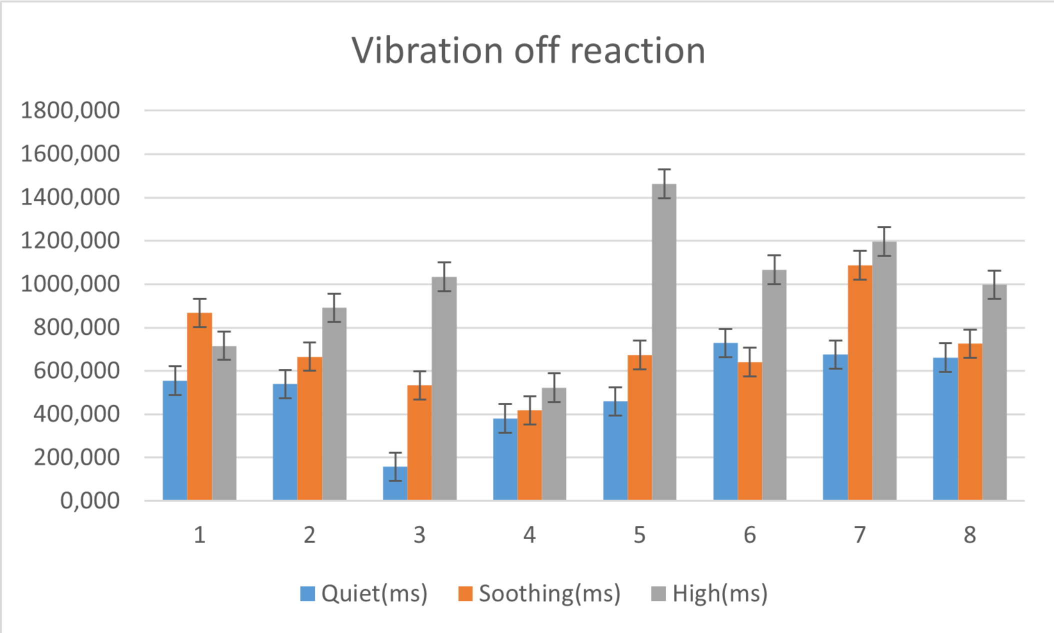

FIGURE 4.8: Vibration off reaction graph

Secondly, we can roughly see that the reaction time of the experimental subjects for vibration off is slightly faster than that for vibration onset, mostly concentrated between 400-700ms. Moreover, the participants show relatively more stable reaction times in the quiet and soothing music conditions. Relatively speaking between the different sound conditions, participants still showed the same response trends as in the first three stimulus conditions.

4.3.2.5 Average response time analysis

Figure 4.9 shows the mean reaction time of the participants for different stimuli.

As we can see from the figure, the average reaction times of the participants in the different sound conditions are still arranged in the order mentioned before. Except for individual participants, such as No.5 and No.8, all of them showed similar responses in the experiment as in the eye-hand response experiment. That is, the reaction speed performed in the eye-hand response experiment is the same as the reaction speed performed in the VR scenario. For example, subject No.2, in the eye-hand reaction experiment, the reaction time in the noise-reduced environment is 232 ms, 255 ms in the soothing music condition, and

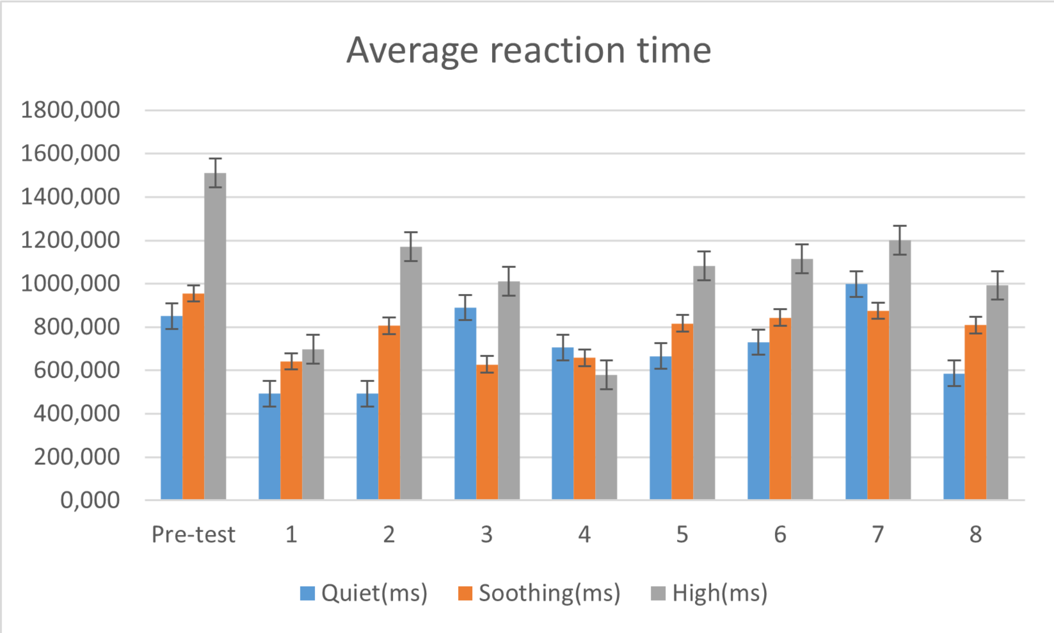

FIGURE 4.9: Average reaction time graph

284 ms in the high music environment, while his corresponding reaction times in the VR scene simulating the terrain are 492 ms, 806 ms, and 1171 ms, in that order.

4.3.2.6 Error rate analysis

In addition to the analysis under response times in the three different cases, the participants' response tolerance to the stimulus is also analyzed. Table 4.2 shows the data on the participants' error rate to the stimulus.

This table shows the actual situation of participants making incorrect judgments about the stimuli in the response experiment of the VR scene simulating the terrain. Lower values indicate higher correctness and more accurate responses to the stimuli. Whereas high values mean that participants miss more stimuli, higher values mean that they did not respond to more stimuli.

First of all, the most obvious column in the table is the column of inflation. The stimulus itself and the participants' insensitivity to it result in a much higher

Error Rate					
Number	Inflation	Deflation	Vibratio on	Vibration off	Average
Pre-test	18,18%	10,00%	None	None	14,09%
1	75,00%	14,29%	8,33%	8,33%	26,49%
2	42,86%	14,29%	0,00%	8,33%	16,37%
3	22,22%	0,00%	0,00%	33,33%	13,89%
4	60,00%	0,00%	0,00%	33,33%	23,33%
5	14,29%	0,00%	0,00%	0,00%	3,57%
6	37,50%	0,00%	0,00%	11,11%	12,15%
7	33,33%	0,00%	0,00%	0,00%	8,33%
8	25,00%	0,00%	0,00%	0,00%	6,25%
Average	36,49%	4,29%	1,04%	11,81%	13,83%

TABLE 4.2: Error rate data

error rate than the other stimuli. The error rate for participant No.1 is a staggering 75%, which meant that he barely felt the insole inflate. Secondly, the participants are extremely accurate in their response to deflation and the onset of vibration. About 75% or so of the participants did not miss in these two stimuli. This indicates that the participants are able to feel both stimuli clearly enough to make an accurate response. In contrast, for stopping the vibration, participants did not show a similar rate of correctness as for starting the vibration. This may be due to the fact that participants are more sensitive to the no-to-no stimulus and more sluggish to the no-to-no stimulus where the vibration disappeared.

Overall, the error rate of participants' responses to stimuli is mainly influenced by inflation and vibration disappearance. However, the mean of the error rates generally hover around 10%. Therefore, the response time of the inflatable stimulus can be appropriately reduced in the course of the subsequent discussion, focusing on the other three stimuli for a reasonable analysis.

4.3.3 Confidence analysis

As shown in the table 4.3, the last column shows the P-values of the participants' response time series in the eye-hand response test and in the terrain change test for the three sound conditions. Clearly all P-values are less than 0.05. We

Number	Eye-hand reaction			VR-Scene reaction			P-Value
	Quiet(ms)	Soothing(ms)	High(ms)	Quiet(ms)	Soothing(ms)	High(ms)	
Pre-test	256	274	295	850,000	954,861	1510,833	0,015567092
1	234	242	297	492,865	641,806	698,292	0,005373442
2	232	255	284	492,833	806,549	1171,208	0,044932677
3	238	258	250	889,944	627,514	1011,333	0,006341292
4	237	239	240	705,604	657,597	579,278	0,000374529
5	239	238	260	666,236	816,778	1082,750	0,007503493
6	265	291	264	730,083	843,333	1114,125	0,005515136
7	329	264	363	998,222	875,063	1200,778	0,002067193
8	241	257	288	586,000	809,417	991,778	0,010678179
Average	252,333	257,556	282,333	712,421	781,435	1040,042	0,004402208

TABLE 4.3: Reaction time and confidence under different sound conditions in two experiments

therefore consider the reaction times measured in both tests to be significantly different for each participant.

4.3.4 Correlation analysis

With all the previously mentioned data, we can calculate the correlation between the simple eye-hand reaction time and the reaction time to terrain changes under the same sound conditions, as shown in Figure 4.4.

Number	Eye-hand reaction			VR-Scene reaction			Relevance
	Quiet(ms)	Soothing(ms)	High(ms)	Quiet(ms)	Soothing(ms)	High(ms)	
Pre-test	256	274	295	850,000	954,861	1510,833	0,9457
1	234	242	297	492,865	641,806	698,292	0,7894
2	232	255	284	492,833	806,549	1171,208	0,9997
3	238	258	250	889,944	627,514	1011,333	-0,5792
4	237	239	240	705,604	657,597	579,278	-0,9468
5	239	238	260	666,236	816,778	1082,750	0,9190
6	265	291	264	730,083	843,333	1114,125	-0,2621
7	329	264	363	998,222	875,063	1200,778	0,9497
8	241	257	288	586,000	809,417	991,778	0,9712
Average	252,333	257,556	282,333	712,421	781,435	1040,042	0,9993

TABLE 4.4: Reaction time and correlation under different sound conditions in two experiments

The last column of the table shows the Pearson Correlation Coefficient(Cohen et al., 2009), which is calculated as follows(Adler and Parmryd, 2010).

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

We can note that for most of the experimental subjects, their correlations are above 0.9. This indicates that there is indeed a strong positive correlation between participants' simple responses and responses to topographic changes in the three different sound conditions. In other words, the different sound conditions equally affect the participants' reaction speed in the simple response experiment and in the topographic change response experiment. Chapter 1.2.5 mentions that distraction is a factor affecting human reaction time, which is reflected in the fact that different sound conditions affected the participants' results in the simple response experiment. The higher the sound level, the greater the effect on the participants' responses, which also influenced the participants' responses in the topographic change response experiment. This is also consistent with hypotheses H1, H2 and H3 mentioned in chapter 4.1. That is, the different sound conditions affect the responses of participants in both experiments.

Some participants, such as No.3, No.4 and No.6, had negative correlation coefficients for their response times in both experiments. This indicates that the performance of these participants in the two experiments is hardly consistent. They show a different reaction speed in some of the response tests than the other participants. For example, participant No.3, his reaction time is shorter in the high music condition than in the soothing music condition in the eye-hand response. In the topographic change response test, his reaction speed is again slower in the quiet condition than in the soothing music condition, which made it difficult to see whether participant No.3's reaction speed is affected by sound as much as the other participants. The same is true for participant No.6. For participant No.4, the correlation coefficient is less than -0.9, which means that the effect of the sound condition is negatively correlated, probably due to individual differences.

4.3.5 Reaction time difference analysis

After subtracting the reaction times for the different sound conditions, we can obtain the difference in the reaction times of the participants for the different sound conditions(Figure 4.5). In both experiments, this gives an indication of whether the sound affects the participants to the same extent.

Number	Eye-hand reaction			VR-Scene reaction		
	S-Q(ms)	H-S(ms)	H-Q(ms)	S-Q(ms)	H-S(ms)	H-Q(ms)
Pre-test	18	21	39	104,861	555,972	660,833
1	8	55	63	148,940	56,486	205,426
2	23	29	52	313,715	364,660	678,375
3	20	-8	12	-262,431	383,819	121,389
4	2	1	3	-48,007	-78,319	-126,326
5	-1	22	21	150,542	265,972	416,514
6	26	-27	-1	113,250	270,792	384,042
7	-65	99	34	-123,160	325,715	202,556
8	16	31	47	223,417	182,361	405,778
Average	5,222	24,778	30,000	69,014	258,606	327,621

TABLE 4.5: Difference in response time for different sound conditions

By comparing the columns between the different experiments, we can see that the difference values in each column in the VR scenario experiment are much larger than the values in the corresponding columns in the eye-hand response experiment. This suggests that sound brings a greater effect on the haptic response of the participant's foot than the eye-hand response.The effect of sound is approximately ten times greater in the VR scene experiment than in the eye-hand response.

4.4 Qualitative Analysis

This section will address the information collected from the questionnaire, combined with some elements from the quantitative analysis.

1. Did you have fun, and are you entertained during the test?

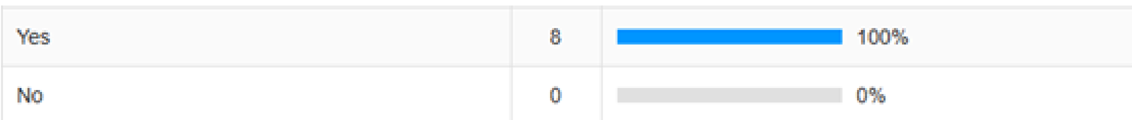

FIGURE 4.10: Answer for question 1

According to the figure 4.10, a total of 8 people participate in this question and 100% of them said that they found the experiment interesting and no one chose the "no" option. Therefore, it can be concluded that the experiment is highly evaluated by the participants and all of them found it interesting.

2. Which parts do you think are interesting?

网站测试反应速度 Reaction test on website	5	62.5%
VR场景 VR scene	6	75%
智能鞋垫 Smart insoles	2	25%
模拟地形反应测试 Simulated Terrain Response Test	4	50%
田 其它 [详细]	0	0%

FIGURE 4.11: Answer for question 2

According to the figure 4.11, this multiple choice question had 8 valid completions. Among all options, the VR scenario is the most popular, with 75% of valid completions choosing it. This is followed by the website test reaction speed and the simulated terrain reaction test, which receive 62.5% and 50% respectively. Smart insoles are the least popular, with only 25% of valid completions choosing them. Therefore, the VR scenario is the most interesting part of this question, and the website test response speed and simulated terrain response test also receive a lot of attention. This shows that the scenes simulated by VR in this experiment can attract participants and keep them entertained. The experiment is also not boring but full of fun, which help the experimenter to collect more accurate and effective data.

3. are you concerned about your reaction time?

Yes	6	75%
No	2	25%

FIGURE 4.12: Answer for question 3

According to the figure 4.12, the number of valid completions for this question is 8. Among them, 75% express they are concerned about their reaction time, while 25% express they are not concerned about their reaction time. It can be seen that most people are concerned about their reaction time. In general, people who are more concerned about their reaction time are able to adapt to various response tests, which means that they are able to provide more positive and valid data to the experimenter.

4. Did the VR device cause you some stress to the point that you are slow to react?

Yes	6	75%
No	2	25%

FIGURE 4.13: Answer for question 4

According to the figure 4.13, a total of 8 people effectively fill out this single-choice question. Seventy-five percent of them chose "No," indicating that the VR device did not slow down their reaction. On the other hand, 25% of the people choose "Yes", saying that the VR equipment cause them some pressure, resulting in slower response. It can be seen that most of the experimental subjects are quite confident in their own reactions. They believe that the VR equipment itself did not cause too much stress, but there are still a small number of people who feel that the discomfort of the headset has more or less affect their reaction speed.

5. Did the scenes in the VR field of view distract you?

Yes	4	50%
No	4	50%

FIGURE 4.14: Answer for question 5

According to the figure 4.14, a total of 8 people participate in this question, with 50% of them believing that the VR scenes distract them and the other 50% believing that they did not. Unlike the VR device itself, more participants felt that the game scenes are more able to hold their attention.

Participants are able to immerse themselves in the scenes, thus showing a slow response at a particular stimulus.

6. Do you think your reactions are the same under different sound conditions?

Yes	4	50%
No	4	50%

FIGURE 4.15: Answer for question 6

According to the figure 4.15, a total of eight people participate in this question, of which 50% believe that the response speed is the same under different sound conditions and the other 50% believe that the response speed is different under different sound conditions. However, due to the limitation of experimental time and money, there is a need to further set up more specific situations under different sound conditions, such as the effect of sound intensity, frequency and other factors on the reaction speed, in order to analyze the data more deeply.

7. Do you usually play sports that require fast reactions?

Yes	4	50%
No	4	50%

FIGURE 4.16: Answer for question 7

According to figure 4.16, a total of 8 people fill out this single choice question. Fifty percent of them said they regularly play sports that required reflexes, while the other 50 percent said they did not regularly play such sports. Nuri et al. (2013) note that people who regularly play sports that require reflexes tend to have faster reflexes, such as soccer players who have faster reflexes than the average person. Subjects who chose "Yes" to the question of which sports they play on a daily basis are given as figure 4.17.

The most popular sport among respondents is basketball, accounting for 75% of the total valid times. This is followed by Csgo, other sports and

basketball	3	75%
soccer	1	25%
badminton	0	0%
ping pong	0	0%
csgo	2	50%
valorant	0	0%
OW2	0	0%
Apex	0	0%
PUBG	0	0%
⊟ others [详细]	2	50%
音游	1	25%
FIFA	1	25%

FIGURE 4.17: Daily exercise in which the participant participates that requires a response

audio games, accounting for 50%, 50% and 25% of the total valid times. Soccer, FIFA, PUBG, OW2, Apex and table tennis and badminton are chosen by 0% of the respondents. Two respondents chose "other sports", and their choices are audio games and FIFA soccer. These traditional sports or e-sports can play the role of exercise reaction speed to varying degrees, which also cause some of the experimental subjects in all tests are faster than others.

4.5 Results and discussion

4.5.1 Answering hypothesis

We made six different hypotheses in order to answer the research questions.

Different sound conditions affect participants' eye-hand responses and also equally affect the response of participants to terrain changes. We are able to accept hypothesis H1 because the participants' response speed did change significantly across sound conditions in both responses.

Different sound conditions affect participants' responses to terrain changes more than eye-hand responses. We can accept hypothesis H2.The data analyse indicates that the different sound conditions affect all participants in both experiments and generally had a greater effect in the experiment with the terrain change response.

Different sound conditions affect participants' responses to terrain changes less than eye-hand responses. Although this assumption is the opposite of assumption H2, we can neither accept nor reject hypothesis H3. The effect of sound on reaction speed is inconsistent with individual difference, this does exist for some participants.

Different sound conditions did not affect participants' eye-hand responses, nor did they affect participants' responses to terrain changes. We reject hypothesis H4. The different sound conditions produce significant changes in reaction speed in both experiments for all participants.

The different sound conditions did not affect participants' eye-hand responses, but did affect participants' responses to terrain changes. We also reject hypothesis H5 for the same reason as the previous hypothesis.

The different sound conditions affect participants' eye-hand responses, but not their responses to terrain changes. We also reject hypothesis H6. Similar to the previous two hypotheses, the participants' reaction speed is affected in both experiments.

4.5.2 Conclusion

All the previous qualitative and quantitative analyses allow us to draw preliminary conclusions. Based on chapter 4.3.3, we believe that the data measured in the two sets of experiments, the eye-hand simple response experiment and the terrain change response experiment, are significantly different and that the confidence level for most of the data measured in the experiments is high. This is corroborated by the error rate analysis in chapter 4.3.2.6, where participants show low error rates for only some of the stimuli.

Secondly, based on the results of our study, we can respond to the research questions. For the question 1: *How much correlation exists between human eye-hand reaction time and haptic foot reaction time?* We can say that there is a strong correlation. Almost every participant's eye-hand reaction time and haptic foot reaction time change in the same way as the sound condition. The noisier the sound in the participant's ears, the slower the response they make. The analysis of reaction times in Chapter 4.3.1 and 4.3.2 for the different sound conditions gives support for the data.

In response to question 2: *To what extent do factors affecting the human eye-hand response influence the haptic foot response?* We can answer that, although this influence varies from individual to individual, our current findings and the experimental data in this project suggest that factors affecting the human eye-hand response bring about a greater influence on the haptic foot response. This is evidenced by the difference in response time between the different sound conditions in the chapter 4.3.5.

5 DISCUSSION

5.1 Key insights

1. *Simple reaction experiment*: In this project, we gave each participant a simple eye-hand reaction test through the humanbench website (https://humanbenchmark.com). The environment and hardware in this test are identical, and it is reasonable to use this result as a reference for each participant's reaction speed.

2. *VR scene*: In order to make the participants not affected by visual interference, we built a VR virtual scene to solve this point well. All participants are in the same scene, which help us to get more objective data.

3. *Meta Quest Pro*: The VR headset we used is Meta Quest Pro. As the most advanced headset all-in-one on the market, it is able to simulate realistic VR scenes. As well as its excellent range, it is able to cover the entire experiment time.

4. *Smart Insoles*: The smart insoles used in this project are provide by my mentor, Marco Gabrecht. It is capable of simulating up to five types of terrain. We simulate the change of terrain by inflating and deflating the insoles and vibrating the motors to send stimuli to the participants.

5. *Participant feedback*: Participants give feedback in the experiment using a clenched fist to let the experimenter know that they felt a change in the terrain. This is a more visual representation of what they are trying to say than the experimental design of having participants lift their arms or lift their feet.

6. *Data collection*: The experimental data are derived by analyzing the video frame by frame at a later stage. This observe experimental data can well reflect the real responses of the participants.

5.2 Limitations and future directions

In view of the time and financial constraints, the experimental methodology of this study has many shortcomings. There is room for improvement in terms of participant selection, experimental tool's, experimental design, and data analysis.

5.2.1 Sample

Since this research project is conducted at the University of Applied Sciences in Lübeck, Germany, the selection of participants is limited to residents of the local community and is not effectively representative of human performance as a whole. In addition, the small sample size and possible geographic differences may have skewed the results of this project. If we want to obtain objective and valid data, we need a large sample size and a representative sample of participants from different occupations, age groups, and interests from all over the world to conduct the experiment.

5.2.2 Hardware

Camera: Due to financial constraints, the tools used in this research project are generic and not very specialized in nature. The iPhone 12pro, for example, is only capable of capturing 4k, 60fps video. The minimum unit of data captured in the experiments of this project is 16.667 ms due to the limitation of frame rate. although this has been able to meet the basic requirements of the undergraduate bachelor thesis, if better equipment can be used to increase the frame rate of the video to 120 or higher per second, then smaller calculation units will be obtained to further improve the accuracy of the video.

Smart insoles: The smart insoles used in this research project are limited in the amount and realism of the terrain they can simulate, so the realistic devices can greatly improve the accuracy of this project. In future studies, better feedback from participants would be obtained if the changes in topography could be made more realistic. The more realistic the simulated terrain is, the better the study of human tactile responses will be.

VR scenes: The use of VR-HMD only shows the tip of the iceberg of its many powerful features, if we can create more realistic scenes will greatly enhance the user experience. The construction of more realistic scenes requires computers with powerful computing power for hardware support. It also requires more manpower and resources to build a simulation scene.

5.2.3 Experimental design

Eye-hand reaction test: The eye-hand response of the participants in this project is only the simplest test using the website, and the number of tests is only the most basic requirement. If a systematic study is to be conducted, the reaction speed of each participant needs to be examined in detail. This may be a challenge as human reaction speed is affected by many factors.

Simulation of terrain change response experiments in VR scenarios: Owing to time constraints, the experimental steps in this project are abbreviated. Nevertheless, it still took a long time to complete the test for each participant. If we had more time, we would have been able to design more different scenarios and variables, and the resulting data would have been larger, which would have further improve the objectivity of the experiment and the accuracy of the data. Conducting more realistic and detailed experiments is a huge challenge for experimenters, whether in terms of money, people or time.

5.2.4 Data collection

Quantitative data: The quantitative data in this project is derived from manual analysis of the video taken during the experiment. This is to some extent subject to error due to manual work. A more intelligent approach could have been used when collecting the data from the experiment, for example by having participants hold a button in their hands that they press to indicate that they feel a change in the terrain. We have envisaged this approach, but it is a difficult task to align the timeline of the button with the panel giving the command.

Qualitative data: The qualitative data in this project are derived from questionnaires completed by participants after the completion of the experiment. Because of the simplicity of the design process of the experiment itself, each participant had a limited amount of time to experience it and is not able to explore it freely. The feedback from the user experience is therefore also limited. In a larger scale experiment that allows each participant to fully experience virtual reality and simulated terrain, this would allow for better quality feedback.

6
CONCLUSION AND OUTLOOK

This thesis aims to investigate the speed of human response towards changes in terrain. This study validates and extends the findings of other researchers on human reaction speed. We found that human eye-hand and haptic response of foot responses are correlated and are influenced by external factors in approximately the same way.

6.1 Conclusion

In this paper, we made a study of human reaction speed. We focused on the factors that affect participants' eye-hand reaction times and haptic foot reaction times to changes in terrain, and how sound, can affect both responses. This led to a series of studies centered on this topic, exploring how human reaction times to stimuli can be affected. We conducted an experiment to collect the required data and invited eight participants. It is confirmed that our conjecture of a simple eye-hand response is almost consistent with previous studies. The effect is greater with noisier environments. This finding also holds true for human responses to topographic changes. Overall, the participants' responses are influenced by the sound conditions in both tests. We conclude with this preliminary conclusion and a vision for the future, which we hope will contribute to the study of human haptic response speed.

6.2 Outlook

Based on the findings of this project, more new research could be carried out. For example

- The design of foot control pedals.
- The use of VR technology to recreate realistic scenarios.
- Research on the integration of VR running movements.
- Feedback for VR physical games.
- Determination of accidental release of pedals by the driver during driving of the vehicle.

A APPENDIX

The appendix contains the data for all participants.

A.1 Pre-test data

Number	Type	Sound	Start	Respond	Reaction	RT/ms
1	Inflation	Quiet	889	N		None
2	Deflation	Quiet	1620	N		None
3	Inflation	Quiet	2283	N		None
4	Deflation	Quiet	3169	Y	3246	1283
5	Inflation	Quiet	4132	Y	4186	900
6	Deflation	Quiet	4970	Y	5017	783
7	Inflation	Quiet	5781	Y	5807	433
8	Deflation	Soothing	6389	Y	6456	1117
9	Inflation	Soothing	7289	Y	7319	500
10	Deflation	Soothing	7975	Y	8034	983
11	Inflation	Soothing	8454	Y	8511	950
12	Deflation	Soothing	9054	Y	9147	1550
13	Inflation	Soothing	9820	Y	9872	867

14	Deflation	Soothing	10459	Y	10513	900
15	Inflation	High	11162	Y	11201	650
16	Deflation	High	11686	Y	11824	2300
17	Inflation	High	12250	Y	12320	1167
18	Deflation	High	12898	Y	12992	1567
19	Inflation	High	13359	Y	13404	750
20	Deflation	High	13919	Y	14015	1600
21	Inflation	High	14398	Y	14429	517
22	Deflation	High	14892	Y	15094	3367
23	Inflation	High	15393	Y	15452	983
24	Vibration on	Quiet	6435	Y	6469	147
25	Vibration off	Quiet	6660	Y	6710	251
26	Vibration on	Quiet	7010	Y	7067	91
27	Vibration off	Quiet	7241	N		
28	Inflation	Quiet	7656	N		
29	Deflation	Quiet	7958	Y	8014	361
30	Vibration on	Quiet	8208	Y	8246	257
31	Vibration off	Quiet	8430	Y	8464	81
32	Inflation	High	10502	Y	10594	667
33	Deflation	High	10860	Y	10939	294
34	Vibration on	High	11095	Y	11142	81
35	Vibration off	High	11316	Y	11363	240
36	Vibration on	High	11560	Y	11601	71
37	Vibration off	High	11874	Y	11950	72
38	Inflation	High	12444	N		
39	Deflation	High	12786	Y	12974	2256
40	Vibration on	High	13120	Y	13187	310
41	Vibration off	High	13548	Y	13597	236
42	Vibration on	High	13795	Y	13845	231
43	Vibration off	High	14234	Y	14279	206

A.2 Data for participant No.1

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Inflation	Quiet	793	N			0
2	Deflation	Quiet	2461	Y	2587	837	1263
3	Inflation	Quiet	2992	Y	3101	995	822
4	Inflation	Quiet	3789	N			0
5	Deflation	Quiet	5520	N			0
6	Vibration on	Quiet	5827	N			0
7	Vibration off	Quiet	6033	Y	6154	1375	642
8	Vibration on	Quiet	6142	Y	6315	1546	1337
9	Vibration off	Quiet	6256	Y	6354	564	1069
10	Inflation	Soothing	364	Y	398	24	543
11	Deflation	Soothing	876	Y	937	23	994
12	Vibration on	Soothing	1223	Y	1292	150	1000
13	Vibration off	Soothing	1489	Y	1582	213	1337
14	Vibration on	Soothing	2076	Y	2248	2113	754
15	Vibration off	Soothing	2435	Y	2504	227	923
16	Inflation	Soothing	2695	N			0
17	Deflation	Soothing	3132	Y	3369	3075	875
18	Vibration on	Soothing	3733	Y	3758	171	246
19	Vibration off	Soothing	3919	Y	3979	198	802
20	Vibration on	Soothing	5247	Y	5292	144	606
21	Vibration off	Soothing	5505	Y	5530	12	405
22	Inflation	Soothing	5769	N			0
23	Deflation	Soothing	6124	Y	6177	147	736
24	Vibration on	Quiet	6435	Y	6469	147	420
25	Vibration off	Quiet	6660	Y	6710	251	582
26	Vibration on	Quiet	7010	Y	7067	91	859
27	Vibration off	Quiet	7241	N			0
28	Inflation	Quiet	7656	N			0
29	Deflation	Quiet	7958	Y	8014	361	572
30	Vibration on	Quiet	8208	Y	8246	257	376
31	Vibration off	Quiet	8430	Y	8464	81	486

32	Inflation	High	10502	Y	10594	667	866
33	Deflation	High	10860	Y	10939	294	1023
34	Vibration on	High	11095	Y	11142	81	702
35	Vibration off	High	11316	Y	11363	240	543
36	Vibration on	High	11560	Y	11601	71	612
37	Vibration off	High	11874	Y	11950	72	1195
38	Inflation	High	12444	N			0
39	Deflation	High	12786	Y	12974	2256	877
40	Vibration on	High	13120	Y	13187	310	807
41	Vibration off	High	13548	Y	13597	236	581
42	Vibration on	High	13795	Y	13845	231	602
43	Vibration off	High	14234	Y	14279	206	544

A.3 Data for participant No.2

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Vibration on	Quiet	4186	Y	4212	98	335
2	Inflation	Quiet	4622	Y	4675	234	649
3	Deflation	Quiet	5056	Y	5134	486	814
4	Vibration off	Quiet	6993	Y	7056	565	485
5	Vibration on	Quiet	7454	Y	7520	464	636
6	Vibration off	Quiet	7933	Y	8216	3989	728
7	Inflation	Quiet	8439	Y	8523	1017	383
8	Deflation	Quiet	8621	Y	8693	256	944
9	Vibration on	Quiet	8841	Y	8901	562	438
10	Vibration off	Quiet	9206	Y	9259	371	512
11	Vibration on	Quiet	9814	Y	9912	1079	554
12	Vibration off	Quiet	10178	Y	10253	813	437
13	Vibration on	Quiet	10438	Y	10499	416	601
14	Inflation	Quiet	11129	N			0
15	Deflation	Quiet	11652	N			0
16	Vibration off	Quiet	12139	Y	12202	517	533

17	Vibration on	Quiet	12405	Y	12483	851	449
18	Vibration on	Soothing	19521	Y	19569	190	610
19	Vibration off	Soothing	19833	Y	19883	155	678
20	Inflation	Soothing	20276	N			0
21	Deflation	Soothing	20652	Y	20759	153	1630
22	Vibration on	Soothing	21079	Y	21130	111	739
23	Vibration off	Soothing	21360	Y	21418	126	841
24	Vibration on	Soothing	21637	Y	21712	126	1124
25	Vibration off	Soothing	21907	N			0
26	Vibration on	Soothing	22398	Y	22457	90	893
27	Vibration off	Soothing	22707	Y	22794	307	1143
28	Inflation	Soothing	23017	Y	23076	133	850
29	Deflation	Soothing	23099	Y	23145	20	747
30	Inflation	Soothing	23249	Y	23320	210	973
31	Deflation	Soothing	23560	Y	23645	460	957
32	Inflation	High	26143	Y	26252	362	1455
33	Deflation	High	26742	Y	26823	83	1267
34	Vibration on	High	27019	Y	27060	62	621
35	Vibration off	High	27249	Y	27303	261	639
36	Vibration on	High	27540	Y	27595	126	791
37	Vibration off	High	28026	Y	28096	243	924
38	Vibration on	High	28285	Y	28515	209	3624
39	Vibration off	High	28961	Y	29033	268	932
40	Inflation	High	29237	N			0
41	Deflation	High	29609	Y	29685	257	1010
42	Vibration on	High	29867	Y	29926	213	770
43	Vibration off	High	30118	Y	30198	265	1068

A.4 Data for participant No.3

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Inflation	Quiet	219	Y	366	30	2420

2	Deflation	Quiet	659	Y	771	167	1700
3	Vibration on	Quiet	961	Y	1024	283	767
4	Vibration off	Quiet	1305	Y	1349	261	472
5	Vibration on	Quiet	1521	Y	1578	346	604
6	Vibration off	Quiet	1759	N			0
7	Inflation	Quiet	1985	Y	2052	289	828
8	Deflation	Quiet	2283	Y	2382	162	1488
9	Vibration on	Quiet	2578	Y	2629	174	676
10	Vibration off	Quiet	2797	N			0
11	Inflation	Quiet	3116	Y	3173	82	868
12	Deflation	Quiet	3347	Y	3411	210	857
13	Vibration on	Soothing	5326	Y	5368	213	487
14	Vibration off	Soothing	5733	Y	5809	264	1003
15	Inflation	Soothing	5964	Y	6043	142	1175
16	Deflation	Soothing	6210	Y	6266	147	786
17	Vibration on	Soothing	6582	Y	6632	321	512
18	Vibration off	Soothing	6783	Y	6811	23	444
19	Vibration on	Soothing	7085	Y	7139	310	590
20	Vibration off	Soothing	7331	Y	7403	516	684
21	Vibration on	Soothing	7882	Y	7938	243	690
22	Vibration off	Soothing	8179	N			0
23	Inflation	Soothing	8672	N			0
24	Deflation	Soothing	8994	Y	9050	110	823
25	Inflation	Soothing	9354	N			0
26	Deflation	Soothing	9613	Y	9726	445	1438
27	Vibration on	High	9854	Y	9921	113	1004
28	Vibration off	High	9996	Y	10064	63	1070
29	Vibration on	High	10112	Y	10176	240	827
30	Vibration off	High	10129	Y	10194	106	977
31	Inflation	High	10145	Y	10198	97	786
32	Deflation	High	10245	Y	10321	43	1224
33	Vibration on	High	10427	Y	10503	132	1135
34	Vibration off	High	10645	Y	10716	128	1055

35	Inflation	High	10856	Y	10953	210	1407
36	Deflation	High	11210	Y	11276	119	981
37	Inflation	High	11332	Y	11396	57	1010
38	Deflation	High	11475	Y	11576	430	1253
39	Inflation	High	11712	Y	11786	265	968
40	Deflation	High	11932	Y	12031	530	1120

A.5 Data for participant No.4

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Vibration on	Quiet	215	Y	297	130	1237
2	Vibration off	Quiet	1232	Y	1294	290	743
3	Vibration on	Quiet	1927	Y	2003	564	703
4	Vibration off	Quiet	2036	Y	2064	120	347
5	Inflation	Quiet	2340	Y	2413	109	1108
6	Deflation	Quiet	3022	Y	3128	1280	487
7	Vibration on	Quiet	3866	Y	3929	280	770
8	Vibration off	Quiet	4137	N			0
9	Vibration on	Quiet	4652	Y	4707	236	681
10	Vibration off	Quiet	4888	Y	4929	251	432
11	Inflation	Soothing	6846	Y	6914	79	1054
12	Deflation	Soothing	7171	Y	7214	26	691
13	Vibration on	Soothing	7441	Y	7524	332	1051
14	Vibration off	Soothing	7676	N			0
15	Vibration on	Soothing	7897	Y	7961	263	804
16	Vibration off	Soothing	8129	Y	8168	132	518
17	Inflation	Soothing	8533	N			0
18	Deflation	Soothing	8884	Y	8952	186	947
19	Vibration on	Soothing	9103	Y	9157	156	744
20	Vibration off	Soothing	9343	Y	9398	181	736
21	Inflation	High	10901	N			0
22	Deflation	High	11367	Y	11453	172	1261

23	Vibration on	High	11636	Y	11682	143	624
24	Vibration off	High	11888	Y	11924	71	529
25	Inflation	High	12086	Y	12163	84	1199
26	Deflation	High	12409	Y	12604	2312	938
27	Vibration on	High	12965	Y	13012	164	619
28	Vibration off	High	13172	N			0
29	Inflation	High	13407	N			0
30	Deflation	High	13731	Y	13780	100	717
31	Vibration on	High	13980	Y	14034	233	667
32	Vibration off	High	14226	Y	14293	80	1037

A.6 Data for participant No.5

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Vibration on	Quiet	234	Y	268	130	437
2	Vibration off	Quiet	622	Y	654	144	389
3	Inflation	Quiet	1081	Y	1155	107	1126
4	Deflation	Quiet	1352	Y	1396	103	630
5	Vibration on	Quiet	1539	Y	1573	193	374
6	Vibration off	Quiet	1738	Y	1771	62	488
7	Inflation	Quiet	1988	Y	2046	203	764
8	Deflation	Quiet	2229	Y	2298	76	1074
9	Vibration on	Quiet	2487	Y	2530	301	416
10	Vibration off	Quiet	2832	Y	2865	50	500
11	Inflation	Soothing	4606	N			0
12	Deflation	Soothing	4862	Y	4925	202	848
13	Vibration on	Soothing	5102	Y	5155	200	683
14	Vibration off	Soothing	5326	Y	5373	280	503
15	Vibration on	Soothing	5567	Y	5625	305	662
16	Vibration off	Soothing	5760	Y	5822	331	702
17	Inflation	Soothing	6002	Y	6100	203	1430
18	Deflation	Soothing	6683	Y	6740	202	748

19	Inflation	Soothing	6920	Y	6977	261	689
20	Deflation	Soothing	7140	Y	7282	183	2184
21	Vibration on	Soothing	7378	Y	7424	229	538
22	Vibration off	Soothing	7605	Y	7662	136	814
23	Inflation	High	8719	Y	8799	243	1090
24	Deflation	High	8957	Y	9016	246	737
25	Vibration on	High	9350	Y	9399	113	704
26	Vibration off	High	9560	Y	9708	242	2225
27	Vibration on	High	9785	Y	9834	113	704
28	Vibration off	High	10006	Y	10054	101	699
29	Inflation	High	10287	Y	10351	162	905
30	Deflation	High	10519	Y	10593	193	1040
31	Inflation	High	10830	Y	10888	166	801
32	Deflation	High	11009	Y	11079	176	991

A.7 Data for participant No.6

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Inflation	Quiet	216	N			0
2	Deflation	Quiet	505	Y	559	231	669
3	Vibration on	Quiet	786	Y	858	146	1054
4	Vibration off	Quiet	1015	Y	1060	56	694
5	Inflation	Quiet	1219	Y	1333	995	905
6	Deflation	Quiet	1908	Y	1988	569	764
7	Vibration on	Quiet	2167	Y	2229	266	767
8	Vibration off	Quiet	2443	Y	2496	72	811
9	Vibration on	Quiet	2629	Y	2680	73	777
10	Vibration off	Quiet	2833	Y	2889	254	679
11	Inflation	Quiet	3176	Y	3269	498	1052
12	Deflation	Quiet	3509	Y	3549	79	588
13	Inflation	Soothing	5807	Y	5874	179	938
14	Deflation	Soothing	6124	Y	6181	31	919

15	Vibration on	Soothing	6381	Y	6438	142	808
16	Vibration off	Soothing	6590	N			0
17	Vibration on	Soothing	6857	Y	6930	130	1087
18	Vibration off	Soothing	7094	Y	7168	203	1030
19	Inflation	Soothing	7313	Y	7409	269	1331
20	Deflation	Soothing	7568	Y	7645	403	880
21	Inflation	Soothing	7856	N			0
22	Deflation	Soothing	8081	Y	8169	310	1157
23	Vibration on	Soothing	8282	Y	8423	1270	1080
24	Vibration off	Soothing	8487	Y	8555	243	890
25	Vibration on	High	9899	Y	9982	232	1151
26	Vibration off	High	10118	Y	10196	193	1107
27	Inflation	High	10388	N			0
28	Deflation	High	10656	Y	10726	188	979
29	Vibration on	High	10918	Y	10997	273	1044
30	Vibration off	High	11237	Y	11308	237	946
31	Vibration on	High	11465	Y	11564	113	1537
32	Vibration off	High	11691	Y	11769	119	1181
33	Inflation	High	11968	Y	12053	120	1297
34	Deflation	High	12226	Y	12294	121	1012
35	Inflation	High	12494	Y	12568	120	1113
36	Deflation	High	12973	Y	13078	225	1525
37	Vibration on	High	13382	Y	13451	236	914
38	Vibration off	High	13651	Y	13724	184	1033

A.8 Data for participant No.7

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Vibration on	Quiet	486	Y	655	177	2640
2	Vibration off	Quiet	1134	Y	1175	132	551
3	Vibration on	Quiet	1581	Y	1641	403	597
4	Vibration off	Quiet	1888	Y	1959	609	574

5	Inflation	Quiet	2129	Y	2226	665	952
6	Deflation	Quiet	2371	Y	2441	268	899
7	Inflation	Quiet	2720	Y	2797	391	892
8	Deflation	Quiet	3236	Y	3369	1146	1071
9	Vibration on	Quiet	3601	Y	3888	3785	998
10	Vibration off	Quiet	4168	Y	4402	3002	898
11	Inflation	Soothing	4451	Y	4512	103	914
12	Deflation	Soothing	4533	Y	4603	67	1100
13	Vibration on	Soothing	4713	Y	4789	75	1192
14	Vibration off	Soothing	4864	Y	4943	206	1111
15	Vibration on	Soothing	5032	Y	5087	97	820
16	Vibration off	Soothing	5198	Y	5307	576	1241
17	Inflation	Soothing	5416	N			0
18	Deflation	Soothing	5571	Y	5643	334	866
19	Vibration on	Soothing	5746	Y	5824	356	944
20	Vibration off	Soothing	5913	Y	5971	58	909
21	Vibration on	Soothing	6155	Y	6214	47	936
22	Vibration off	Soothing	6345	Y	6427	276	1091
23	Inflation	High	7167	N			0
24	Deflation	High	7212	Y	7297	103	1314
25	Vibration on	High	7411	Y	7489	117	1183
26	Vibration off	High	7532	Y	7597	49	1034
27	Vibration on	High	7691	Y	7813	541	1492
28	Vibration off	High	7948	Y	8103	744	1839
29	Inflation	High	8449	Y	8506	104	846
30	Deflation	High	8751	Y	8814	124	926
31	Inflation	High	8974	Y	9078	668	1065
32	Deflation	High	9207	Y	9294	487	963
33	Vibration on	High	9436	Y	9507	245	938
34	Vibration off	High	9674	Y	9742	416	717

A.9 Data for participant No.8

Number	Type	Sound	Start	Respond	Reaction	Error/ms	RT/ms
1	Inflation	Quiet	794	Y	865	197	986
2	Deflation	Quiet	887	Y	926	138	512
3	Vibration on	Quiet	979	Y	1026	300	483
4	Vibration off	Quiet	1104	Y	1154	359	474
5	Vibration on	Quiet	1257	Y	1375	1389	578
6	Vibration off	Quiet	1476	Y	1588	1020	847
7	Inflation	Quiet	1684	N			0
8	Deflation	Quiet	1798	Y	1875	872	411
9	Vibration on	Quiet	1995	Y	2054	481	502
10	Vibration off	Quiet	2148	Y	2218	526	641
11	Inflation	Quiet	2315	Y	2374	487	496
12	Deflation	Quiet	2414	Y	2457	74	643
13	Vibration on	Quiet	2667	Y	2716	377	440
14	Vibration off	Quiet	2824	Y	2867	35	682
15	Inflation	Quiet	2976	Y	3065	419	1064
16	Deflation	Quiet	3256	Y	3305	200	617
17	Vibration on	Soothing	4107	Y	4184	442	841
18	Vibration off	Soothing	4336	Y	4402	191	909
19	Inflation	Soothing	4581	Y	4651	131	1036
20	Deflation	Soothing	4713	Y	4766	306	577
21	Vibration on	Soothing	4969	Y	5032	472	578
22	Vibration off	Soothing	5113	Y	5174	404	613
23	Vibration on	Soothing	5226	Y	5274	38	762
24	Vibration off	Soothing	5831	Y	5893	414	619
25	Inflation	Soothing	6003	Y	6064	285	732
26	Deflation	Soothing	6108	Y	6165	62	888
27	Inflation	Soothing	6288	Y	6392	333	1400
28	Deflation	Soothing	6586	Y	6634	96	704
29	Vibration on	Soothing	6839	Y	6897	214	753
30	Vibration off	Soothing	7001	Y	7056	157	760
31	Inflation	High	8965	N			0

32	Deflation	High	9146	Y	9218	308	892
33	Vibration on	High	9369	Y	9441	232	968
34	Vibration off	High	9513	Y	9584	16	1167
35	Vibration on	High	9668	Y	9733	190	893
36	Vibration off	High	9863	Y	9947	468	932
37	Inflation	High	10036	Y	10238	1713	1654
38	Deflation	High	10335	Y	10457	718	1315
39	Vibration on	High	10578	Y	10683	651	1099
40	Vibration off	High	10772	Y	10832	109	891

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