BSc Thesis Creative Technology

Designing a VR application as cross-modal extension of the Cutaneous rabbit effect.

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Abstract

Objective The goal of this thesis is to investigate whether synchronized visual input can influence the perception of the CRE, specifically in a VR context.

Methods First, background research was conducted to identify key factors influencing tactile illusions and cross-modal perception. A prototype combining visual and vibrotactile stimuli was developed, including a vibrotactile sleeve synchronized with VR visuals through audio signals. User experiments were conducted to assess how visual input affected the perception of the CRE across six different timing intervals, with participants rating synchronization, illusion perception, and visual appeal. A pilot test refined the prototype and testing procedure.

Results The results suggest that the perception of the CRE can be influenced by visual stimuli. At slower timing intervals of the CRE the addition of a visual seems to enhance perception, at faster speeds, the visual disrupts the illusion. Participants preferred appealing visuals, although improvements to the arm visualization were recommended for enhanced realism.

Conclusion This research shows that visual input could influence the timing and perception of the CRE in VR. To improve on this research, future work should refine visual-tactile synchronization and explore other types of tactile feedback, as well as further analyze the relationship between timing and perception thresholds.

Keywords: CRE, Tactile illusions, Cross modal effects, Crows

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1 Introduction

There is a limited understanding of how the brain processes different sensory signals. Studying cross-modal effects can help in trying to understand these processes. Understanding these processes can improve the immersive quality of virtual reality (VR) and augmented reality (AR) technologies. Immersion increases the realism in VR, engagement is important in VR applications like virtual training, and therapeutic interventions [1]. One way to improve engagement in VR is to use perceptual illusions

This project focus will be on the cutaneous rabbit effect (CRE) within a VR context and its emotional aspects. The CRE is a tactile illusion, a type of perceptual illusion, that occurs when a person's experience of a tactile action is at odds with reality [2]. The CRE is an example of a cutaneous haptic illusion [3]. The illusion occurs when 2 or 3 points on a less sensitive area of the body (in this case the forearm) are stimulated. The effect is that these stimuli are felt not only on the actual points of stimulation but also in areas in between these points. This sensation can be described as a rabbit hopping across the forearm [1]. This research combines the CRE with a visual element in VR, to create a cross-modal effect. Cross-modal perception means perceiving information by combining multiple different senses [4].

The CRE is a useful illusion to explore because it requires only a few motors to generate a smooth, continuous sensation. An advantage is that it uses minimal motors, so it is inexpensive and relatively easy to implement, making it accessible for integration into existing systems. Specific applications could include insect phobia therapy. For instance, the final step in spider phobia therapy is typically for participants to hold a spider in their hand. By getting accustomed to the sensation of a spider crawling on their arm in VR, participants may feel more comfortable completing the therapy. Additionally, the CRE could be applied to stress reduction, as touch has been shown to influence stress levels.

In the previous research, findings suggested that tactile stimulation in VR can alter emotional responses to different stimuli [1]. Further recommendations were to improve the positioning and timing of the animation [1].

1.1 Research Questions

The goal of this project is to discover if VR visuals can affect the tactile perception of the CRE. To answer this question, literature on this topic is explored with the guidance of the following questions. These questions are used to gain more knowledge about the topics and define some key concepts

RQ1 What is the cutaneous rabbit effect?

RQ1.1 What is a tactile illusion?

This question provides the broader context for understanding the phenomenon of tactile illusions, of which the cutaneous rabbit effect (CRE) is a specific example.

RQ1.2 How is the CRE perceived?

This question focuses on the perception of the cutaneous rabbit effect. How the effect is induced and how it is experienced.

RQ1.3 What are cross-modal effects in perception?

This question explores how sensory systems interact, particularly how multisensory integration may influence tactile perception.

RQ1.4 What are the technical challenges in the design of a cross-modal illusion?

This question examines the technical challenges in designing experiments to create and study cross-modal illusions like the CRE.

the second research question is used in the development of the prototype. These questions are related to the creation of the 3D models, requirements, and how to evaluate the prototype.

RQ2 Can visual input influence the timing requirements for perceiving the cutaneous rabbit effect?

RQ2.1 What are the requirements for the visual input?

RQ2.2 How to realize the multi-modal (haptic & visual) input and their synchronization?

RQ2.3 How to perform the user experiments?

2 Background Research

2.1 Science

2.1.1 Tactile Illusions

A tactile illusion is a type of perceptual illusion, that occurs when a person's experience of a tactile action is at odds with reality. According to McIntosh [2]. The effects of these illusions are consistent across people and over time. Additionally, it is suggested that the effects persist even when a person is aware that the perception is incorrect. Tactile illusions can be sorted into several categories [3, 5]. The taxonomy suggested by Lederman and Jones [5] (figure 1), splits tactile illusion into two groups one small branch that is about illusions of how an object is perceived. The other branch is Haptic space perception.

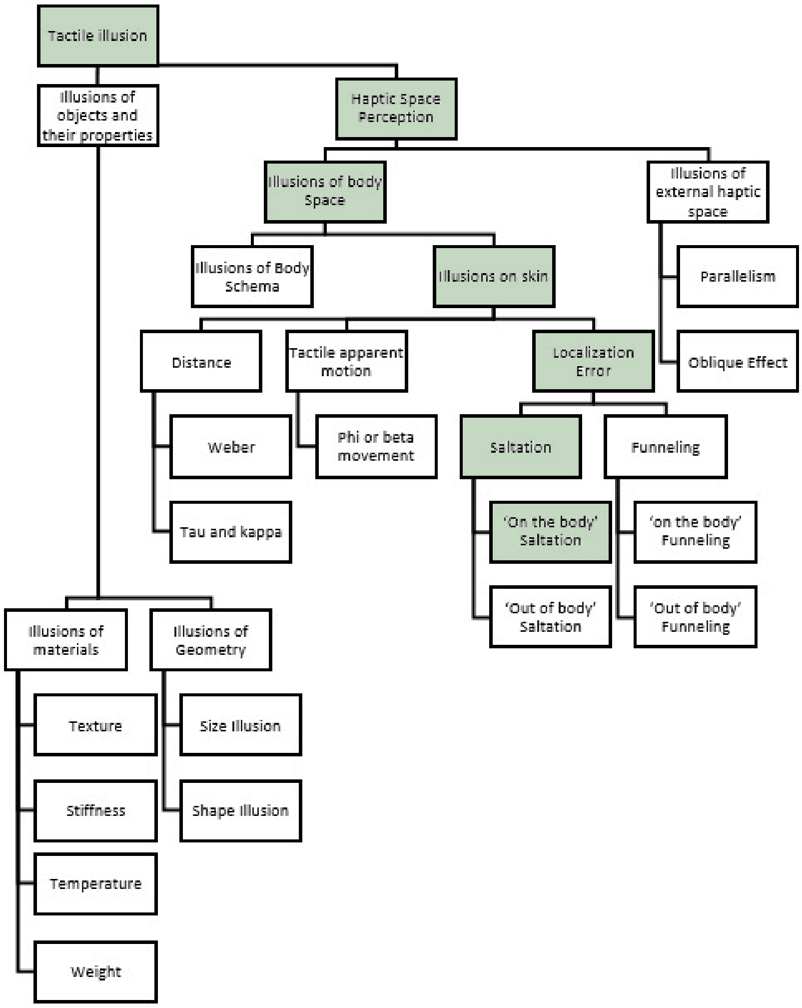

FIGURE 1: Tactile illusion taxonomy, proposed by Lederman and Jones

2.1.2 Cutaneous rabbit effect

In this project, the focus will be on the cutaneous rabbit effect (CRE). the CRE is an example of a cutaneous haptic illusion. According to the taxonomy proposed by [5] (figure 1), this illusion falls within the broader category of haptic space perception, which relates to how we perceive spatial information through touch. More specifically, it is classified under illusions on body space, which refers to distortions in our perception of where sensations occur on the body. Within this, it is further categorized under illusions on skin, specifically involving localization errors, where the sensation is felt at locations other than the actual points of stimulation. This leads to the phenomenon of saltation, with the illusion here being a specific type known as on-the-body saltation [3].

The illusion occurs when 2 or 3 points on a less sensitive area of the body(in this case the forearm) are stimulated. The effect is that these stimuli are felt not only on the actual points of stimulation but also in areas in between these points. This sensation can be described as a rabbit hopping across the forearm. The vibrations will be in bursts during 24 ms, with a 24-ms interval between bursts (IBI), this results in a total duration of 408 milliseconds [1].

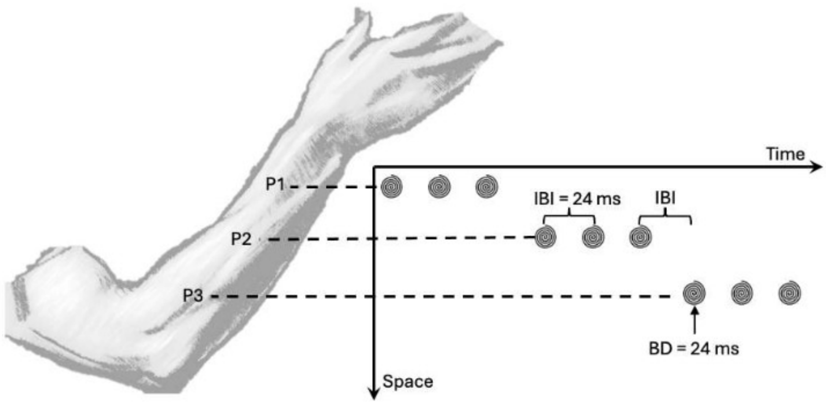

FIGURE 2: CRE explained, this variant consisting of three location points (P1, P2, P3), with each point receiving three vibrations with a duration of 24 ms, each vibration is separated by 24 ms, the inter-burst interval (IBI).

2.1.3 Cross-modal effects in perception

Cross-modal perception means perceiving information from combining multiple different senses [4]. People perceive the world with five senses: sight, hearing, smell, taste, and touch [6]. According to Lalanne and Lorenceau [6] most studies have pointed to the dominance of visual inputs over the other sensory signals. However, by combining the input from multiple senses the interpretation of the information is improved [4]. In the context of an illusion, instead of better understanding the sensory, the brain misinterprets the data.

2.1.4 Multisensory processing in the brain

There is limited understanding of how the brain processes the different sensory signals and combines them in a coherent perception [6]. According to [7], "Neurons in the superior colliculus (SC) are able to alter their sensitivity to external events". Various spatial, temporal, and inverse effectiveness principles of multi-sensory integration principles have been noticed. These can be an important predictive framework that helps to understand how stimulus characteristics shape multi sensory interactions in SC neurons [7]. These principles are not enough to completely explain all the multi sensory interactions in SC neurons. In the context of processing tactile stimuli, the brain is especially challenged when it needs to process stimuli applied to places with low receptor density. Processing stimuli in these places is even harder when they have a short duration. Some research suggests that the brain uses prior knowledge to enhance perceptual resolution beyond the restrictions of tactile receptor resolution. [8, 9]. This idea was explored in a Bayesian perceptual model that replicated the CRE, by assuming the brain expects tactile stimuli to move slowly [9]. The results of this study suggest indeed that the brain uses previous knowledge. Illusions can be used to hint at the brain's perceptual strategies. In certain illusions, a seemingly unrelated variable can influence perception. For example, in tactile illusions such as the CRE the perceived distance between 2 points of stimuli is not only dependent on the actual distance of the point but also the time between the stimuli [10].

2.1.5 Cross modal effects in VR context

This thesis will focus on visuo-tactile sensations in combination with VR. Combining cross-modal visuo-tactile sensations with VR can improve the user's experience. For instance, in a study by [11] a visuo-tactile VR system was created, that allows to the perceived hardness of virtual objects. To make visual and tactile effects function correctly the spatial and temporal should be consistent and well-timed [12].

2.1.6 What are the technical challenges in the design of a cross-modal illusion?

An important technical challenge in designing cross-modal illusion is the spatiotemporal consistency [12, 13]. The first aspect of spatiotemporal consistency, is the correct positioning of animations in VR/AR [14, 15]. Errors in tracking weaken the perception and experience of the user [15]. Tracking errors can be put into two categories. The first category is dynamic errors these are for instance measurement noise and jitter. The second category is "static errors such as spatial distortion, calibration errors, and stability errors such as slowly accumulated drift" [15]. According to Madsen & Rasmus Stenholt [15] there is not one best solution to localization error, and there is not yet enough knowledge to completely eliminate error.

The second aspect of spatiotemporal consistency is timing. In a multimodal system, differences between sensory stimuli need to be avoided. To achieve this, it is important to focus on "the synchronization of system components to minimize time-lagged movements due to different delays of the data streams" [16]. With some tactile illusions, the effect may be more apparent when it is demonstrated rapidly, however, sometimes concessions are necessary to ensure smooth integration with virtual reality (VR) systems. In these situations, the right balance between perceptual impact and technological constraints of VR should be determined [1].

- **Tracking System:** The system used to track the user's movements is a contributor to latency. Tracking cameras each have a delay, that is due to the capturing and transmission of the images. After this, the tracking software also contributes to latency by having to process the images and produce locational information [17].

- **Rendering:** generating the virtual environment contributes to latency. Multiple render techniques exist that each have different latency. Also limited rendering power of the hardware can add latency[18].
- **Display System:** The final stage of presenting the rendered images to the user also introduces latency [17].

Acceptable Delay or Latency From the literature different values for allowable delays arise. According to these, the allowable delay should be between 45ms an 150ms. To ensure that the cross-modal experience is realistic the delay between the different types of feedback cannot be too large. Because the delay cannot be eliminated completely, it is important to know what amount of delay is not noticeable or does not interfere with the experience [15]. One studies that the allowable maximum delay between visual stimulus and tactile stimulus is between 100-120 ms [19]. Another research did an experiment where the minimum delay at which participants judged the stimuli as asynchronous was on average 45 ms [20]. Another study conducted an experiment to test visual and haptic synchronization and the result showed that visual and haptic feedback was the most synchronized with latencies around 150 ms [21].

2.1.7 Types of haptic feedback

Vibration Feedback Vibrotactile feedback is created by vibrating actuators or motors in contact with the user's skin. Prbn imary application areas include navigation, motor learning, and event triggering, as depicted in Fig. 1-(b). When used in navigation applications, vibrotactile feedback can work as a sensory substitution, providing users directional cues to prevent injuries and accidents by sending alerts [22].

Electrotactile Feedback Electrotactile feedback delivers haptic sensations to the user's skin using electrodes placed on the surface of the skin [22]. enrich the virtual reality experience by employing Neuromuscular Electrical Stimulation (NMES) to create in the antagonists' muscles the haptic sensation of being loaded [23].

Force Feedback Force Feedback represents the resistance of obstacle. Thus, force feedback is crucial for needle placement tasks where the resistance of different tissue types when being penetrated needs to be perceived. Blunt dissection is another important surgical task where force feedback leads to lower error rates and reduced task completion times [Wagner et al., 2002]. Simulations and Virtual Reality (VR): Force feedback is critical in VR and simulator applications, such as flight simulators or surgical training, where users need to feel resistance or the weight of virtual objects to achieve a realistic experience [24].

Thermal Feedback Thermal feedback uses actuators that move heat around the skin. For example, thermal feedback has been employed as a nonvisual notification channel for situations poorly suited to either vibrotactile or audible feedback, because the environments were too bumpy or noisy [22].

2.2 Existing projects

2.2.1 Emotional Dimensions of the Cutaneous Rabbit Illusion in Virtual Reality: The Interplay of Visual and Tactile Stimuli - Ziat 2024

In this research by Ziat et al. [1], the emotional impact of a visuo-tactile CRE within virtual reality (VR) was investigated. This research displayed visuals on a Meta Quest Pro VR headset. The visuals used were a rabbit, kangaroo, spider, grasshopper, frog, flea, and sphere. The VR experience was manipulated by making the 3D models hop three times, consistent with the tactile stimuli, or nine times, to create a more distributed sensory illusion across the arm. the results of the experiments suggest that the type of animation or frequency of hopping influenced emotional responses.

This research stated that the burst duration interval is an important factor in how strongly the illusion is felt. Shorter intervals (12 ms) are effective but too rapid for synchronization in VR. It was decided to use a duration interval of 24 ms to balance perceptual impact and VR integration constraints.

The VR experience was created in Unity. To synchronize the visuo-tactile experience without too much latency, ASIO4ALL was used. This is a universal audio driver that has low latency and high- fidelity sound transmission. The motors were driven through an audio signal by designing a customized wave file.

Future research can be about integrating physiological measures, to provide a better understanding of the multi-modal interactions underlying emotional responses in virtual environments.

2.2.2 HaptoMapping - Miyatake 2021

In this research by Miyatake et al. [13] explains HaptoMapping, which is a projection-based visuo-haptic augmented reality (VHAR) system. The system can independently render visual and haptic content. Because the visual and haptic feedback are not linked, the system can project a smooth visual texture while providing a rough tactile sensation. Additionally, because projection are used and external tracking systems are not necessary, the system could achieve high spatiotemporal consistency For the project, it was important to know the latency to evaluate whether it was perceivable by users. It was discovered that in the developed haptic devices the visual-haptic unperceived latency was established at 500ms for arm-mounted devices.

2.2.3 Visuo-Haptic Illusion to Perceive and Manipulate Different Virtual Objects in Augmented Reality

This article [25] describes a new way to manipulate virtual objects in AR using visuo-haptic illusions. A dynamic finger-remapping approach is presented. With this approach, it is possible to create visuo-haptic illusions that dynamically adjust the virtual hand posture to fit different sizes and shapes of virtual objects in AR. In this study, a Microsoft HoloLens VR headset was used. The virtual experience was created in Unity. The CPU of the HoloLens was responsible for the remapping process. It is suggested that the CPU is fast enough to have low latency because the system had negligible low-latency tracking and visualization with around 40-millisecond delay.

2.2.4 An Immersive Visuo-Haptic VR Environment with Pseudo-haptic Effects on Perceived Stiffness - Matsumoto 2016

This article [11] describes a VR system that enables users to have a realistic stiffness perception of virtual objects. The system combines a VR headset with gloves that apply resistance when a person makes a grabbing motion. The resistance was created by adding piano strings to the gloves. So this means there is not real haptic feedback, the resistance is not dynamic. The perception of different levels of resistance is created by varying the animation of the user's virtual hand when a virtual object is grabbed. Because it pseudo haptic feedback there is no need to synchronize the visual feedback with haptic feedback. This eliminates the challenge of optimizing multiple systems for spatiotemporal consistency.

2.2.5 Physical Perception of a VR Handshake - Lenders 2022

This research focuses on developing a vibrotactile glove for a VR handshake. Several vibration patterns were investigated to find the most effective way to simulate a handshake in VR. Additionally, different placements of vibration motors on the hand were tested and assessed on user experience. The vibration motors are placed at the bottom of the hand and the purlicue-thumb interlock because these locations provided the most effective vibrotactile feedback. To access the 3D environment, the Vive Pro HMD was used. For the Vive the update frequency is 90Hz (90FPS). Additionally, Dexmo Gloves are used for hand tracking. For two sided communication between the glove and the Virtual environment a Feather was used this is a wireless Arduino. Next to this, a Vive tracker was used to track the user's hand in the virtual environment.

2.2.6 Spider phobia therapy

This research article [26] explores the efficacy of multiple context exposure (MCE) in reducing the renewal of fear after exposure therapy for spider phobia. In contrast to single context exposure (SCE), this paper hypothesized that exposing patients with spider phobia to a virtual spider in various contexts would result in a more widespread decrease in fear. Thirty participants were randomly assigned to either the MCE or SCE group for the study. Four virtual reality exposure sessions were conducted for both groups; however, the MCE group was exposed to the spider in four distinct virtual surroundings, whereas the SCE group was exposed in the same setting. Skin conductance levels, self-reported fear ratings, and an in-vivo behavior avoidance test (BAT) using a real spider were used to gauge participants' degrees of fear. The findings showed that MCE considerably reduced

2.2.7 The cutaneous rabbit illusion affects human primary sensory cortex somatotopically

This study [27] explores how the brain processes the cutaneous rabbit illusion. With the use of high-resolution fMRI, the researchers found that both real and illusory stimuli activated the primary somatosensory cortex (SI) at the corresponding location with the location of stimuli on the arm. The brain's response was just as strong for the illusion as for actual touch, showing that SI represents what is perceive and not only just the physical stimuli. This study provides clear evidence that illusory touch can shape brain activity in a highly organized way.

2.3 Conclusion

From these existing projects, a few key aspects can be observed. Proper synchronization is important for a cross modal illusion. Incorrect synchronization decreases the perception of the illusion. ASIO4ALL can be used to achieve low-latency and high-fidelity sound transmission, enabling precise synchronization between haptic motors and visuals. Additionally, [13] suggested that the latency between haptic visual and haptic feedback can be imperceptible up to 500ms for arm-mounted haptic devices. This means that systems can have a slight delay between visual and haptic feedback without users noticing.

An important factor is the duration of the CRE this affects how strongly the illusion is felt. It was decided that a duration interval of 24 ms was optimal to balance perceptual impact and VR integration constraints. Another factor is the placement of the vibration motors, this affects how effective the tactile feedback is.

3 Methods and Techniques

This chapter outlines the methods used to design, implement, and evaluate the visuo-tactile VR system. From the background knowledge it could be concluded that there is a limited understanding of how the brain processes stimuli. The second part of this thesis will focus on this topic. The main question is:

RQ 2 Can visual input influence the timing requirements for perceiving the cutaneous rabbit effect?

This research question focuses on the interaction between visual and haptic multimodal perception. In specific, whether a visual can affect the timing to perceive the cutaneous CRE. The question can be divided into several sub-questions to structure this research.

RQ 2.1 What are the requirements for the visual input?

To create a prototype for user testing, it is important to know what requirements the prototype should have. Because aspects like timing, intensity, and duration influence how the visual interacts with the tactile illusion (CRE).The requirements of the project will come from 2 categories. Requirements specified by stakeholders, and requirements that arise from the background research. This includes the literature review and overview of existing projects.

RQ 2.2 How to realize the multi-modal (haptic & visual) input and their synchronization?

To test whether visual input influences the timing of the CRE, the experiment must have synchronized haptic and visual stimuli. If the inputs are not properly aligned, the results could be affected by errors in timing instead of the multi-sensory effects. This sub-question aims to create the device to test how visual input affects the timing of the tactile illusion.

RQ 2.3 How to perform the user experiments?

User experiments are needed to collect data to answer the research question. This sub-RQ focuses on the design of the experiment for measuring perceptual changes in the timing of the CRE. An experiment procedure has to be developed additionally participants have to be recruited. Before the real user tests a pilot test will be done to verify everything works accordingly.

4 Realization

4.1 RQ 2.1 What are the requirements for the visual input?

First the requirements are developed, these are the guidelines of the necessary functionalities and characteristics of the prototype.

- **The vibrotactile sleeve is able to produce the CRE.**

  If the sleeve cannot reliably produce this tactile illusion, the experiment's primary objective—testing the influence of visual input on the timing of the CRE—cannot be achieved.

- **The visual must be synchronized with the vibrotactile sleeve.**

  Synchronizing ensures that the visual and tactile inputs align in terms of spatial and temporal characteristics, reinforcing the illusion. Incongruent stimuli may create conflicting sensory signals, potentially introducing confounding variables or weakening the CRE. Congruency allows for a controlled and interpretable study of the interaction between modalities.

- **The VR visual should look appealing.**

  Participants are more likely to focus and respond accurately in experiments when the stimuli are not visually distracting or unpleasant. This is particularly crucial for experiments requiring precise timing and attention.

- **The speed of the visual should be adjustable.**

  Adjustable visual speed allows researchers to investigate how variations in visual timing affect the CRE and whether different speeds produce different perceptual effects.

- **The setup should be durable, it should not break during testing**

  Durability ensures the equipment can withstand repeated use throughout the experiment, maintaining consistency in stimulus delivery. A durable setup minimizes downtime and ensures reliable performance across trials, which is crucial for collecting high-quality data.

4.2 RQ 2.2 How to realize the multi-modal (haptic & visual) input and their synchronization?

4.2.1 Requirement: The visual should look appealing.

To create an appealing VR visual experience 4 parts need to be completed: creating the 3D model, rigging, animating, and programming the animations in Unity.

3D-Moddeling & Rigging The 3D model creation and rigging was done in Blender, this software is versatile and has lots of options. It allows for detailed bone setups, inverse kinematics, control bones, and custom rigging features[28]. The body of the animal was created by using a reference image. The body is relatively low poly, to keep the model responsive. Blender's particle system was used to recreate feathers. To animate and move the crow a custom rig was created. Inverse Kinematics were incorporated to make animating easier.

FIGURE 3: Body of the crow

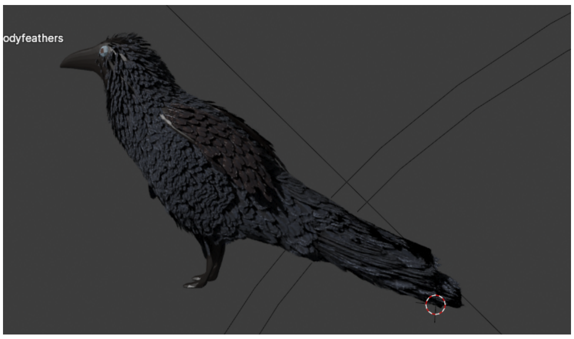

FIGURE 4: Feathers

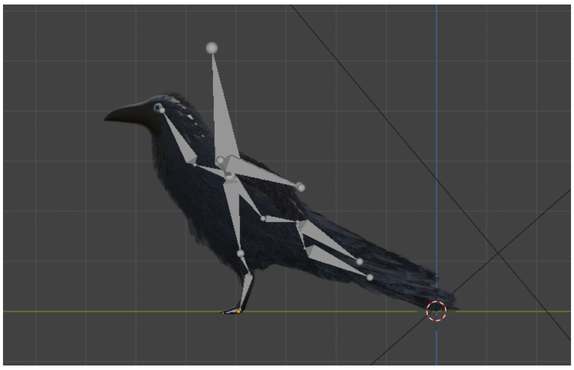

FIGURE 5: Crow rig

Animation A jump animation was created, this animation was made stationary so any movement can be done by scripting in Unity.

Exporting to Unity The blender model was exported for Unity into an FBX file. Before exporting the particle system was converted into a mesh to reduce the amount of separate particles and make the model more responsive. For some textures or materials, Blender uses a node system that is incompatible with Unity. To use these materials in Unity, the textures were baked into an image format that could be applied to the model.

FIGURE 6: Crow in the unity environment

4.2.2 Requirement: The vibrotactile sleeve is able to produce the CRE.

The tactile sleeve that produces the CRE uses an Arduino, Connected to it are 2 vibration motors, a potentiometer, and an audio jack socket. An Arduino replaced the ESP that the sleeve initially used because esp can only supply 3.7V and Arduino can supply 5V which results in stronger vibrations. The sleeve vibrates three times near the elbow and once near the wrist (4 jumps).

4.2.3 Requirement: The visual should be synchronized with the vibrotactile sleeve

Timing animation in Unity Using the animator controller and scripting the jump animation is timed. The jump animation starts when the space bar is pressed. The script uses a list of 4 jump positions, to indicate where the animal has to jump to. Horizontal speed is calculated with the interpolation factor between start and end positions.

```
float t = Mathf.Clamp01(jumpTimer / jumpDuration);
```

To simulate the jump height a quadratic curve is used:

```
float height = Mathf.Sin(t * Mathf.PI) * jumpHeight;
```

To start the jump animation a boolean that checks whether the animal is jumping is used. There is a check for when the landing begins, to stop the jump animation and land back on the arm.

potentiometer to change the time between vibrations. Has audio jack to receive animation start signal from Unity.

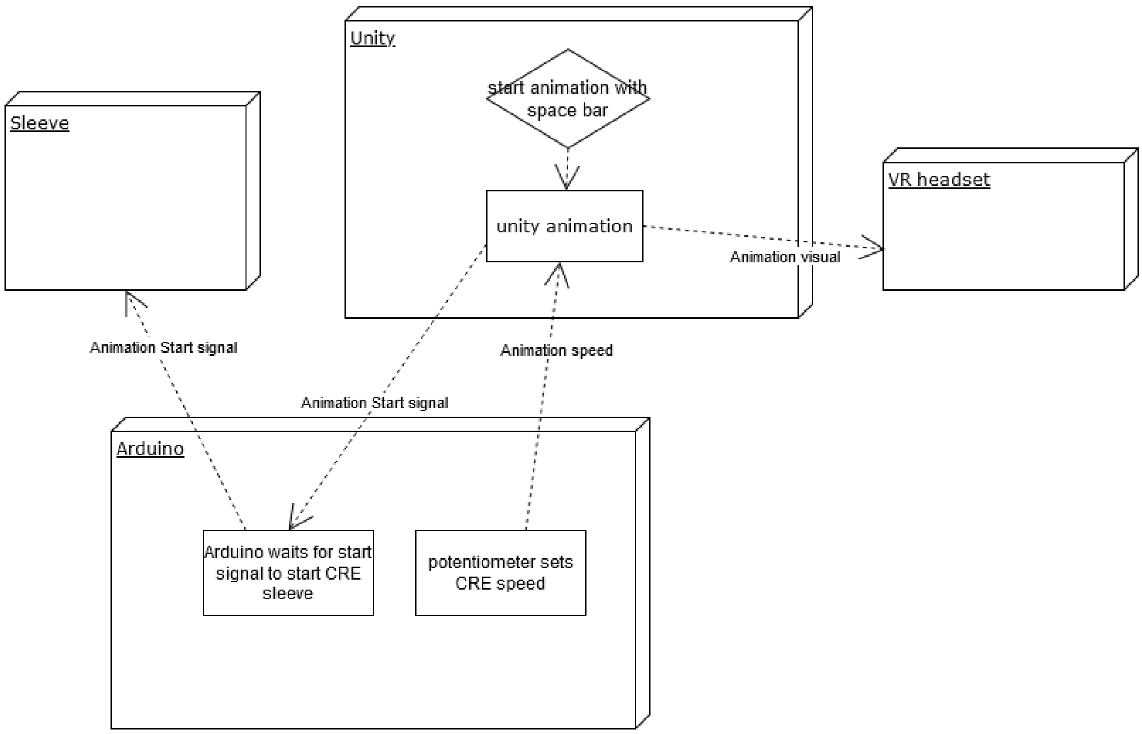

FIGURE 7: system overview

Communication between Unity and vibrotactile sleeve an overview of the system is shown in fig 7

vibrotactile sleeve –> Unity The vibrotactile sleeve uses a potentiometer to set the speed of the bursts. To match the Unity animation to the illusion speed, the Arduino sends the value over the serial monitor. A Unity script reads this value and applies it to the animation.

Unity –> vibrotactile sleeve To give a start signal vibrotactile sleeve. This signal is audio signal that is send when the animal jump animation starts. This sound signal is connected to an analog input of the Arduino. To connect the sound signal of the laptop to the analog input of the Arduino a diode was used, this way there is not a negative input on the Arduino. When the analog value reaches the threshold, it knows that the Unity visual starts, and begins the tactile feedback. Audio was used because serial communication was too slow to keep the tactile feedback and the animation synchronous.

4.2.4 Requirement: The setup should be durable, it should not break during testing

To make the test setup more durable it was soldered on a breadboard and put into an enclosure. This way the soldered connection were more secure against the breaking of the connections.

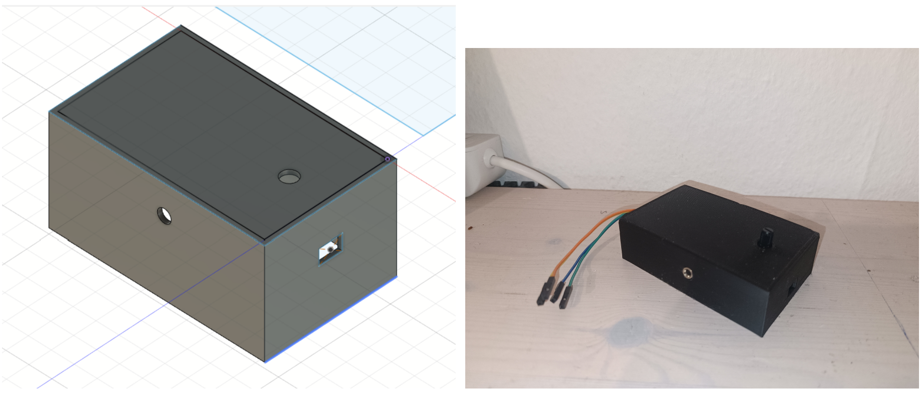

FIGURE 8: Enclosure made in Fusion

4.3 RQ 2.3 How to perform the user experiments?

4.3.1 Ethics

To perform user experiments, permission was needed from the EEMCS etchical committee of the University of Twente. To apply for permission the ethics review application was submitted (application number 241267). This contained the topic of the research and an overview of the test procedure that was used. To ensure ethical user evaluations, any data that was collected would be anonymized by using a participant number on the questionnaire without keeping a key that links the number to the participant.

4.3.2 Study design

This user test consisted of a survey, which can be found in Appendix A. The aim was to collect data on perception of the CRE at 6 different speeds, with and without the visual.

are the visuals and illusion synchronized? The last part of the questionnaire evaluated whether the visuals were pleasing. Before testing participants read an information letter which can be found in Appendix C and sign a consent form (Appendix B).

4.3.3 Participants and recruitment

The participants for this study were students. A minimum of five students should be required to conduct the user test, but recruiting more participants is better. The took place during Week 3.

4.3.4 Procedure

Setup procedure

1 The Researcher charges the devices (laptop and VR headset) sufficiently before the test begins

2 The Researcher ensures that the information letter, consent form, and user evaluation form are present.

3 The headset and sleeve are connected to the laptop before the experiment starts.

4 With an online random sequence generator the order of the tests are determined.

User test procedure

1 The researcher introduces themselves and the graduation project

2 The researcher takes the user through the ethics information brochure and consent form and gets it signed. Will also explain how the study will go.

3 User puts on the sleeve

4 In the previously determined order the user will experience the differently timed CRE's. Between the tests there will be a short break to not

5 The researcher asks the user to test out the illusion with the visual

6 Participant fills in the document whether the illusion was felt.

4.3.5 Pilot Test

Before the real experiment a pilot test was done, to ensure everything works correctly. When starting the test, it was discovered that the setup of the test can take quite a long time, especially connecting the VR headset to the Unity program and putting on the sleeve. A small inconvenience that also occurs during the set-up, is that the headset loses connection with the Unity program. This happens when a participant puts the headset on and accidentally goes out of the VR- boundary, pushes a button, or moves the headset too much that the PC-link cable comes loose. Another small observation was that the cables connecting the sleeve and the Arduino were a little short. This did not result in a big problem while testing but it could be slightly annoying. When starting the animation a small error was found in the VR program. In the program the crow starts jumping from the shoulder to the wrist, however, the sleeve only applies stimuli between the elbow and wrist. Another detail is that in the VR environment, the right arm is visible, this is not necessary because the animation only occurs on the left arm. Also after jumping the crow waits on the wrist for quite a long time, this could be shorter. The placement of the jump positions could also be improved, sometimes the legs of the bird went in the arm.

Before pilot test	After pilot test
Participant puts VR headset on themselves	Researcher puts on VR headset, participant can use the adjustment knob on the headset to make it fit better.
Unity animation jumps from shoulder to wrist	Unity animation jumps from elbow to wrist
both arms are visible	only the left arm is visible
Wait time after jumping 7 seconds	Wait time after jumping 4 seconds
Stationary boundary	Bigger custom boundary
jump position not properly aligned with the arm	Some fine-tuning to place the jump position correctly on the arm

TABLE 1: Changes after pilot testing

4.3.6 User Test

Most of the user tests were conducted on the UT campus, it was made sure that it was done in a room where there were not a lot of distractions such as sound or a lot of people walking by. The testing setup up is shown in Figure 9

FIGURE 9: Testing setup

5 Results

Eight participants, six females and two males, aged between 19 and 24 years, were recruited for the study.

5.1 Total number of participants that felt the CRE with and without the visual.

Figure 10 shows the total number of participants that felt the CRE with and without visuals across the six different trials(with 25ms being the fastest speed and 98ms the slowest). As indicated in the legend the blue bar is the number of participants that felt the CRE before the visual, and the orange bar is the total number after adding the visual.

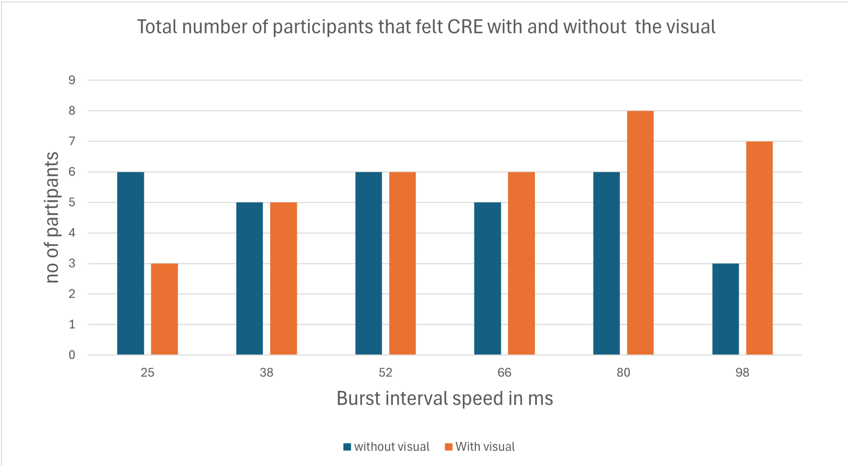

FIGURE 10: Total number of participants that felt the CRE with and without the visual at the six different test speeds.

Without the visual Generally, the illusion was perceived by a similar amount of participants (5–6 participants) across nearly all six durations. This result is somewhat unexpected compared to findings from the background research which indicated that around 24ms should be an optimum. An exception is at the slowest timing (98ms), at this speed only three participants experienced the illusion.

With the visual At 80ms, all participants felt the illusion, making it the timing with the most consistent effect. At 25ms, the fewest participants experienced the illusion. The most noticeable change after adding a visual occurs at 25ms, where the number of participants experiencing the CRE decreases from six to three. At 38ms and 52ms, the total number of participants remains the same. This raises the question: is this because the same individuals consistently experienced the effect (or not), or did the addition of the visual result in changes at an individual level?

5.2 Positive and negative effect of visuals on CRE perception per person

Figure 11, shows the number of participants that had negative/positive change in perception of the CRE after adding the visual. The red bar indicates the number of participants that had a negative change in perception after adding the visual, they switched from "Yes" (feeling the illusion) without visuals to "No" with visuals (negative change). The green bar indicates the positive change in perception, the switch from "No" to "yes".

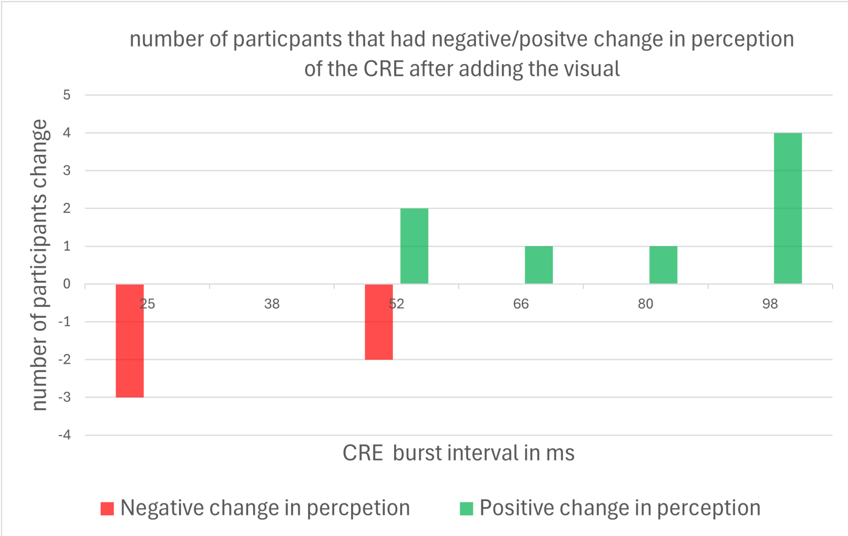

FIGURE 11: Positive and negative effect of the visual on CRE perception per participant

At the fastest timing (25ms) the number of participants experiencing the illusion decreased significantly after adding the visual. hree participants switched from "Yes" to "No", indicating that visuals disrupted their perception of the illusion at this speed. This could be due to the visuals being too fast and feeling disconnected from the haptic feedback.

At the slowest timing (98ms), The addition of visuals had the opposite effect 4 participants switched from "No" to Yes", meaning visuals enhanced their ability to feel the illusion at this duration.

At 38ms, there were no individual changes. The same participants who felt the illusion without the visual continued to feel it with visuals, and vice versa. At 52ms, there was a balanced effect: two participants switched from "Yes" to "No", and two others switched from "No" to "Yes", resulting in no net change in the total number of participants feeling the illusion.

An additional observation is that timings faster than 52ms tended to result in a negative change in perception, while timings slower than 52ms generally led to a positive change in participants' perception of the illusion. The data from 52ms suggests that there might be a tipping point at this timing. Here both positive and negative changes in perception are observed, resulting in a balance between the two effects.

5.3 Order and CRE perception

Figure 12 shows the total number of participants that perceive the CRE with/without the visual across trials. It could be the case that feeling the illusion a lot of times could decrease the perception, to try to minimize this effect the order of trials was randomized. This graph is to discover if the order of the trials affected the perception.

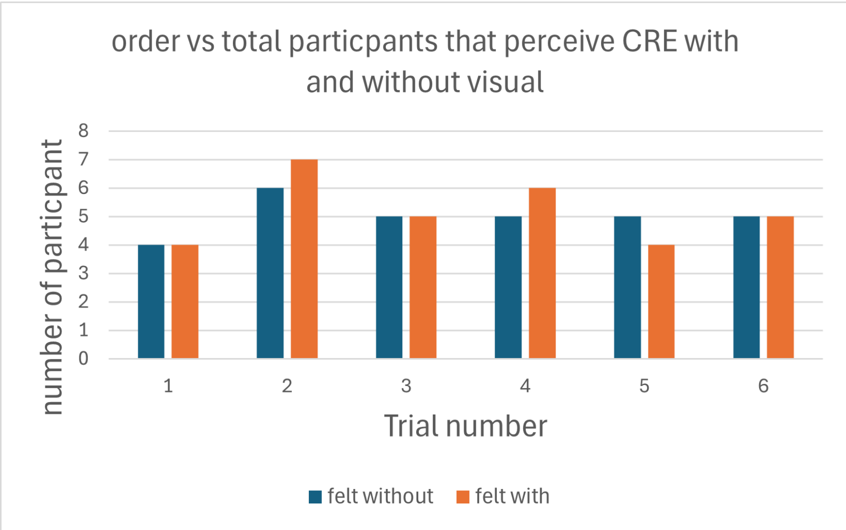

FIGURE 12: order vs CRE perception with and without visual

At first glance the order of trials does not appear to have a strong overall effect on perception. However, trial one shows a slightly lower perception than average, while trial two is higher. This could be related to trial 1 including the 25ms timing twice, and participants commented that the 25ms visual felt too fast and did not fit well with the haptic feedback. This mismatch may have influenced the perception of this trial. Overall for the other timings, there does not seem to be a consistent pattern of order effects, a larger sample size would be needed for clearer conclusions.

5.4 Synchronization of the Visual and CRE

The graph in Figure 13 shows the synchronization across the six different timings of the CRE. The bars represent the number of participants who rated the visual as synchronous. This graph was compared to the one in Figure 11, to look how much synchronization affected the perception of the CRE.

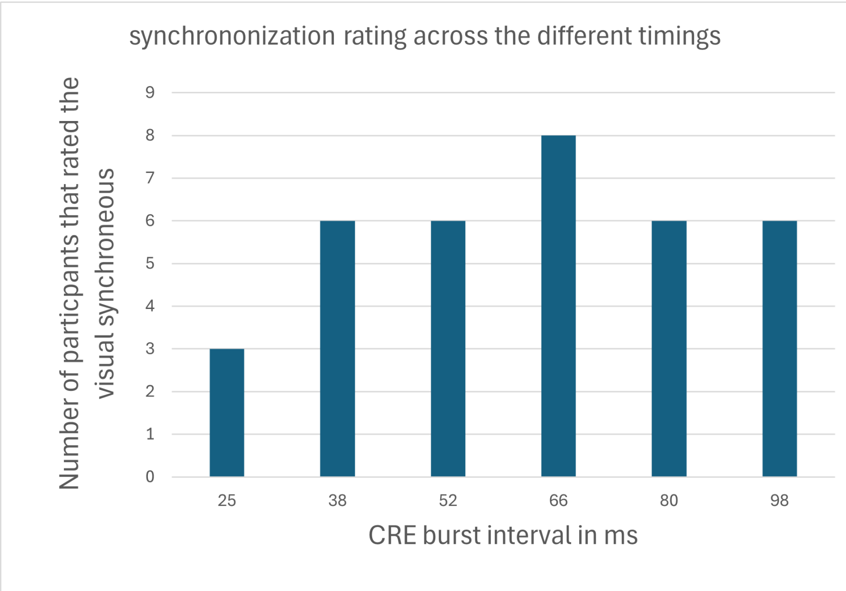

FIGURE 13: Amount of participants that rated the visual synchronous with the CRE across the different speeds

At 25ms, five participants felt the visuals were not synchronized. From these five, two participants shifted from feeling the illusion ("Yes") without visuals to not feeling it ("No") after visuals were added. In total, three participants switched from "Yes" to "No" at 25ms after adding visuals. Additionally, this means two out of these three participants that switched from "Yes" to "No", perceived the visual as not synchronous. At 38ms, 52ms, 80ms, and 98ms, synchronization ratings were the same, this, however, did not result in a similar change of perception per person. As shown in Figure 11 this number ranged between -2 and 4. With the strongest change of four people switching to "Yes" at 98ms.

Overall, there does not appear to be a strong correlation between perceiving the visual as synchronous and also perceiving the CRE. It might be a combination of factors: the likelihood of feeling the illusion increases with the addition of visuals at slower speeds, while it decreases at faster speeds. Furthermore, synchronization appears to have the most significant influence at the extremes of the timing spectrum.

5.5 Rating of the Visual

visual appeal Participant opinions on the visual.

The average rating for the visual was 4.1 out of 5, indicating that participants generally liked the visual.

The arm visual, however, received some criticism, it was perceived as too large. Additionally, its position was described as strange and inconsistent with the actual arm position of the participants.

Several participants noted that at the fastest timing, the animation was too quick and felt unnatural.

5.6 Additional Observations from Participants

(translated)

- "No big difference with or without visual"
- Keeps vibration for a short while after the visual ends
- at 80ms and 98ms without visuals: "The effect is weaker but still noticeable."
- at 38ms with visuals: Felt like "sliding."
- at 66ms with visuals: Felt like "hopping."
- "struggled to fit the sleeve to arm."

5.7 Conclusion of Results

To conclude, at the fastest CRE speed (25ms), the data suggests that perception was disrupted when the visual was added, while at the slowest speed (98ms) the visual seems to enhance perception. A tipping point was observed at 52ms, where equal positive and negative changes occurred. It seems like synchronization has the most influence at extreme speeds. The crow model was generally well-received, but the arm visual's size and position should be refined for better realism and immersion. Animation speeds at fast timings should also be calibrated to align better with haptic feedback.

6 Discussion

6.1 Expectations & Key Findings

This study aimed to determine whether visual input influences the perception of the Cutaneous Rabbit Effect (CRE) in a VR environment. Based on previous research by Ziat et al. [1] and findings from the literature, it was expected that adding visual input would generally enhance CRE perception.

The results mostly support this expectation. For slower timing intervals (66ms, 80ms, 98ms), the illusion was reinforced when visual input was added. For 38ms, however, no significant change in perception was observed after adding the visual.

6.2 Unexpected Findings

- At 52ms, the effects of visual input were inconsistent, two participants reported an enhanced illusion, while two other participants experienced disruption. This suggests there might be a threshold where the addition of a visual changes from a positive to a negative effect on the perception of the CRE.
- At 25ms, the illusion was disrupted, even though previous literature identified 24ms as an optimal timing interval for the CRE.
- One participant noted that at 25ms, the sensation felt more like something sliding over their arm instead of hopping.
- Compared with perception without the visual, at 98ms the perception increased the most after adding a visual. This is quite slow timing so it is surprising that people still felt the illusion.

6.3 Future Research

Future research could incorporate the following recommendations:

- Greater sample size to increase generalizability of the results.
- Longer wires to make testing more convenient.
- Explore integrating the user's arm into the AR environment to make it appear the animal is actually on the participant's arm, instead of on a large floating arm.
- Use stronger motors, the last vibration was made longer to make it more noticeable (because without it was barely noticeable). It seemed that this final vibration disrupted the synchronization. so, using a stronger motor and eliminating the longer vibration might improve synchronization
- At 98ms intervals, many participants could still perceive the effect when paired with the visual stimulus. Investigate how far this threshold can be pushed.
- Explore alternative types of tactile stimulation, such as pressure or electrical stimulation, to see if these influence the experience.
- Some participants mentioned that the CRE felt like it was "sliding" at faster speeds. Test whether a more "sliding" visual effect enhances the illusion compared to the current hopping effect.

- The arm model didn't fit well, so improving the visualization by matching it to the user's real arm in AR would likely enhance the experience.
- Invesigate the combination of a visual and the CRE, using brain sensors to analyze neural activity. A study that was discussed in the background research [27], demonstrated that the cutaneous rabbit illusion activates the primary somatosensory cortex (SI) at locations corresponding, to both real and illusory touches, suggesting that SI activity is also what linked to what is the perceived sensation rather than just real physical stimuli. A similar approach could be used to investigate whether the addition of visual stimuli changes activity in these regions or maybe if processing shifts toward visual areas instead. This could reveal whether visual input can override or integrate with tactile processing, providing deeper insights into cross-modal perception.

7 Conclusion

This Bachelor Thesis aimed to explore the following research question:

RQ: Can VR visuals affect the tactile perception of the cutaneous rabbit effect (CRE)?

The cutaneous rabbit effect, a tactile illusion, was studied within a virtual reality (VR) context to investigate the influence of a visual on the perception of the CRE. Background research revealed that the illusion occurs when tactile stimuli are applied to less sensitive areas of the body, such as the forearm. These stimuli are perceived as a hopping motion between the stimulated points.

Research also highlighted the importance of synchronization between visual and tactile stimuli to maintain spatiotemporal consistency, a key factor for successful cross-modal integration. Previous studies demonstrated that mismatched timing or positioning can weaken the illusion and reduce user engagement. Therefore, the prototype tried to achieve good synchronization between a vibrotactile sleeve and a VR visual, representing the CRE as a crow hopping across the forearm.

The addition of visual stimuli in VR, was hypothesized to enhance this effect, building upon theories of multisensory processing, which suggest that the brain combines multiple sensory inputs to create a better understanding of what is happening.

The prototype incorporated findings from the literature, such as the optimal timing of tactile stimuli at 24 ms intervals and strategies for minimizing latency. To create a visually appealing and immersive experience, a 3D model of a crow was animated to simulate the hopping motion, synchronized with vibrations on the user's arm. User tests were conducted to evaluate the perceived synchronization, the strength of the illusion, and the appeal of the visual. The results suggest that at the fastest CRE speed (25ms), the perception was disrupted when the visual was added, while at the slowest speed (98ms) the visual seems to enhance perception. A tipping point was observed at 52ms, where equal positive and negative changes occurred. Additionally, it seems like synchronization has the most influence at extreme speeds, while at other speeds, it might not make a big difference. The crow model was generally well-received, but the arm visual's size and position should be improved for better realism and immersion. Animation speeds at fast timings should also be calibrated to align better with haptic feedback.

Because of the small testing population (n=8), the results of the user test remain somewhat limited. Despite the small sample size and limited generalization of the results, this study hints that VR visuals are able to affect the CRE. Future research could explore improving the synchronization techniques, alternative haptic feedback mechanisms, and the integration of user-specific features, such as adapting the visual model to match the user's real arm in VR.

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Appendix A User test form

User Test cutaneous rabbit

Participant nr:

Without Visual

order	Illusion Felt?		Yes	No
		25ms		
		80ms		
		38ms		
		66ms		
		52ms		
		98ms		

With Visual

	Illusion Felt?		do you feel haptics and visuals were synchronized?	
	Yes	No	Yes	No
25ms				
80ms				
38ms				
66ms				
52ms				
98ms				

	1	2	3	4	5
do you think the VR visuals look appealing?					

Remarks:

Appendix B Consent Form

Consent form template for research with human participants

Consent Form for Designing a VR application as cross-modal extension of the cutaneous rabbit effect.

YOU WILL BE GIVEN A COPY OF THIS INFORMED CONSENT FORM

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated [19/12/2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions, and I can withdraw from the study at any time, without having to give a reason.	□	□
I understand that taking part in the study involves a questionnaire filled in by the participant.	□	□
Risks associated with participating in the study		
I understand that taking part in the study involves the risk of experiencing dizziness. This can happen when using the headset for a long time.	□	□
Use of the information in the study		
I understand that the information I provide will be used for a Creative Technology bachelor's thesis. The data that will be collected are the test results, age, left or right-handed. *The data will be anonymized by using a participant number on the questionnaire without keeping a key that links the number to the participant.* The participant can choose to withdraw their data, till the end of the experiment after this the data will be anonymized.	□	□
I understand that personal information collected about me that can identify me, such as my name, will not be shared beyond the study team.	□	□
Future use and reuse of the information by others		
I give permission for the anonymized questionnaire data that I provide to be archived in the thesis repository of University of Twente, so it can be used for future research and learning.	□	□

Signatures

____________________ ______________ __________________

UNIVERSITY OF TWENTE.

Name of participant Signature Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ ________________ ______________________

Name of researcher Signature Date

Contact details for future questions

Milou de Zwaan
m.z.dezwaan@student.utwente.nl

supervisor:
Angelika Mader
a.h.mader@utwente.nl

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science: ethicscommittee-CIS@utwente.nl

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Appendix C Information Letter

Information Sheet

Purpose of the Study

The purpose of this study is to study the timing of cross-modal effects, in specific the "cutaneous rabbit effect" (CRE) within a virtual reality (VR) context.

Background and Significance

The CRE is a tactile illusion that occurs when a person feels sensations not only at points of stimulation but also in the areas between those points. For example, when two or three points on the forearm are stimulated, it can feel like a rabbit is "hopping" across the skin. This study combines the CRE with visual elements in VR to create a cross-modal experience, which involves perceiving information by combining multiple senses.
Understanding these sensory processes has the potential to improve VR and augmented reality (AR) technologies. Enhancing the immersive quality of VR can increase realism and engagement, which are crucial for applications like virtual training, therapeutic interventions, and stress reduction.
The CRE offers several practical advantages It requires only minimal equipment, making it cost-effective and easy to integrate into existing systems.

Experiment

It is possible to withdraw from this study at any time. You can do this by notifying the researcher.
In this user test, you will be asked to experience the cutaneous rabbit effect in a VR setting.
Your task is to change the timing of the haptic feedback and animation with the use of a knob and find the optimal timing, where you feel the illusion the most strongly.
After experiencing the illusion, you will be asked to fill in a short questionnaire on how you experienced the illusion.
A small risk of VR is that people can get dizzy after using the headset for a long time.
If you experience dizziness or any other negative symptom, remove the headset and notify the researcher.

Data privacy

Personal information will be safeguarded, by maintaining confidentiality and de-identifying data. No retraceable personal details will be published in the research, instead, the data will be categorized by participant numbers. The de-identified data will be used in a Creative Technology bachelor’s thesis.

Contact details for future questions

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Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science:
ethicscommittee-CIS@utwente.nl