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Enhancing Immersion in Virtual Reality Through Facial Airflow Haptic Feedback

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Resumo

A realidade virtual (RV) consolidou-se como um meio poderoso para interação imersiva, com aplicações que abrangem os videogames, a formação profissional, a simulação médica e a reabilitação. O sentido de presença — a sensação de existir fisicamente dentro de um ambiente virtual — é um fator determinante da eficácia da RV, sendo fortemente influenciado pelo feedback multissensorial. Embora o realismo visual e auditivo tenha avançado consideravelmente, o feedback háptico em RV de consumo continua largamente confinado a atuadores de vibração manuais. A face, apesar da sua elevada sensibilidade tátil e relevância perceptiva, permanece maioritariamente inexplorada como alvo de estimulação háptica em ambientes imersivos. Esta dissertação apresenta o design, implementação e avaliação de um sistema de feedback háptico facial de baixo custo para realidade virtual, combinando atuadores de fluxo de ar por ventoinhas e atuadores de ar comprimido para fornecer estimulação tátil localizada na face do utilizador. O sistema foi avaliado num cenário de RV de montanha-russa ao longo de quatro configurações hápticas — sem háptica, apenas ventoinhas, apenas ar comprimido, e ambos combinados — com 20 participantes. O realismo percebido foi avaliado através de classificações durante testes para cada um dos cinco tipos de eventos hápticos; o sentido de presença foi avaliado com o questionário de Slater-Usuh-Steed. A avaliação revelou que o feedback háptico melhorou significativamente o realismo percebido, com as condições baseadas em ventoinhas a produzirem os maiores ganhos face à linha de base sem háptica. Uma interação significativa entre a configuração háptica e o tipo de evento indicou que os diferentes tipos de atuadores beneficiaram de forma distinta dos vários eventos hápticos, com a condição combinada a produzir o efeito mais forte nos eventos compostos. Não foi encontrado nenhum efeito significativo nas pontuações gerais de presença, embora a análise ao nível dos itens tenha revelado diferenças significativas em cinco dos seis itens individuais do questionário de presença, predominantemente impulsionadas pelas comparações entre as condições sem háptica e com ventoinhas. O trabalho futuro aborda a limitação atual de design do tripé fixo e explora configurações alternativas.

Palavras-chave: Realidade Virtual • Feedback Háptico • Háptico Facial • Realismo Percebido

Abstract

Virtual reality (VR) has matured into a powerful medium for immersive interaction, with applications spanning gaming, training, medical simulation, and rehabilitation. The sense of presence — the feeling of physically existing within a virtual environment — is a key determinant of VR effectiveness, and is known to be influenced heavily by multisensory feedback. While visual and auditory realism have advanced considerably, haptic feedback in consumer VR remains largely confined to handheld vibration actuators. The face, despite its high tactile sensitivity and perceptual significance, remains largely unexplored as a target for haptic stimulation in immersive environments. This thesis presents the design, implementation, and evaluation of a low-cost facial haptic feedback system for virtual reality, combining fan-based airflow actuators and compressed-air actuators to deliver localised tactile stimulation to the user's face. The system was evaluated in a roller coaster VR scenario across four haptic configurations — no haptics, fans only, compressed air only, and both combined — with 20 participants. Perceived realism was assessed via in-session ratings for each of five haptic event types; sense of presence was assessed using the Slater-Usuh-Steed questionnaire. The evaluation revealed that haptic feedback significantly improved perceived realism, with fan-based conditions producing the largest gains over the no-haptics baseline. A significant interaction between haptic configuration and event type indicated that different actuator types benefited differently from the varying haptic events, with the combined condition producing the strongest effect for compound events. No significant effect on general presence scores was found, though item-level analysis revealed significant differences on five of six individual presence questions, predominantly driven by comparisons between the no-haptics and fan-based conditions. Future work addresses the current design limitation of the fixed tripod and explores alternative configurations.

Keywords: Virtual Reality • Haptic Feedback • Facial Haptics • Perceived Realism

UN Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) provide a global framework for achieving a better and more sustainable future for all. It includes 17 goals to address the world's most pressing challenges, including poverty, inequality, climate change, environmental degradation, peace, and justice.

This thesis contributes to the following Sustainable Development Goal through the development of a low-cost, open and modular haptic feedback prototype for virtual reality environments, built upon accessible hardware and open-source software infrastructure.

The specific Sustainable Development Goal mentioned has the following name:

SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation

SDG	Target	Contribution	Performance Indicators and Metrics
9	9.5	The prototype demonstrates that facial haptic feedback in Virtual Reality can be achieved using low-cost, widely available components (Arduino, L298N motor driver, 3D printed shell), lowering the barrier to entry for researchers and developers in the field of human-computer interaction.	Number of off-the-shelf components used; total hardware cost compared to existing commercial haptic solutions.
	9.b	The open and modular software architecture — built on Unity and standard serial communication protocols — enables the system to be extended to support additional actuator types or alternative Virtual Reality environments, fostering further technological development and innovation.	Extensibility of the system architecture.

SDG 9 contributions and performance indicators.

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Finally, I would like to extend my thanks to all the participants who volunteered their time to take part in the user study. Their patience and honest feedback were essential to the evaluation of this work.

Tomás Filipe Fernandes Xavier

Declaration of honour

I declare that this dissertation is my own work and has not previously been submitted or assessed at this or any other institution. References to other authors (statements, ideas, thoughts), as well as the use of published works, strictly comply with the rules of attribution and are duly identified in the text and in the bibliographic references, in accordance with the applicable referencing standards. I am aware that the practice of plagiarism or self-plagiarism constitutes an academic offence, as established in the U.Porto Code of Ethics.

I also declare that I have used Artificial Intelligence tools, namely Claude and codex as an assistant to the unity and Arduino documentation and to assist academic writing and quality assessment. However, the results arising from this use have been carefully checked for errors, inaccuracies, unfounded attributions or other forms of bias in content and arguments, as well as determining authorship.

Tomás Felipe Fernandes Xavier

“Life isn’t just about passing on your genes. We can leave behind much more than just DNA. Through speech, music, literature and movies... what we’ve seen, heard, felt... anger, joy and sorrow... these are the things I will pass on. That’s what I live for. We need to pass the torch, and let our children read our messy and sad history by its light. We have all the magic of the digital age to do that with. The human race will probably come to an end some time, and new species may rule over this planet. Earth may not be forever, but we still have the responsibility to leave what traces of life we can. Building the future and keeping the past alive are one and the same thing.”

Solid Snake - Metal Gear Solid 2: Sons of Liberty

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List of Acronyms

VR	Virtual Reality
HMD	Head-mounted Display
DOF	degrees of freedom
2DOF	two degrees of freedom
3DOF	three degrees of freedom
PWM	Pulse Width Modulation
DC	Direct Current
SUS	Slater–Usch–Steed

Chapter 1

Introduction

Virtual Reality (VR) is maturing into a powerful medium for immersive interaction, widely adopted across various domains, including gaming, industrial training, medical simulation, and motor rehabilitation [37, 58].

The sense of presence—the feeling of physically existing inside a virtual environment—is one of the key factors that determines the effectiveness of VR experiences [24, 75]. While visual and auditory realism have improved dramatically, the ability to physically feel and manipulate virtual objects remains limited. Consumer VR controllers primarily provide non-specific vibration feedback, which does not accurately simulate contact with solid surfaces or physical constraints [8]. The absence of convincing haptic sensations weakens interaction fidelity, reducing realism and immersion during tasks that require precise perception of touch, resistance, or motion limitation.

1.1 Context

VR systems aim to create immersive experiences by stimulating multiple sensory channels, most prominently vision and hearing through Head-mounted Display (HMD)’s and spatial audio. While visual and auditory technologies have advanced considerably, the tactile dimension of VR remains comparatively limited, often restricted to vibration-based feedback delivered through handheld controllers.

Touch plays a fundamental role in human perception, contributing to spatial awareness, embodiment, and emotional interpretation of events [16, 52]. In immersive environments, haptic feedback can reinforce the illusion of physical interaction by conveying contact, resistance, and proximity cues. However, most consumer VR systems primarily target the hands, leaving other perceptually sensitive regions of the body—such as the face—largely unexplored.

The face is particularly significant due to its high tactile sensitivity and its strong association with affective perception, threat detection, and social interaction. Incorporating facial haptic stimulation into VR experiences represents an opportunity to expand multisensory immersion beyond traditional hand-centered interaction models.

1.2 Motivation

Despite the growing sophistication of consumer VR platforms, haptic feedback remains largely confined to handheld vibration actuators that provide limited spatial and mechanical realism. While such feedback can signal discrete events, it cannot convincingly reproduce physical contact, proximity, or impact sensations that occur near the user's face—interactions that are perceptually meaningful in many virtual scenarios.

Facial contact cues are especially relevant in applications involving social presence, environmental interaction, or dynamic events such as collisions, wind, or object proximity. The absence of facial haptic feedback can therefore reduce perceived realism and emotional engagement, weakening the sense of presence in immersive environments.

Existing high-fidelity haptic systems are often bulky, expensive, or impractical for integration into consumer VR workflows, with many wearable solutions adding significant encumbrance to the user or requiring complex calibration procedures. This creates a need for simple, low-cost facial haptic solutions that can augment existing VR setups without significantly increasing user encumbrance. A fixed facial interface capable of delivering localized tactile stimuli could enable richer multisensory interaction while remaining compatible with current consumer hardware ecosystems.

1.3 Problem

Delivering convincing haptic feedback to the human face presents a set of unique technical and ergonomic challenges that are not adequately addressed by current virtual reality systems. Unlike the hands, the face is highly sensitive, unevenly contoured, and closely associated with safety and comfort constraints. Any haptic interface designed for facial stimulation must aim to achieve precise, localized actuation while remaining lightweight, unobtrusive, and safe for prolonged use.

Existing consumer VR hardware offers limited mechanisms for facial feedback, typically focusing on handheld vibration-based interaction. While research prototypes have explored thermal, vibrotactile, or airborne stimulation near the face, there is still no widely adopted approach that balances expressive feedback, wearability, and compatibility with commercial VR ecosystems.

The core problem addressed in this work is how to design and implement a portable facial haptic actuation system capable of delivering controlled tactile sensations—ranging from subtle contact cues to higher-intensity impact signals—without compromising user comfort, safety, or immersion. Solving this problem requires careful consideration of actuator selection, spatial placement, control strategies, and system integration within existing VR workflows.

1.4 Research question

Based on the challenges outlined in the problem statement (section 1.3), it is investigated whether facial haptic feedback can meaningfully contribute to immersive virtual reality interaction. As

the work focuses on user perception, comfort, and experiential qualities, an exploratory research approach is adopted. The following research questions are used to guide the research for the development of the prototype system and to structure its user-centered evaluation.

1. How do different types of facial haptic stimuli—such as subtle tactile cues and higher-intensity impact cues—influence users’ perception of realism and engagement in virtual reality?
2. How to make a device that the user can differentiate between the different facial haptic stimuli?
3. What is the perceived impact of a facial haptic interface on user comfort and encumbrance during VR interaction?

1.5 Hypothesis

Based on the identified gap in facial haptic feedback for virtual reality and the proposed prototype design, the following hypotheses guide this research. These hypotheses focus on evaluating whether subtle facial haptic stimuli can enhance perceptual realism and immersion while maintaining user comfort and usability.

1. The inclusion of subtle facial haptic feedback will increase perceived immersion and presence compared to a VR experience without facial haptics.
2. Subtle facial haptic cues will enhance the perceived realism of close-proximity and face-related interactions relative to visual and auditory feedback alone.
3. Subtle facial haptic feedback can be delivered without significantly reducing user comfort or usability during short VR sessions.

1.6 Dissertation Structure

This dissertation is organized into six chapters, progressing from the research context and theoretical foundation to the design, implementation and evaluation of a facial haptic feedback system for virtual reality.

Chapter 1 introduces the research context and motivation, defines the problem addressed in this work, and presents the research questions and hypotheses that guide the investigation. This chapter establishes the relevance of facial haptic feedback in virtual reality and outlines the goals of the dissertation.

Chapter 2 reviews the state of the art in haptic interface design, categorizing prior work into graspable, wearable, and touchable systems. The chapter highlights current capabilities and limitations, emphasizing the relative lack of exploration in facial haptics and motivating the proposed approach.

Chapter 3 describes the design of the proposed facial haptic prototype. It details the hardware architecture, integration with commercial VR equipment, and the software framework used to generate and control haptic stimuli. It also describes the implementation of the facial haptic prototype. It details the hardware used, all the electronics and the software code created to control the haptic stimuli.

Chapter 4 details the environment and the design of the tests carried out to evaluate the haptic prototype. It also details the test results and the statistical analysis of them.

Chapter 5 concludes this document, summarizing our results and sharing limitations found and possible future improvements.

Chapter 2

State of the Art

As outlined in Chapter 1, this work is motivated by the observation that current haptic research predominantly focuses on hand- and arm-based interaction, leaving other perceptually significant body regions, namely the face, comparatively underexplored. This chapter addresses that by reviewing prior work on haptic interfaces relevant to immersive virtual reality interaction, with a particular focus on systems designed to enhance physical plausibility and user immersion through tactile and kinesthetic feedback. As haptic technologies span a wide range of form factors, actuation principles, and interaction paradigms, this review adopts a structured taxonomy to provide a coherent overview of the field.

The literature review was conducted following a Scoping Review approach. The sources stemmed from Elicit, Google Scholar, IEEE and ACM. Through the use of 10 queries, 72 haptic devices and 17 supplementary sources were obtained (full details in chapter A). The chosen devices that were primarily selected were from 2015 onwards and with a focus on graspable, wearable, and touchable devices, following the categorization proposed by Culbertson, Schorr, and Okamura [14]. These categories reflect fundamental differences in how haptic feedback is delivered to the user—through handheld interfaces, body-mounted devices, or external physical proxies occupying real space (fig. 2.1).

- Graspable devices are handheld interfaces designed to be physically held by the user. They usually focus on kinesthetic (affects motion of hand/controller) and/or cutaneous sensations (affects skin, fingertips). These devices are either Grounded (i.e. attached to a table, floor or wall) or ungrounded (i.e. held in hand and using some internal mechanism to produce force or sensation on the user). This modality contributes to immersion by reinforcing physical plausibility through motion cues.
- Wearable devices are attached to the hands or other body parts of the user and focus primarily on cutaneous feedback, including vibration, lateral skin stretch (shear), and normal skin deformation (perpendicular indentation). This particular category is highly sought after in VR due to their ability to preserve user mobility and minimize motion-to-feedback interference. This modality contributes to immersion by reinforcing physical plausibility through body-level sensation.

- Touchable systems deliver feedback through direct contact with an external physical surface or proxy that occupies real space and may be dynamically modulated. The changing characteristics vary, from purely tactile properties like surface friction or texture to hybrids that also add motion and surface shape. This modality contributes to immersion by reinforcing physical plausibility through real surface contact.

Within each category, systems are further organized according to the primary type of feedback they provide, including force, positioning, shape, and texture. This subdivision highlights the diverse strategies used to convey physical properties of virtual objects and environments, as well as the trade-offs between realism, device complexity, and deployability.

The reviewed work emphasizes relatively recent developments, while also incorporating earlier foundational research where it remains directly relevant. Together, these examples illustrate current trends, limitations, and open challenges in haptic interface design, providing context for the design decisions and research direction pursued in this dissertation.

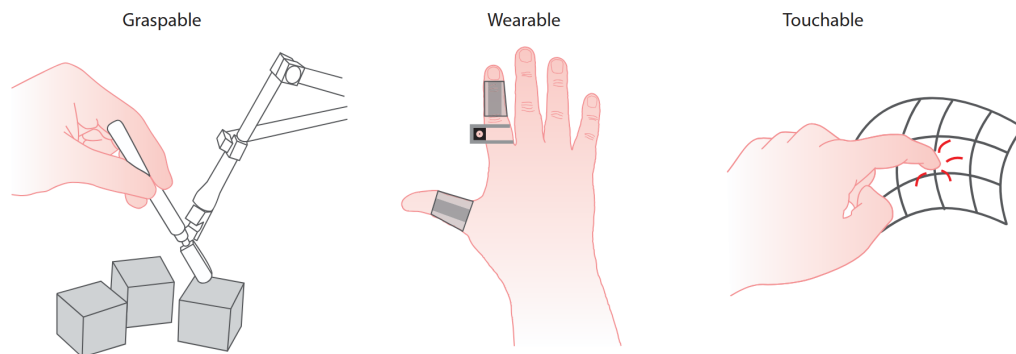


Figure 2.1: Difference between haptic device categories (taken from [15])

In each category, for the same reason as explained in the literature review, we will focus more on more modern projects.

2.1 Graspable devices

We can further subdivide graspable approaches/devices into 4 categories depending on the type of information they give to the user: forces, positioning, shape, texture.

2.1.1 Forces

To increase immersion and physical plausibility in VR, prior research has extensively examined graspable haptic devices that deliver kinesthetic force feedback. These systems apply resistive or inertial forces to the user's hand or controller to simulate interactions with rigid virtual objects, boundaries, or mechanical elements.

Thor's Hammer [30] achieves this effect through the use of a cube of fans (fig. 2.2). By having each fan facing a cardinal direction in relation to the controller, it can create any composite directional force by blowing air so it provides three degrees of freedom (3DOF). It is understandably limited to an average of 4 N of force and has to be plugged in at all times which limits the player's movement a bit.

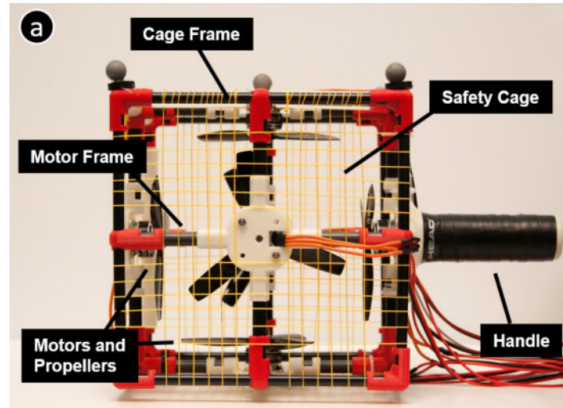


Figure 2.2: Thor's Hammer prototype [30]

Tanabe, Yano, and Iwata [61]'s approach to an untethered graspable device was to create a small vibration speaker. Though the use of asymmetric electric waves fed into the device, a small linear force can be induced on the user holding the device (fig. 2.3).



Figure 2.3: Vibrating Speaker [61]

Fujinawa et al. [22]'s work focuses not on a specific device, but on an algorithmic approach for designing a handheld haptic proxy within a constrained volume, in which weights are placed by the user at computed locations to create the illusion of the intended object. While this represents an interesting solution, it is highly object-specific, as each virtual object requires a complete redesign of the physical proxy, with weights manually placed for each configuration. This makes it not great for dynamic virtual environments.

Shifty [81] explores a more modular design, trading off perceptual accuracy for increased adaptability. By simplifying the device to a tubular form factor, an internal mechanism can shift the weight closer to or farther from the handle (fig. 2.4).

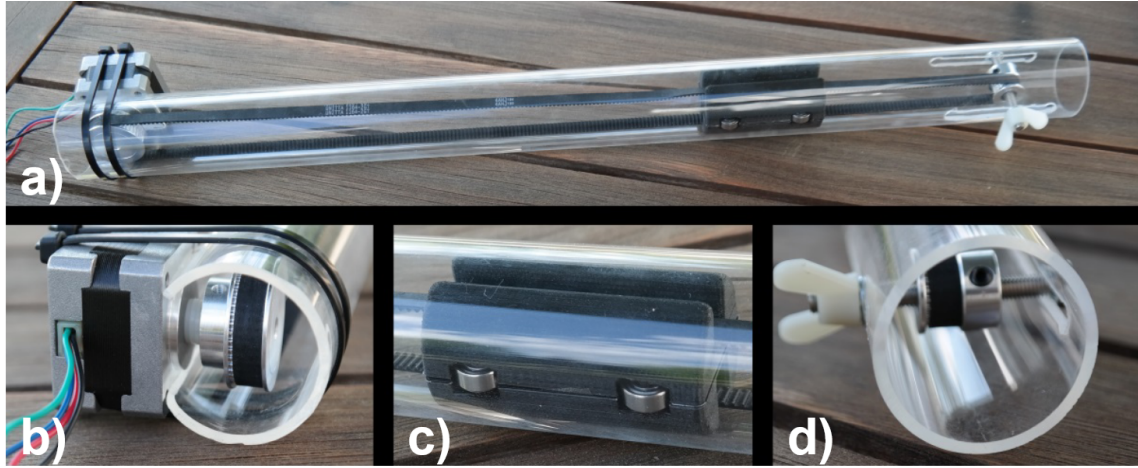


Figure 2.4: Shifty device [81]

Transcalibur [56] can be viewed as a direct evolution of the Shifty concept. Instead of a single linear track, Transcalibur incorporates two tracks that can also rotate around the handle, enabling the representation of more complex weight distributions (fig. 2.5).

Drag:on [80], on the other hand, has a similar physical construction but does not rely on weights moving along tracks. The weight distribution transitions from being concentrated near the handle axis when fully closed to being distributed outward when fully extended (fig. 2.5). In addition, the project incorporates air resistance as an additional feedback given. For example, a virtual object with a large surface area, such as a sign, would be represented by a more distributed weight configuration and would generate increased aerodynamic drag during motion compared to a slender object such as a sword.



Figure 2.5: Transcalibur device (A) [56] and the Drag:on device (B) [80]

The Triggermuscle [59] device was a prototype built by modifying an HTC Vive controller to give it a more dynamic trigger (fig. 2.6). Then in the code, by dynamically changing the trigger resistance according to the virtual object held they can simulate the extra force a user would need to produce to hold on to a heavier object for example.

Similarly, the bstick [36] is a controller that has dynamic buttons but one for each finger (fig. 2.6). Where it differs though is that instead of simulating weight, it focuses on simulating the rigidity of the virtual object. So, for example, a flexible ball offers little resistance on the buttons, while a full metal one would offer the most resistance.

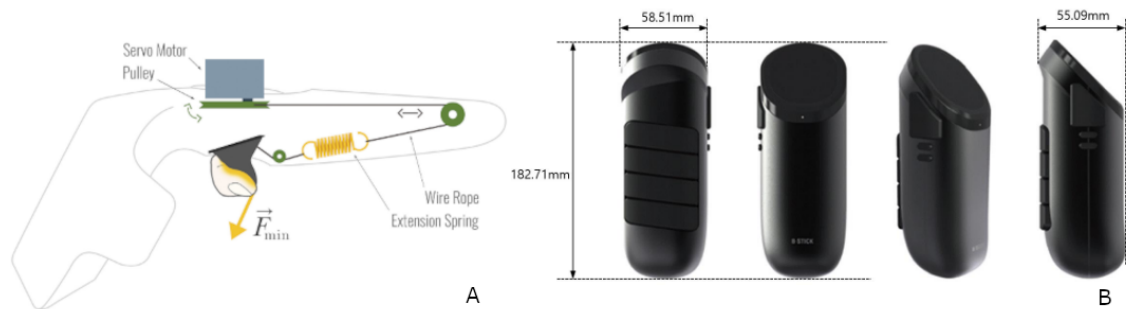


Figure 2.6: Triggermuscle haptic device (A) [59] and the bstick haptic device (B) [36]

The CLAW [13], like the previous two, focus on finger individual forces, but instead of a button, the user's index finger is held on a small cage surrounding it, attached to the controller by an arm (fig. 2.7). Through the mechanism many resistive forces can be applied on the user's index finger, like the force required to pull a trigger in a gun.



Figure 2.7: CLAW handheld haptic device [13]

Grability [14] employs a "pad opposition grip" approach. The device consists of two pads mounted on linear rails that the user grips. These pads mechanically limit finger closure to match the physical constraints of the corresponding virtual object. In addition, the system combines simple vibration cues to signal the initial point of contact with the virtual object and asymmetric

vibration patterns to simulate lateral skin stretch in the lower fingers, conveying the sensation of holding a heavier object.

ReCompFig [77] employs a comparatively complex approach, by having a weight hanging under the graspable part and a series of cables controlling the sensations. By selectively tightening or releasing certain cables, the weight is only able to move along a set of intended degrees of freedom (DOF). Simulating the sensation of holding a cup partially filled with liquid corresponds to leaving all cables unlocked, allowing the weight to move freely (fig. 2.8). In contrast, when simulating a flexible ruler, two cables are locked so that the weight behaves as a pendulum constrained to the plane of the ruler's bending. Finally, when representing a rigid bar, all cables are locked, immobilizing the weight relative to the device's motion.

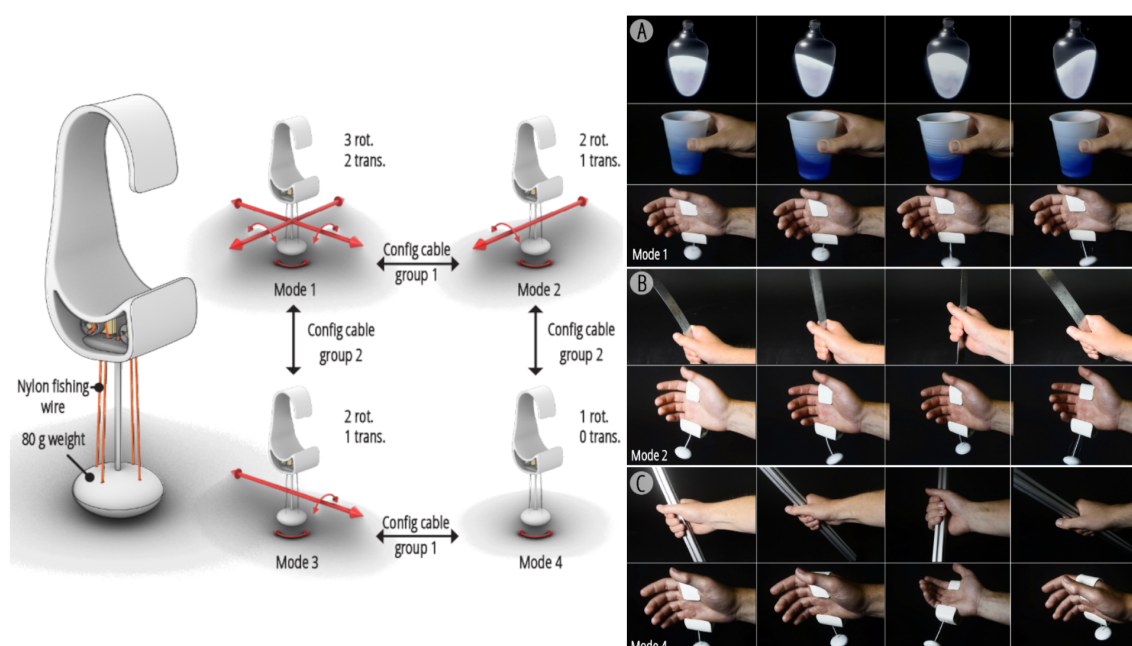


Figure 2.8: Simulation of some objects in ReCompFig [77]. A cup (A), flexible ruler (B), solid bar (C)

ElastOscillation [69] adopts a similar principle but positions the movable mass at the center of a spherical structure mounted above the handle, with the sphere suspended using elastic bands arranged along six directions. As with ReCompFig, the system can constrain motion along selected axes, enabling the weight to move in controlled patterns that modulate the user's perceived sensation (fig. 2.9).

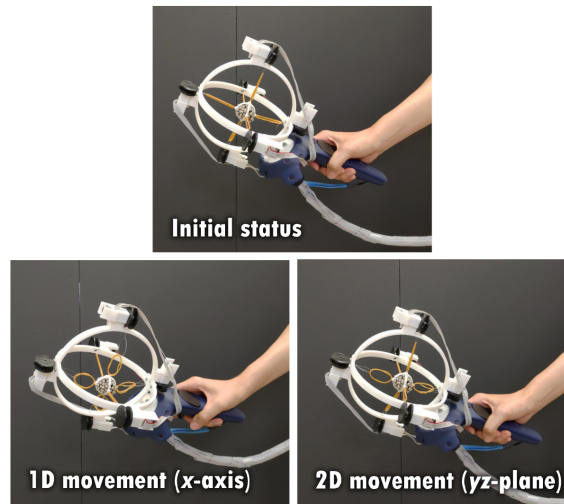


Figure 2.9: ElastOscillation device [69]

DualVib [62] adopts a comparatively complex approach based on the simple principle of vibration (fig. 2.10). Through the use of asymmetric vibration patterns, the system is able to produce "pseudo-force feedback", while "acoustic vibrations" are employed to "reproduce object's surface vibrations to render texture feedback"

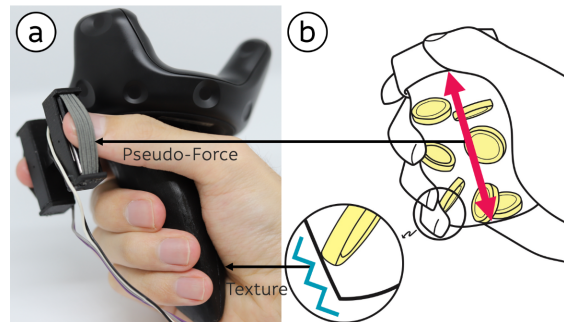


Figure 2.10: DualVib haptic device

ElastiLinks [71] adopts an approach in which resistive feedback is generated between two handheld controllers. By attaching the controllers to one another using two distinct elastic bands and a mechanism for controlling their resistance, the system is able to dynamically modulate feedback according to the requirements of the virtual scene.

As described by the authors, each elastic band serves a separate function. The resistive link consists of a long, slender elastic element designed to provide resistance to the separation of the two controllers. In the reported experiments, this mechanism is used to simulate actions such as drawing a bow. By increasing the elastic tension via a DC motor, the system can represent different interaction profiles—for example, a slingshot, which requires higher force over a shorter displacement compared to a full-sized bow (fig. 2.11).

The second elastic band, referred to as the impact force link, is shorter and thicker. Using the braking mechanism of a DC motor, tension can be accumulated in the elastic and released

on demand, producing a sudden force impulse on the controllers. This allows the simulation of impact events, such as weapon firing. In addition, the system supports attaching one controller to a fixed external object when appropriate within the virtual environment, as demonstrated in the fishing interaction experiment. Consequently, the device can operate in both tethered and untethered configurations (fig. 2.11).

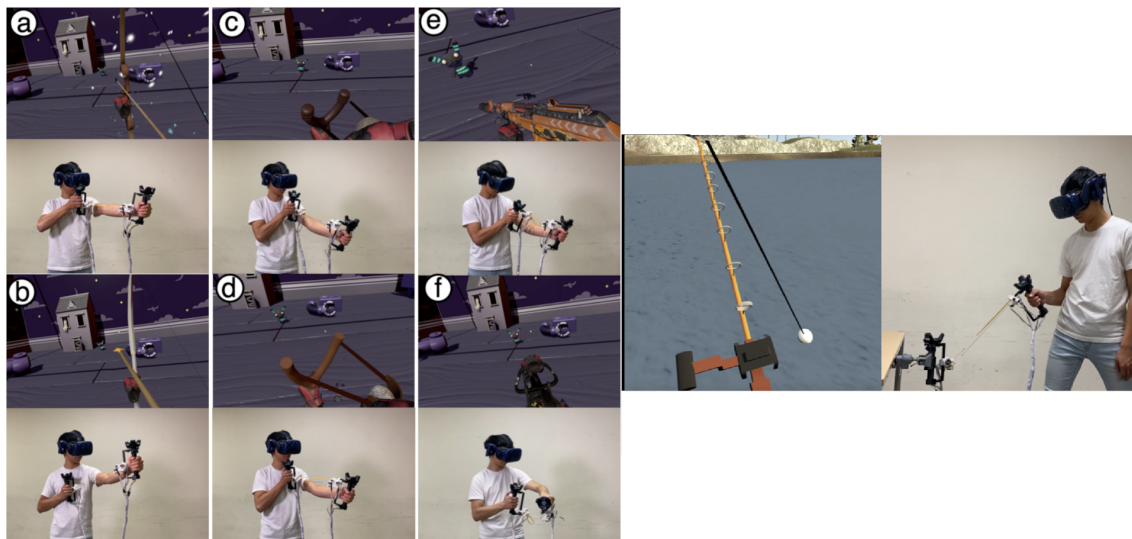


Figure 2.11: ElastiLinks haptic device experiments [71]. Left shows diferent untethered setups, while to the right a tethered setup.

Yoon et al. [78]’s idea was to attach a grabable block to 4 cables and have the cables exert the forces on the block. This way they can represent any force on any direction limited to the plane the block sits on so it only provides two degrees of freedom (2DOF).

2.1.2 Positioning

In Graspable haptic interfaces that rely on their positioning systems, the user holds or manipulates a physical proxy whose position, orientation, or trajectory is actively controlled to match a virtual object’s behavior, conveying spatial constraints, object dynamics, or guided motion paths. This approach reinforces physical plausibility by reducing spatial mismatch between visual and haptic cues, which has been shown to contribute positively to immersion and presence during virtual manipulation tasks [55].

Moreira [47]’s approach is to have a tiny multidirectional robot moving a ball in 2DOF in real space to overlap with an apple’s resting position in the virtual environment, so when the user tries to pick up the apple, their hand would also contact the real ball, adding to the sense of immersion.

Abtahi et al. [1]’s approach was to have a flying drone carry the items around for the user to pick up so it employs 3DOF (fig. 2.12).



Figure 2.12: Abtahi et al. [1]’s haptic device

These projects have, of course, the limitation that they need to have a physical object that matches each virtual one at least somewhat to still have a believable effect, so it’s not very well suited for dynamic virtual reality environments.

2.1.3 Shape

This category focuses on haptic devices that can change their shape to match the interactable item in virtual space. This approach, similarly to positioning, achieves immersion by reinforcing physical plausibility. Unfortunately, unlike positioning, it is much more complicated, as making such a mechanism that can take various shapes still has many limitations.

Pediredla et al. [51]'s proposed mechanism has 2 contact points, where the user is expected to place a finger in each as if to pinch the machine. The machine then has 3DOF, pulling towards you and pushing forward, rotating your hand, and the pinching movement (fig. 2.13). The machine can then increase or decrease the radius of the 2 contact points as to simulate the shape of the virtual object being pinched and can also simulate texture by vibrating the contact points accordingly as the user's rotates the fingers on the surface.

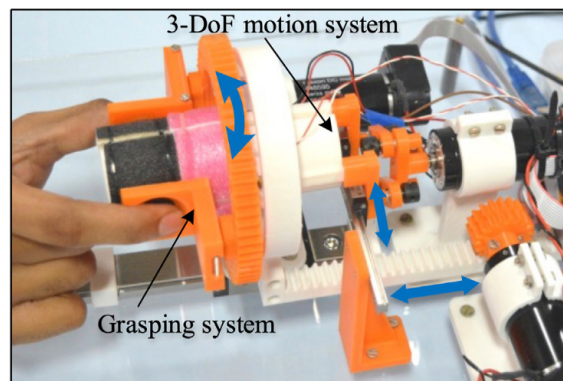


Figure 2.13: Pinch motion on the haptic grabber [51]

X-ring [27] focuses on grasping the item fully, with multiple separate surface sections that extend out to match the virtual object in the game (fig. 2.14). This approach only simulates shape and is limited to objects you can grasp. Also this particular prototype does not have much fidelity as it only divides the handle into 4 layers of 5 surfaces.



Figure 2.14: X-Rings (A) is a 360° shape display designed to support grasping. The device is hand-mounted (B.1), allowing the fingers to grasp and release rendered objects freely (B.2). Four expanding layers enable rendering of many virtual objects, such as a tankard (C) and goblet (D) [27]

Shape-a-Ghetti [6] design was based on "Hoberman's shape-changing sculptures". By rotating the poles you can get all the different shapes between fully open and fully closed (fig. 2.15). It's, unfortunately, a tethered device, so not great for dynamic virtual environments.

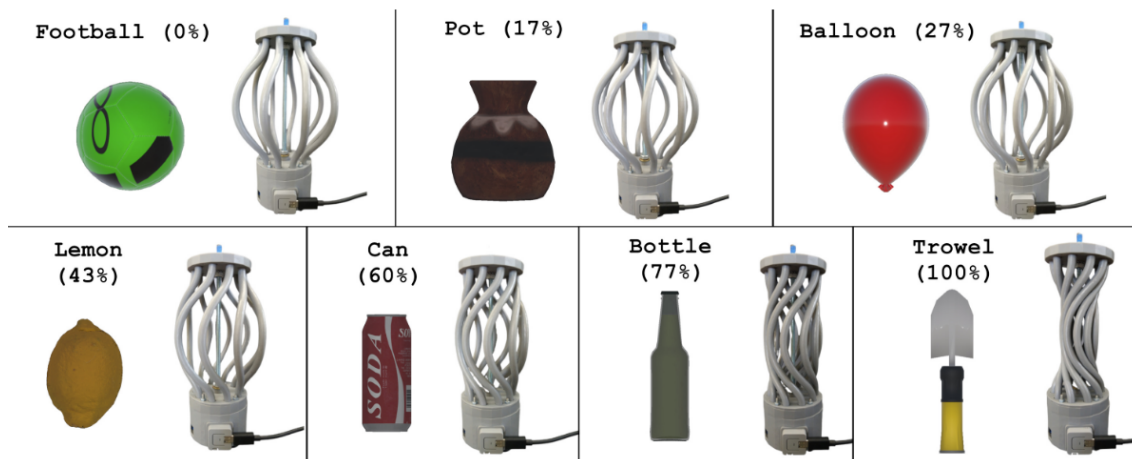


Figure 2.15: Shape-a-Ghetti in various different settings [6]

WeATaViX [64] focuses on representing small ball like objects. This device is attached to the user's arm and has a ball on a lever arm. The arm is moable by a motor and the ball has sensors to detect if the user grabs it (fig. 2.16). By moving the ball into the user's palm they can simulate the user's hand getting close to a similarly shaped virtual object. The user can then throw the ball in the virtual environment as they throw the real ball but the latter one doesn't get much further from the user's hand as the arm doesn't allow it.

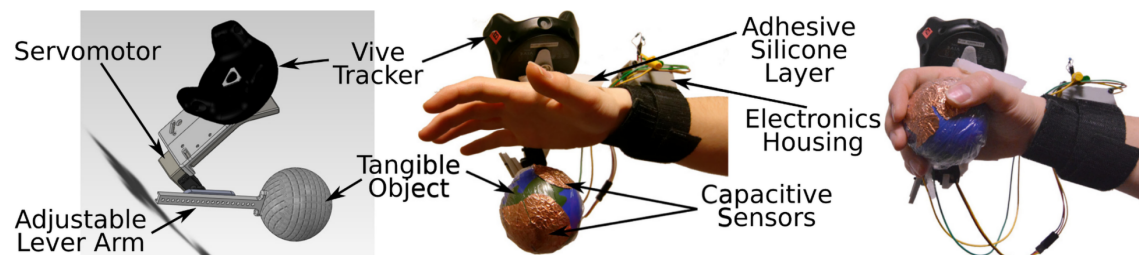


Figure 2.16: WeATaViX device [64]

The PuPoP [63] is a set of haptic devices created around the idea of one or more inflatable bags that can form basic shapes to represent the virtual graspable objects (fig. 2.17).

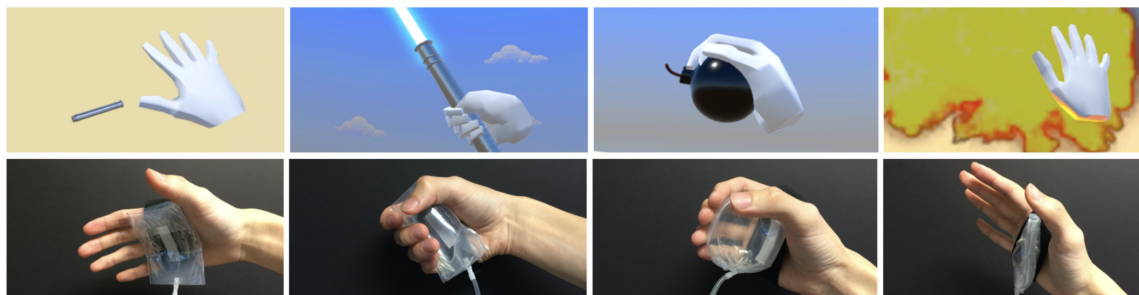


Figure 2.17: PuPoP haptic device [63]

The Haptobend [45] is a controller replacement composed of 4 rectangular sections. The user by bending the sections over each other, a series of 2D and 3D shapes can be created, and the sensors can show the represented shape in game (fig. 2.18). The device's utility seems mostly dependent on software implementation which they did not develop for the prototype's paper unfortunately.

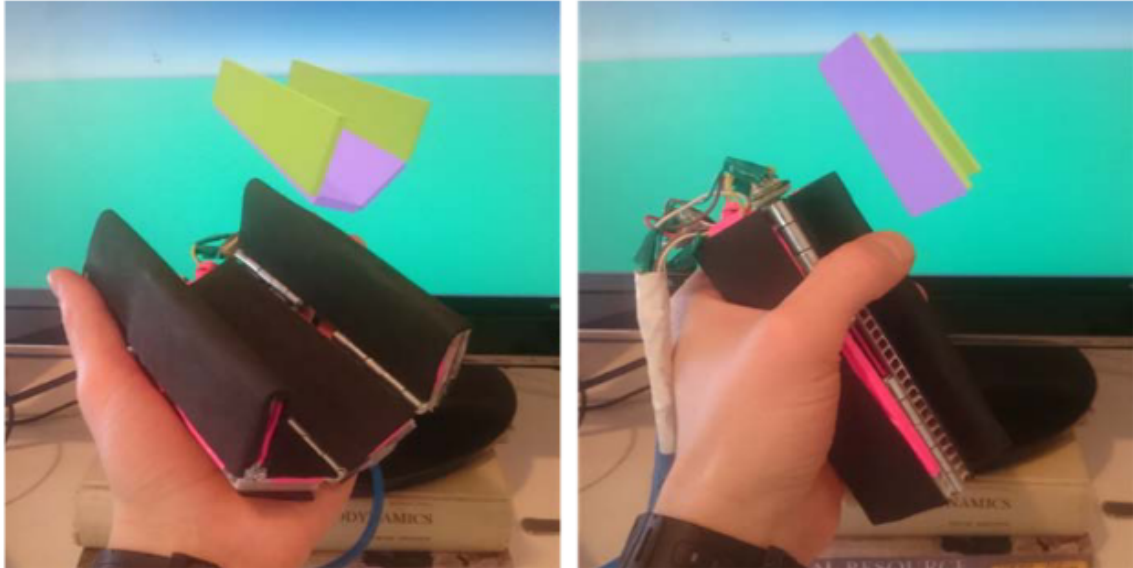


Figure 2.18: Haptobend demonstration [45]

While some different approaches were to make some kind of modular block system:

Zhao et al. [82]'s approach is a set of magnetic blocks that attach to one another to form the desired shape. They have a diverse set of different blocks as well, some are active and move by themselves and drag other blocks while others are passive and need to be moved by the active blocks or a user (fig. 2.19). While a good idea, it's ultimately plagued with occasional building mistakes as they themselves explain on the paper.

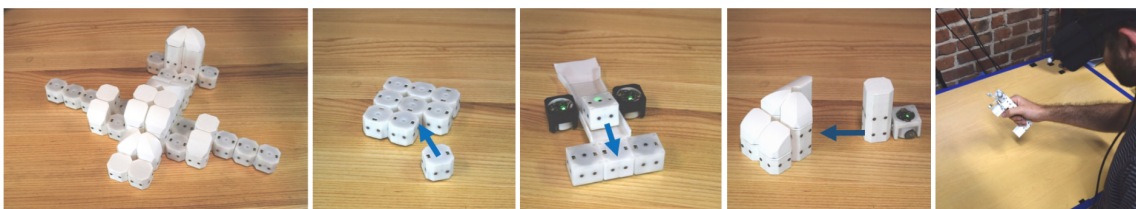


Figure 2.19: Examples of the way the building blocks can be setup [82]

HaptTwist [83] went with a similar idea but bases itself on the rubix's twists, focusing on a simpler, more cost effective design but that unfortunately lacks resolution and the automatic building of the previously mentioned project.

Ninja track [32] is a set of building blocks that can dynamically change the links's stiffness, making the strips both flexible and stiff on demand. They then developed some prototypes to

demonstrate the mechanisms, like a sword/whip hybrid device (fig. 2.20). Very interesting concept, despite being limited to a set of pre-produced shapes, can still be used as a starting point to a various set of prototypes.

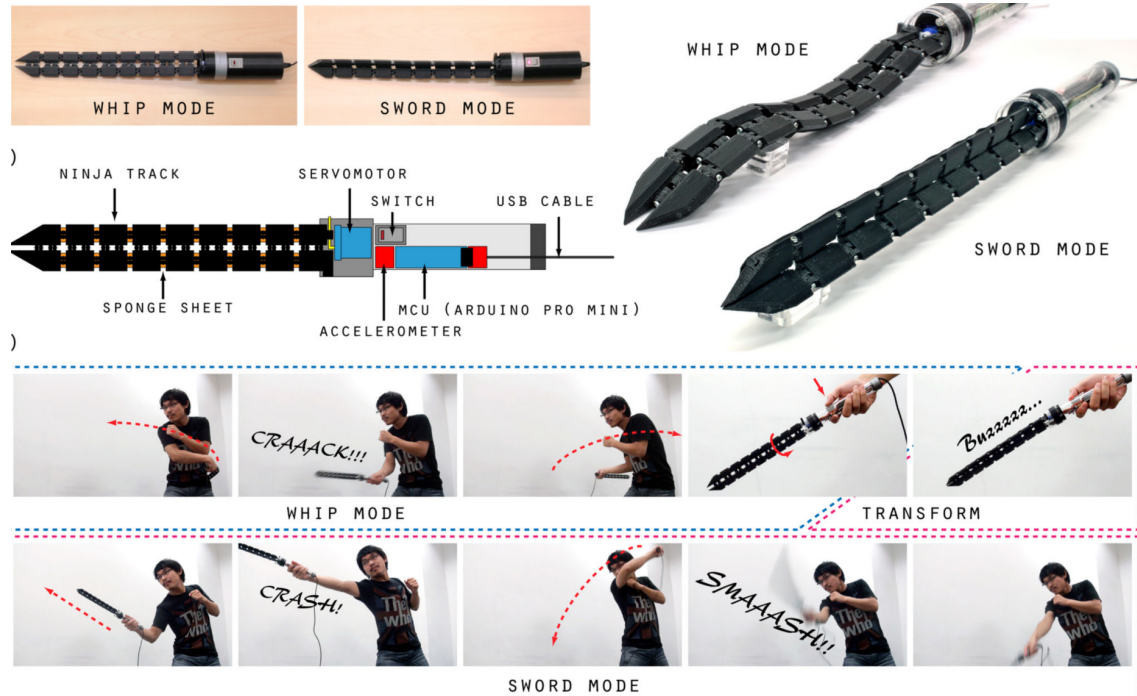


Figure 2.20: Ninja Track sword/whip prototype [32]

PoCoPo's [79] approach is to have a grid of 36 pins that can move up and down to represent basic shapes of part of the graspable object. Very limited in fidelity.

Benko et al. [7]'s paper, defines two prototypes, the NormalTouch and TextureTouch. Both try different approaches of representing finger level haptics, where Normal touch is just a platform that moves up and down and tilts to accompany the virtual objects shape. The Texture touch on the other hand, has a 16 pin array that can individually move up and down to represent the virtual object's shape.

2.1.4 Texture

Texture changing handheld haptics is a fairly underexplored category, mostly because of its difficulty and seemingly diminishing returns.

The Materializer [53] is an approximation of a cylindrical object, with a central ring filled with 5 prism structures, each prism has 3 faces that would be loaded up with a strip of material per face. By turning the mechanism to a specific material facing outwards in each prism, the cylindrical real world object now has a literal texture that you can feel. If the virtual item is made of wood, the prisms would rotate so that the wooden strip would face outward, matching the item's texture in the game. The obvious limitation here is that the Materializer can only have 3 materials available at any point.

Cai and Zhu [9] propose a transformer-based algorithm that, given a specific haptic stylus–display configuration, generates a set of parameters enabling the haptic hardware to reproduce the desired surface texture.

The Haptic Revolver [72] adopts an approach in which a circular cylinder is positioned beneath the index finger’s resting point. The wheel component is replaceable, and by rotating it, the device can generate a variety of tactile effects. For example, a wheel may incorporate multiple strips of different materials; as the user approaches a specific virtual object, the wheel rotates to align the corresponding material with the user’s finger. Upon contact in the virtual environment, the wheel moves upward to make physical contact with the fingertip (fig. 2.21).

Alternatively, a wheel composed of a single material can be used, where lateral finger motion across a virtual surface causes the wheel to rotate accordingly, reproducing friction-related tactile cues associated with the simulated surface.



Figure 2.21: Haptic Revolver with two different cylinders[72]

2.2 Wearable devices

Wearables have a similar set of sub-categories as Graspables, with the exception of positioning feedback as these two characteristics are just incompatible.

2.2.1 Forces

The wolverine’s [12] approach was to attach three of the the user’s fingers to the thumb in the same hand. They’re attached by 3 metal rods that each finger’s holder slides on. With a couple of small motors, they apply force to the fingers, pulling them together or pushing them apart. Though the use of some software, they can give the user the impression that there is something there that they are holding on to (fig. 2.22).

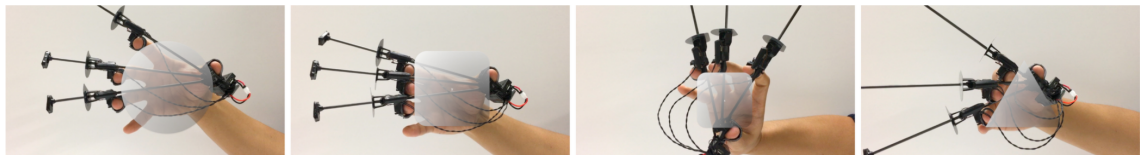


Figure 2.22: Wolverine prototype [12]

Wireality's [19] approach is to have each finger of one of the user's hands attached to a cable, this cable is then attached to a set of motors on the user's shoulder and can pull on each cable independently. By pulling on the cable, certain forces can be applied to the user's hands, namely those forces of interacting with the virtual objects.



Figure 2.23: Wireality haptic device [19]

Fröhner et al. [21]'s approach was to create a glove with two "thimbles", one attached to the index finger, the other to the thumb. Both are trackers that the software uses to track some basic grasping motion and they can also give some basic feedback like vibration and normal feedback.

The LinkTouch [70] archives haptic feedback by having 2 arms moving across or on and off the user's finger. Not a very high fidelity device but very lightweight.

The HapThimble [34] device is both a haptic surface as is a haptic wearable device. The problem they sought to fix is that virtual surfaces through the use of AR, for example, lack the feedback of a physical surface. Their approach is then of a mechanism that can pull on the user's index finger. Through the use of the motor sitting on the back of the user's hands, certain forces can be put on the user's finger, like preventing the finger from moving further than the virtual screen or even some vibration for UX elements.

Dragusanu et al. [17]’s design, is that of a ball that moves on the user’s palm, doing small tilts and up and down movements. It uses cables to move the ball and has dc motors sitting on the back of the users hands to pull on. By moving the ball on the users palms, various forces can be simulated.

Similarly to the graspable thor’s hammer [30], the PropellerHand [2] attempts force feedback through the use of fans. Two fans are mounted on the user’s glove, and by independently controlling their rotation, the system can generate force feedback in multiple directions (fig. 2.24).

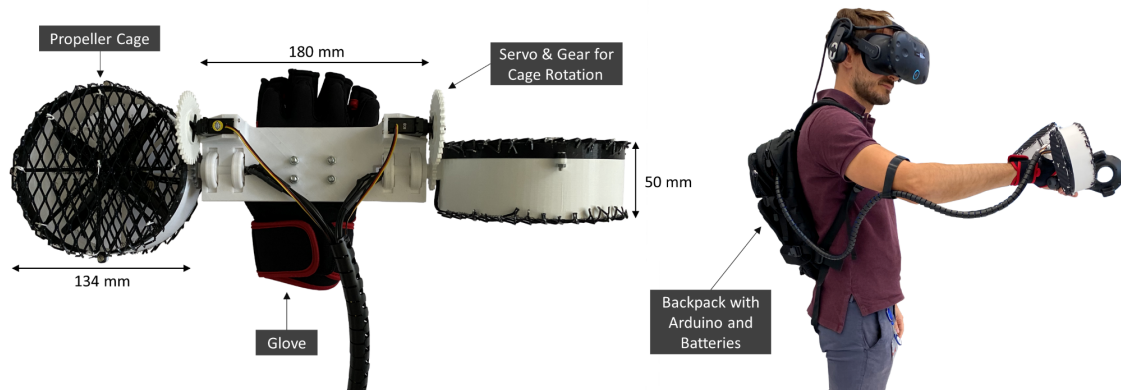


Figure 2.24: PropellerHand Device [2]

The Impacto [42] is a sleeve device that uses electric stimulation and a tactile stimulus to simulate the virtual forces like getting hit with a punch. A small solenoid extends to tap the user’s skin while the small shock works to force the arm backwards. The same authors picked up the project later on and ended up with a more complex version that only does electrical stimulation but has 8 electrodes instead of one, to be able to produce more precise haptic feedback [43].

The SoundHapticVR [11] is a set of head-mounted devices that through vibration, assist the user on locating sound source directions. Through the use of vibrations of various intensities, the user is given cues on the sound source’s location (more vibration means that device is closest to the source). Despite being a novel idea, applications were reduced to only 4 devices on the user’s head, one per cardinal direction. As such, any potential fidelity had to be reduced to sound directions.

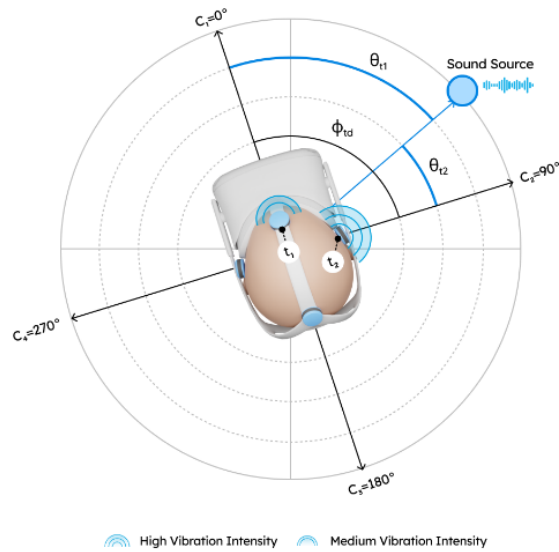


Figure 2.25: Demonstration of the SoundHapticVR device [11]

The faceHaptics [74] is a set of haptics that attach to the **HMD**. The device has a fan that can blow air of various sensations to the user's face. For example, it can heat it up to give a sensation of warm wind, or, in combination with a spray nozzle, make the air more or less humid. Then a moving and rotating arm can with an interchangeable head can give various other sensations. For instance, a feather lightly grazing the user's face (fig. 2.26), or even of a cookie placed on the arm for the user to bite on. As the creators themselves comment on, the act of "reloading" the arm is a limitation.



Figure 2.26: FaceHaptics haptic facial device [74]

Dunkelberger et al. [18]'s approach was of a sleeve device that through tightening and and twisting diferent parts, sentences can be transmited to the user, that is, given that the user learns the code beforehand. Not made for **VR** but still important for the research. Similarly Aggravi et al. [3]'s and the hBracelet's [46] design is also of a sleeve that acts on the user's skin. By tightening or stretching laterlly on the user's arm in on example they give is that informs the user that they

are reaching a constrain in the virtual space. hBracelet has some improvements over the former though as it is capable of making more complex and precise actions on the user's arms.

The hRing [50] approach is similarly of pinching the user to signify a virtual constraint. This device being worn on a finger instead of the arm.

Lee, Lee, and Lee [40] present a wearable glove-based haptic device that applies force feedback to the user's thumb and index finger via a set of actuated cables. By modulating cable tension across different control modes, the system simulates varying material properties of virtual objects during grasping. For instance, a stiff mode restricts finger motion to represent incompressible or rigid objects, whereas an elastic mode allows controlled displacement, conveying the sensation of deformable materials.

Moriyama and Kajimoto [49] addressed the same problem by employing a haptic transfer method. Rather than applying forces directly to the fingers to physically restrict movement, their system uses a five-bar linkage mechanism to transmit the magnitude and direction of virtual forces to the user's forearm. As the forearm is deeply connected to the hand, they can apply precise forces on the forearm to restrict certain finger movement.

The HapPro [54] device has a similar approach but for a different problem. By applying more precise forces on the forearm they can induce on the user the desired restrictive sensation when they attempt to close their hand around a virtual object, reducing the disconnect between the virtual space and the real sensations.

2.2.2 Temperature

Lu et al. [44]'s approach was a sleeve that is capable of giving the user a cooling and heating sensation, by pumping certain chemicals on the sleeve's inner tubing. Similarly, the ThermoCaress [41] and PATCH [26] are also sleeves, but instead of chemicals they simply pump hot or cold water. The ThermAirGlove's [10] approach was of a glove that acts as both a controller and haptic device. So, beyond tracking it has airbag areas for each finger and can pump air of various temperatures through them.

Face/On [76] is a set of devices attached to the user's **HMD**. Through the use of Peltier elements, the system is able to actively heat or cool the contact points depending on the direction and magnitude of the applied current (fig. 2.27). This enables the delivery of localized thermal cues directly to the user's face. In addition, the device integrates vibrotactile actuators to provide complementary vibration-based feedback.

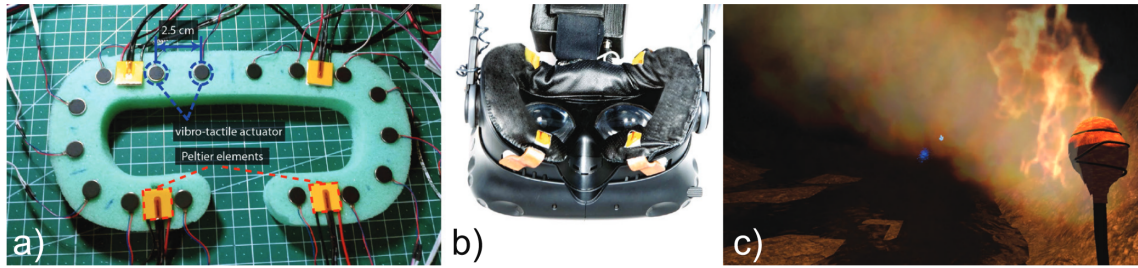


Figure 2.27: Face/On device [76]

2.2.3 Shape

Kuang et al. [38]’s approach is of having changeable parts to represent different materials or shapes. The movement is controlled by two arms who can make the parts move up or down or bend on itself (fig. 2.28). The different parts moving on the user’s palm in accordance to virtual items induces immersion.

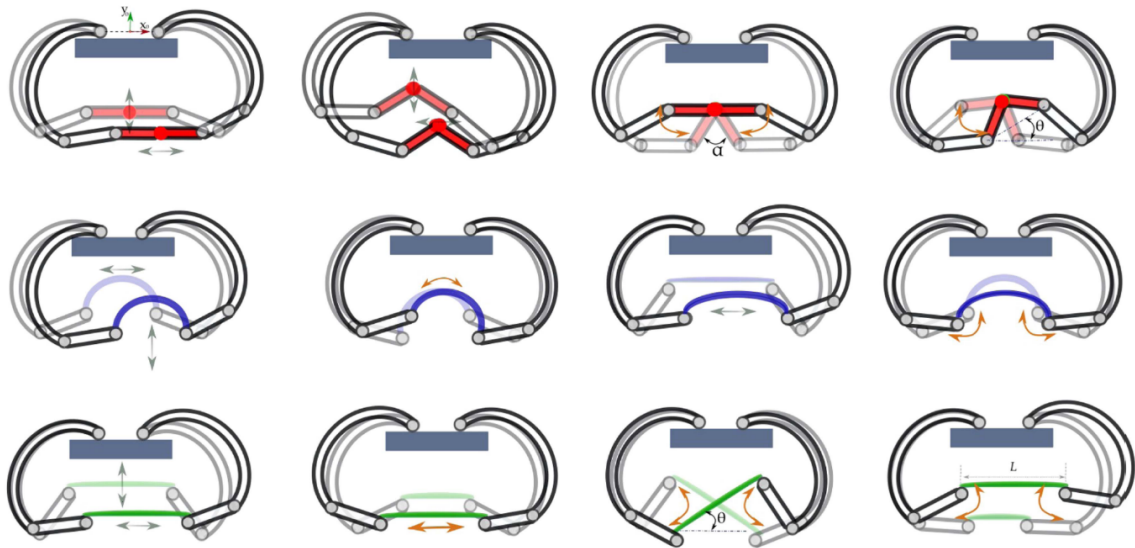


Figure 2.28: Kuang et al. [38]’s haptic device moving the interchangeable parts represented by the colors while the user’s hand sits in the middle of the device, facing down

2.2.4 Texture

DeltaTouch’s [65] approach was to make a tiny ball moving across the user’s palm to simulate certain texture sensations. The ball being moved by 3 independently movable arms that can precisely move the ball to every part of the area of a circle the device is built upon. It was later slightly refined with a more complex set of movable arms [67] and then combined with some extra vibration motors in a haptic glove [66](fig. 2.29).

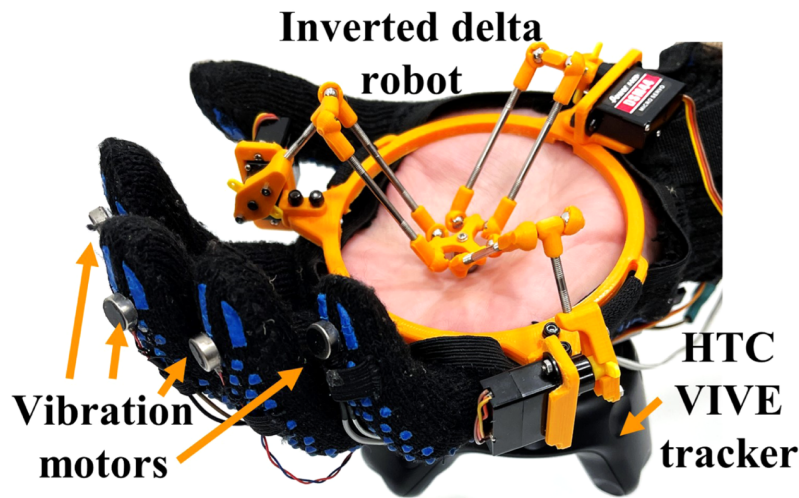


Figure 2.29: DeltaTouchVR's final iteration in [66]

Günther et al. [28]'s haptic device is a movable arm that places a material in contact with the user's forearm. The project shows testing with various materials of varying roughness. By moving the correct material corresponding to the virtual material, it induces immersion as intended. Limitations are the need to have a sample of various physical materials.

2.3 Touchable devices

2.3.1 Force

Hoppe et al. [31], Knierim et al. [35], and Moreno et al. [48] explore a similar concept in which a flying drone delivers force feedback to the user that corresponds to elements of the virtual environment. In these systems, the drone physically interacts with the user. For example, making contact to represent obstacles or virtual walls. FlyHaptics [48] extends this approach by enabling the user to press their hands onto the drone's surface and as the user moves, the drone provides shape-related feedback corresponding to the virtual object being explored (fig. 2.30).

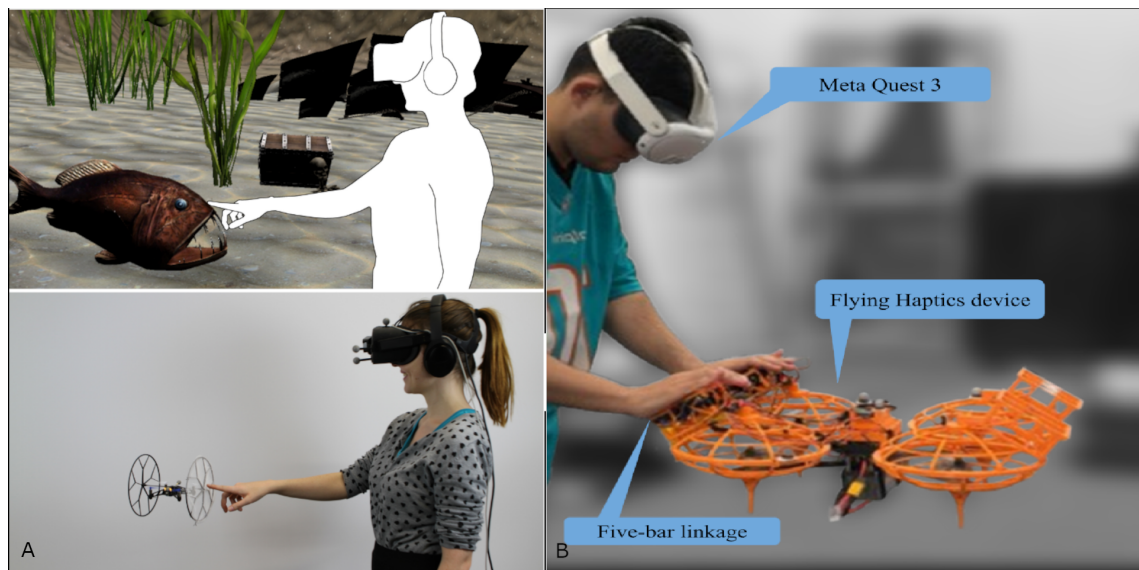


Figure 2.30: a) shows the Hoppe et al. [31]’s drone, while b) shows [48]’s drone

The Whiskers [25] device is not primarily designed as a virtual reality haptic interface and does not clearly fall within the established device categories; however, it remains a relevant reference in the context of facial haptics. By resting the head against the device, focused tactile forces are generated on the user’s face through the use of ultrasonic actuation, enabling localized and spatially precise stimulation.

2.3.2 Shape

ShapeShift [57] is a high-resolution, modular tabletop display consisting of 288 actuated pins. It can render dynamic surfaces, such as terrain maps, in real-time as the user’s hand moves. By adjusting each pin’s height it’s possible to approximate the shape of a virtual item and as the entire platform is movable, it can follow the human’s hand and be able to represent a much bigger virtual surface than it’s real life counterpart. Limitations are that it can only represent a set surface up to a low fidelity of 288 points and it can’t create every shape perfectly. One such example is of a controller that doesn’t have a bottom or is possible to pick up for that matter (fig. 2.31).

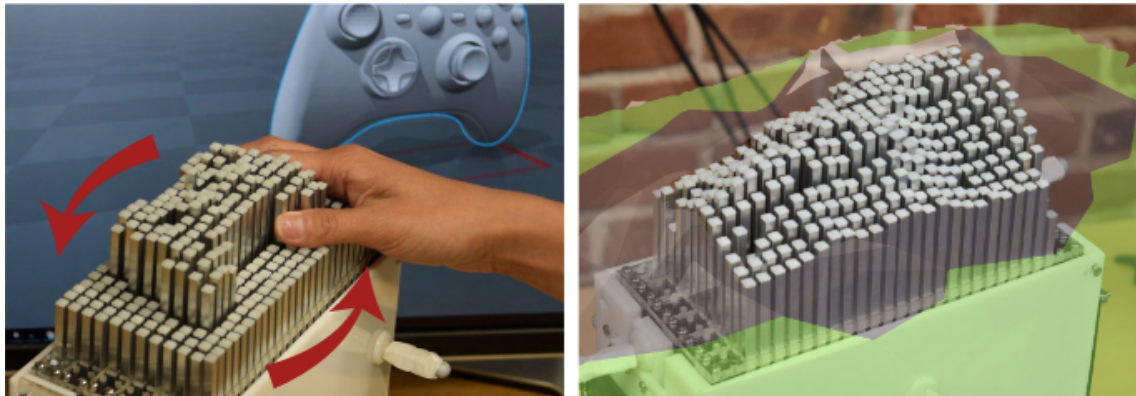


Figure 2.31: ShapeShift adjusted to the shape of a controller 3D model [57]

Non-contact shapes can be achieved via "Airborne Ultrasound Tactile Displays" [60], which use phased arrays of ultrasonic transducers to create mid-air focal points. This technology provides tactile shape sensations through acoustic radiation pressure without any physical attachment. While the range of renderable shapes is currently limited to relatively simple forms, AUTD systems represent an intriguing approach to delivering touch-based feedback in mid-air.

2.3.3 Texture

The Snake Charmer [5] consists of a robotic arm equipped with an interchangeable head. By tracking the user's hand motion using a depth camera, the system spatially aligns a physical surface with a matching texture immediately before contact occurs (fig. 2.32). By swapping the head, different material surfaces can be presented to correspond with the virtual objects being touched. Some heads they show have actual buttons if the virtual environment requires one.

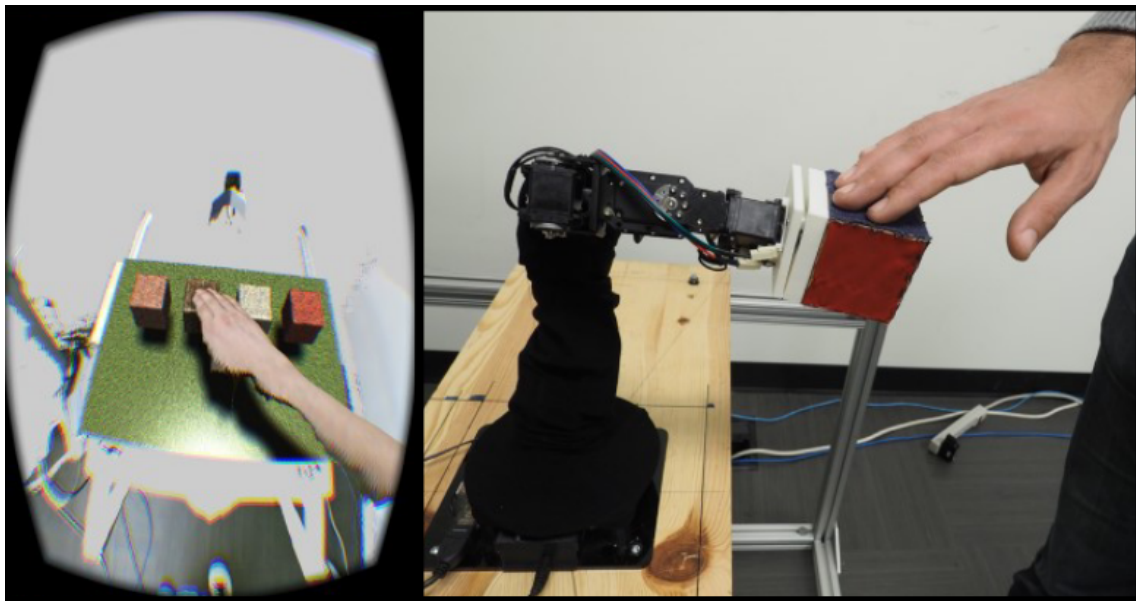


Figure 2.32: Snake charmer device [5]

Germani, Mengoni, and Peruzzini [23] provided a non-mechanical approach to texture. By using a grid of pin electrodes, the system stimulates certain skin receptors to simulate roughness and coarseness derived from real material scans. Thorough testing iteration they combined it with sound to obtain better results.

HAPmini [33] is a touchscreen-based haptic device that uses a set of magnets to generate tactile feedback. The device rests on top of the touchscreen and is dragged by the user during interaction. It employs a simple 1-DoF feedback mechanism, in which magnetic forces either pull the contact surface beneath the user's finger toward the center or push it outward (fig. 2.33).

Through this mechanism, HAPmini is able to render virtual textures by reproducing acceleration profiles derived from real materials (e.g., paper, wood, or sandpaper). The system also features a function referred to as hardware magnetic snap, which uses the same magnetic actuation principle to guide the user's finger toward predefined target locations on the screen.

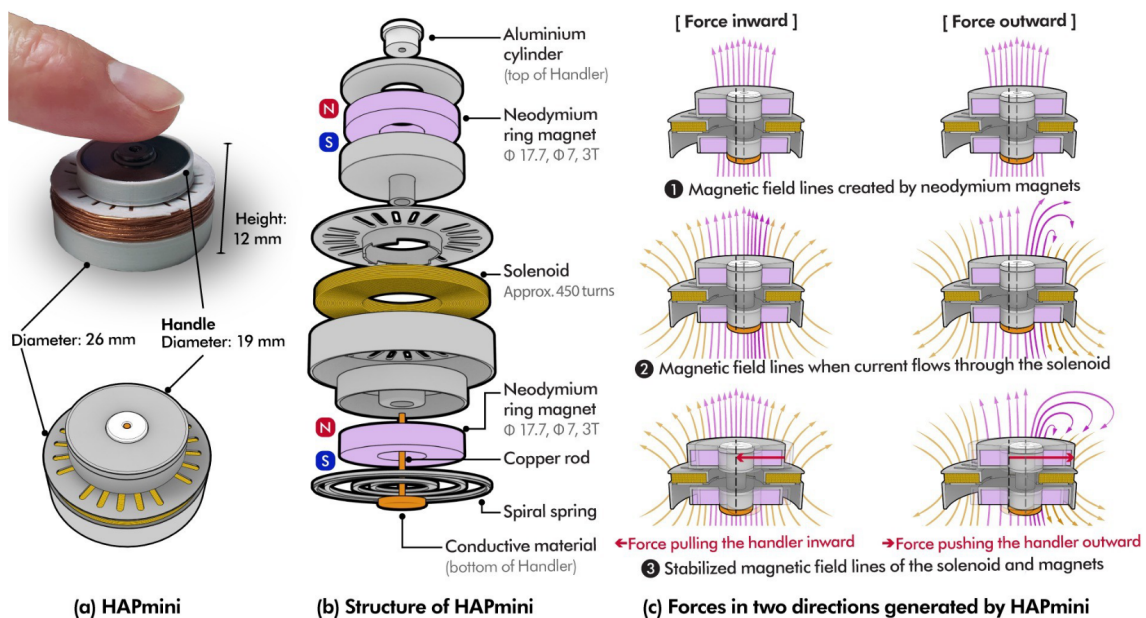


Figure 2.33: HAPmini device [33]

Alma, Rosenkranz, and Altinsoy [4]'s project suggests that most mobile vibration hardware, such as the ones on smartphones, lacks the fidelity to properly utilize the texture info saved in databases. Their solution was to simplify vibrations to the minimum they could without losing any fidelity on those devices, and using paper with graining of various sizes to compensate.

Table 2.1: Summary of researched haptic graspable devices

Graspable Devices			
Forces	Positioning	Shape	Texture
Thor's Hammer [30] Tanabe, Yano, and Iwata [61] Fujinawa et al. [22] Shifty [81] Transcalibur [56] Drag:on [80] Triggermuscle [59] bstick [36] CLAW [13] Grabity [14] ReCompFig [77] ElastOscillation [69] DualVib [62] ElastiLinks [71] Yoon et al. [78]	Moreira [47] Abtahi et al. [1]	Pediredla et al. [51] X-ring [27] Shape-a-Ghetti [6] WeATaViX [64] PuPoP [63] Haptobend [45] Zhao et al. [82] HaptTwist [83] Ninja track [32] PoCoPo [79] Benko et al. [7]	Materializer [53] Cai and Zhu [9] Haptic Revolver [72]

Table 2.2: Summary of researched haptic Wearable devices. To note that the FaceHaptics Device fits into multiple categories

Wearable Devices			
Forces	Shape	Texture	Temperature
FaceHaptics [74] Wolverine [12] Wireality [19] Fröhner et al. [21] LinkTouch [70] HapThimble [34] Dragusanu et al. [17] PropellerHand [2] Impacto [42] SoundHapticVR [11]	FaceHaptics [74] Kuang et al. [38]	FaceHaptics [74] DeltaTouch [65] Günther et al. [28]	Lu et al. [44] Face/On [76]

Table 2.3: Summary of researched haptic Touchable devices

Touchable Devices		
Forces	Shape	Texture
Hoppe et al. [31]	ShapeShift [57]	Snake Charmer [5]
Whiskers [25]	Airborne Ultrasound Tactile Display [60]	Germani, Mengoni, and Peruzzini [23]
Knierim et al. [35]		HAPmini [33]
Moreno et al. [48]		Alma, Rosenkranz, and Altinsoy [4]

2.4 Conclusion

Existing approaches demonstrates significant progress in the design of haptic interfaces for virtual reality, particularly in the domains of hand-centered interaction and object manipulation. Graspable and wearable devices dominate the landscape, reflecting the central role of the hands in interacting with virtual objects. These systems effectively convey force, shape, texture, and temperature cues, often achieving high perceptual realism at the cost of increased mechanical complexity, bulk, or restricted mobility.

Touchable systems, while less prevalent, illustrate the benefits of direct physical contact with external proxies, enabling high-fidelity shape and texture rendering. However, their reliance on grounded or spatially constrained hardware limits their applicability in dynamic or room-scale virtual environments.

Across all categories, a common trend emerges: haptic feedback is overwhelmingly focused on the upper limbs—particularly the hands and fingers—while other body regions remain comparatively underexplored. This focus is understandable given the hands’ role in manipulation, yet it leaves open questions regarding how haptic feedback delivered to alternative, perceptually sensitive body areas may contribute to immersion, presence, and emotional engagement.

In contrast to the hands, the face is a highly sensitive and expressive area, strongly associated with affective perception, social interaction, and threat awareness. Despite this, facial haptics remain largely absent from contemporary VR systems. Only a limited number of approaches have explored facial feedback, including SoundHapticVR [11], Face/On [76], FaceHaptics [74], and Whiskers [25]. These systems demonstrate the potential of facial haptics but are constrained by factors such as limited spatial granularity, restricted force expressiveness, or hardware configurations that are difficult to integrate into mobile VR setups.

Chapter 3

Facial Airflow for Haptic Feedback in VR

The preceding review of the state of the art demonstrates that while haptic feedback research has produced a wide range of graspable, wearable, and touchable solutions, the face remains a comparatively underexplored target for haptic stimulation in virtual reality. This chapter describes the proposed system designed to address this gap. Beginning with an analysis of the haptic modalities best suited to facial stimulation, the chapter then presents the overall system description and architecture, before concluding with the safety considerations that informed the design constraints of the prototype.

3.1 Analysis of possible stimuli

Before committing to a hardware approach, a preliminary analysis was conducted to identify which types of haptic sensations are most relevant to facial feedback in VR and which physical modalities could plausibly reproduce them. Table 3.1 maps a set of target sensations, drawn from common VR scenarios, to the haptic modalities capable of simulating them, while table 3.2 suggests hardware configurations that could implement each modality. This analysis informed the selection of airflow as the primary feedback mechanism, as discussed at the end of this section.

Table 3.1: Examples of simulated sensations and their respective haptic modalities

Sensation	Temperature	Touch	VibroTactile	Electricity	Air	Humidity
Standing near a campfire	•					
Standing under a warm sun	•					
Cool/Freezing wind	•				•	•
Wind blowing on the users face as they run					•	
Getting hit on the face by a branch while running		•	•	•	•	
Getting slightly grazed on the face by some leaves		•	•	•	•	
Getting hit on the face by a punch in a fist fight		•	•	•	•	
Low health in a video game			•	•		
Standing near a waterfall						•

Table 3.2: Haptic modalities and possible hardware configurations

Haptic Modality	Hardware
Temperature	A spray nozzle system that intermittently mists water onto the user's face, or alternatively a moisture-absorbent material held in contact with the skin that is periodically wetted to simulate the sensation of humidity or dampness.
Touch	An array of nubs that would extend onto the user's face through the use of motors.
Vibrotactile	An array of vibration actuators siting near or in someway contacting the user's face. These actuators could vary, ERM's, LRA's, etc.
Electricity	An array of low power electrodes siting in the user's face.
Air	An array of fans siting medium distance from the user's face.
Humidity	Spray nozzles or the fan system spraying water on the user's face or some sort of tissue that can be wetted to pass a the moist sensation by contacting the skin.

We then decided upon airflow as the focus because within all the hardware explored it has also been rarely employed and as such has potential for being relatively simple and low-cost hardware that could add to immersion. For this we require a setup that would allow for controlled directioned airflow that could connect to a **VR** application and could be used in conjunction with existing **VR** hardware.

3.2 System Description

The proposed system consists of a haptic interface designed to be mounted on a commercial camera tripod. The device targets specific facial regions to deliver localized haptic stimuli corresponding to virtual force events. By modulating the intensity, duration, and spatial distribution of these stimuli, the system seeks to convey subtle interactions (e.g., gentle touch or proximity cues) as well as higher-intensity impact sensations associated with virtual collision events, such as those encountered in sports or action-based applications. This approach explores the face as a relatively underutilized body part for haptic feedback in **VR**, with the goal of enhancing presence and emotional engagement without significantly increasing user discomfort.

3.3 System Architecture

The planned system architecture can be divided into the components illustrated in Figure 3.1.

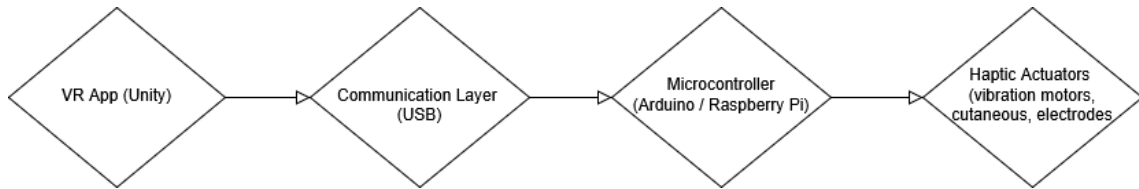


Figure 3.1: Proposed system architecture

Given the that the prototype is fixed to a tripod, the haptic device remains stationary relative to the PC throughout each session, which removes the need for wireless communication. The device is connected to the host PC via USB, providing a reliable, low-latency serial interface. Communication with the Unity application is handled through the `System.IO.Ports` API, which allows Unity scripts to exchange commands with the microcontroller over a standard serial connection.

Regarding the embedded platform, an Arduino-based microcontroller was selected as the most suitable solution for this application. Arduino offers a simple to program, deterministic real-time behaviour, which is particularly important for haptic feedback systems that require precise timing control.

The haptic actuation layer combines two complementary feedback modalities. The primary method consists of an array of fans that deliver airflow across medium-sized areas of the user's face, suitable for representing gentle or sustained forces. While a secondary system uses tubes of compressed air to produce stronger, more concentrated bursts, intended to simulate brief, high-impact forces. Together, these two modalities allow the system to convey a range of haptic sensations with varying intensity and spatial distribution.

3.4 Safety Considerations

Given the sensitive nature of facial stimulation, the following safety measures will be implemented:

Mechanical Safety:

- No sharp edges or pinch points
- Compressed air force must never go over a certain safe amount

Thermal Safety:

- Actuator temperature monitoring

User Control:

- Emergency stop button/command
- Individual actuator enable/disable
- Comfort calibration phase before experiments

3.5 Implementation

Implementation was done with a wired setup, an Arduino uno, a pc power supply, 2 drones as the sources for the fans, 3D printed mount for all the fans and an air compressor. First Thing we tackled was how would the air be applied on the user's face in the first place. Fans was the obvious choice but how would we deal with the more impactfull forces? We tested plastic syringes with the intention of maybe attaching it to a motor to then push air in pressurized small amounts. Unfortunately that never produced any meaningful force so we then looked at the possibility of compressed air. This produced the forces that we needed but required a good enough air compressor, one that could keep up with the air flow demands, so that it could create enough of a noticeable force on the user throughout the test. We then also needed a way to control both haptic modalities electronically.

3.5.1 Fans

As we wanted to have multiple fans working on different areas of the user's face, they have to be relatively small to subdivide the user's face surface into noticeably different areas but still be strong enough to be noticeable. After evaluating several off-the-shelf compact fans, drone propeller fans were found to meet these requirements. Motors and fan blades were harvested from disused drone models and repurposed for this application. To house these fans, mounts matching the geometry of the original drone fan fittings were modeled, as shown in fig. 3.2 and then on the prototype itself, fig. 3.3.



Figure 3.2: The two different fan mounts and their 3D model equivalent

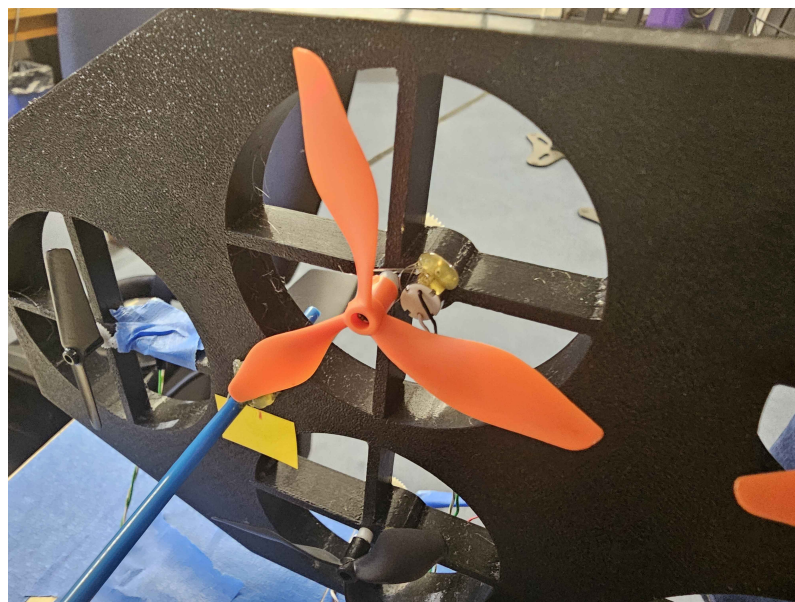


Figure 3.3: Fans fitted into the prototype. To the right of the fan sits the DC motor

3.5.2 Compressed Air

The compressed air subsystem was designed to deliver two independent jets of concentrated air onto the user's face, each targeting a side of the user's face. To achieve this, the system required three core components: a source of compressed air capable of sustaining the desired output pressure, an electronically controlled valve to open and close the air jets in response to software commands, and the necessary airways to conduct the compressed air from the source to the output nozzles.

After testing a couple of air compressors, we ended up going with one with a large capacity tank as seen in fig. 3.4. This way we could accumulate air in between testing and be able to discharge at higher pressures without needing a much more powerful air compressor that would be running at all times.



Figure 3.4: Air compressor sitting under the table

As for the Compressed air, some more hardware is required. The compressor through a series of adapters, connects its output through a standard 6mm air tube to the input of a FESTO CPASC1-V1 electric valve with 2 4mm outputs as seen in fig. 3.5.

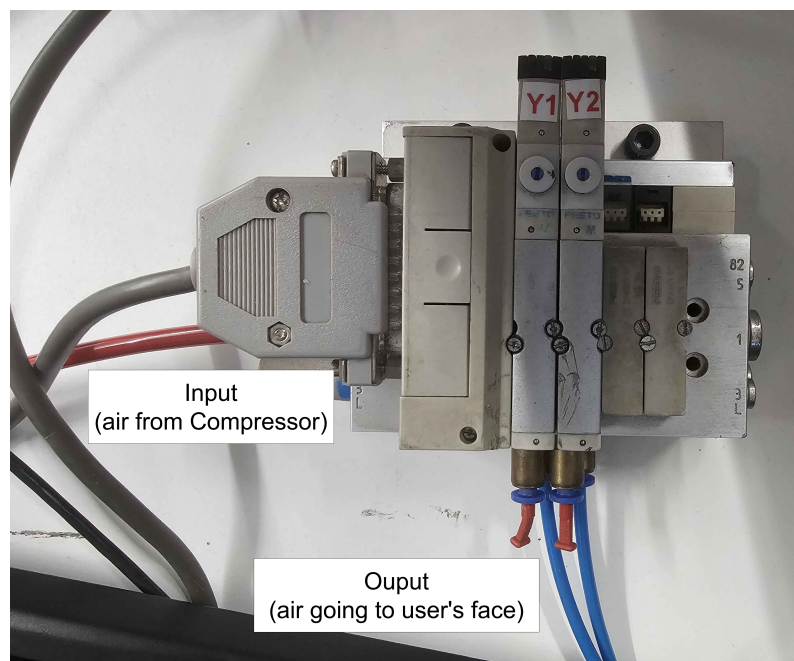


Figure 3.5: The Red 6mm tube is the input air from the compressor while the two 4mm blue tubes are the output blowing air into the user's face

These 4mm outputs then pass through 2 small holes in the prototype's frame to blow air onto the user's face as seen in fig. 3.6.

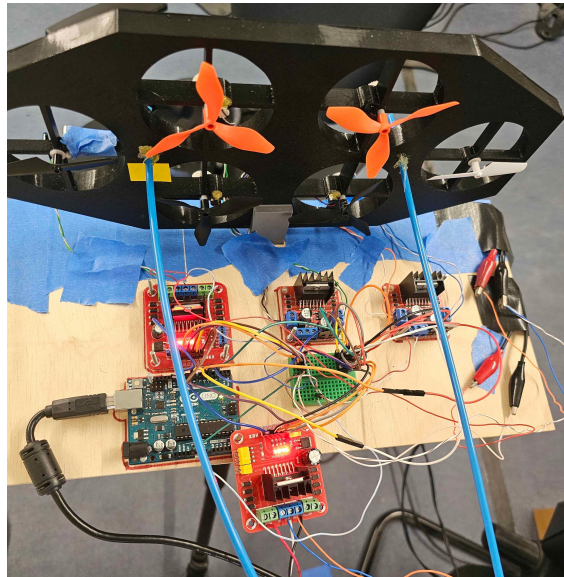


Figure 3.6: The two blue output 4mm tubes passing through the prototype's frame

3.5.3 3D Model

To combine each individual fan mount, we developed this model. It has 6 total fan mounts, with the 4 inner ones differing from the two outer ones, and an overall size that seems to send noticeable air to most user's full facial surface. In the bottom we modeled the base connection with the ISO 1222:2010 standard with stabilizer in mind, to attach to the tripod that we had that had that standard connector. After being printed, some modifications were made to the physical object.

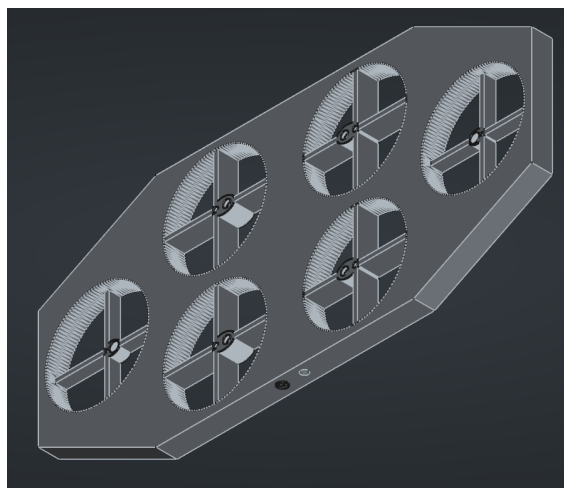


Figure 3.7: Final 3D Model

One such modification was an extension added at the bottom area to attach a wooden board to hold most electronics as seen in fig. 3.8.

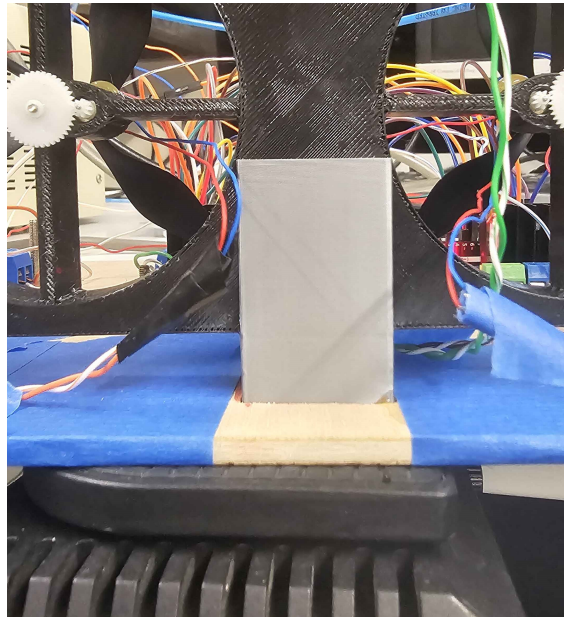


Figure 3.8: The Grey U shaped piece was added so that we could attach the wooden board that holds all electronics.

3.5.4 Electronics

3.5.4.1 Motor and Valve Drivers

To power and control the fans, the L298N motor driver integrated circuit was employed. The chip accepts a Direct Current (DC) supply voltage to drive the fans (in this case 10 V) and two logic signals per channel to control each fan: a pair of direction pins (IN1/IN2), which were fixed to rotate the fans in a single direction throughout the experiment, and a Pulse Width Modulation (PWM) signal to modulate fan speed, as illustrated in fig. 3.9.

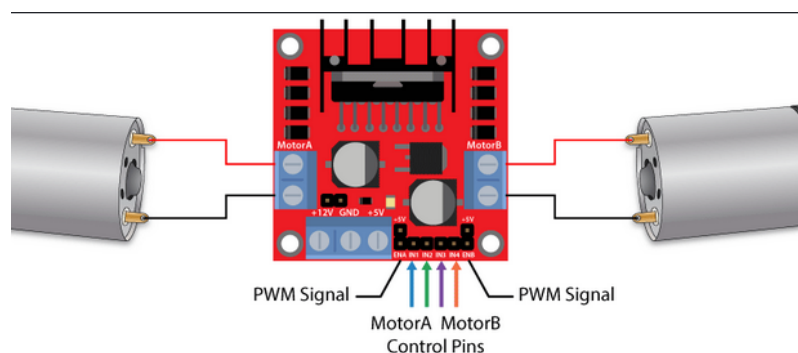


Figure 3.9: L298N motor controller. The three blue unidentified pins are for the DC input that powers the fans. More detail in [39]

As each L298N circuit can drive only two fans, a total of three circuits were required for the six fans. The FESTO CPASC1-V1 electric valve requires a 24 V input across two pins to control the opening of each jet [20]. A fourth L298N circuit was used exclusively to drive the two valves, with the full electrical arrangement shown in fig. 3.10.

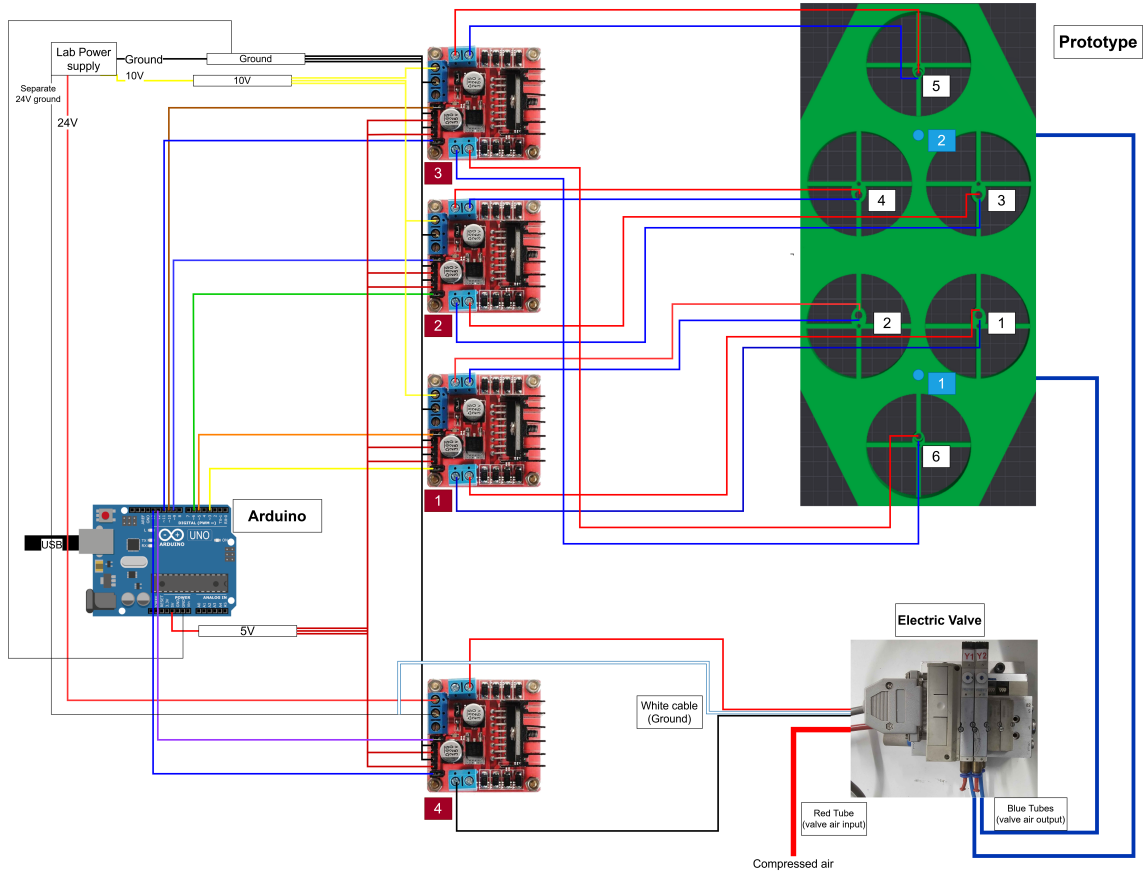


Figure 3.10: Electrical Setup. The Arduino pins picked were the 6 digital outputs with PWM

3.5.4.2 Microcontroller

An Arduino was used to generate the control signals for both the fans and the valves. For fan speed control, **PWM** signals from the Arduino's digital outputs switch between 0 V and 5 V at a fixed frequency: at 0 V the motor is disconnected from the supply, and at 5 V it is connected to the full 10 V. Due to the motor's internal inductance, these rapid pulses are smoothed into an approximately continuous voltage, resulting in an average output proportional to the duty cycle — minus the 2–3 V drop across the L298N's internal transistors. The six PWM-capable digital output pins were assigned to the fan channels accordingly.

For valve control, since the valves operate in a binary open/closed state, two standard digital output pins were used to send a simple on/off signal (0 V / 5 V) to the valve driver circuit, requiring no PWM modulation.

3.5.5 Software

The software architecture spans a set of layers, each responsible for a distinct stage of the pipeline from virtual scene authoring to physical actuation. Figure 3.11 summarizes the full Unity–Arduino–L298N signal chain.

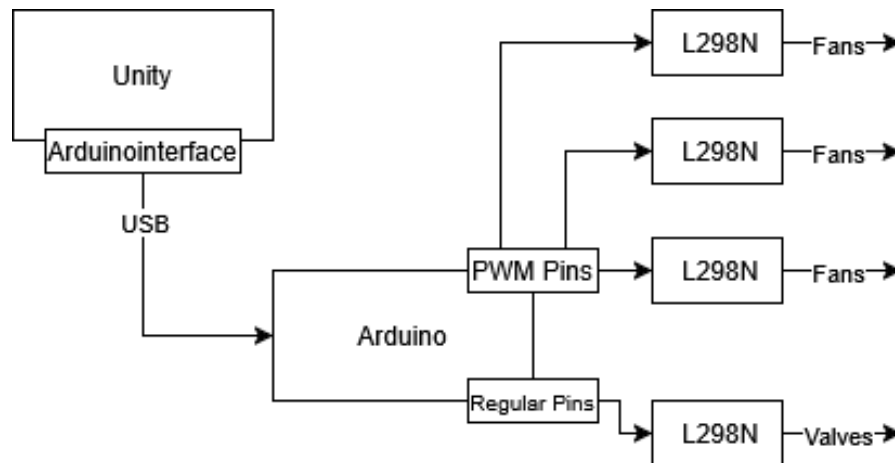


Figure 3.11: Unity–Arduino–L298N connections. PWM pins 3, 5, 6, 9, 10, and 11 drive fans 1–6 respectively; digital pins 12 and 13 control compressed-air outputs 1 and 2.

The four layers are:

- **High-level layer:** Unity components that allow a scene author to place virtual air triggers and define their parameters (type, direction, intensity).
- **Mid-level layer:** Unity backend that maps the properties of those sources to concrete control commands for the microcontroller.
- **Communication layer:** Serial interface through which commands are transmitted from Unity to the Arduino.
- **Firmware layer:** Arduino logic that parses incoming commands and drives the appropriate output pins and actuators.

3.5.5.1 High-Level Layer: Virtual triggers

The scene is populated with virtual air sources, implemented as trigger volumes that can be freely placed by a scene author. Each trigger volume carries parameters describing the type of airflow it represents (fan-based or compressed air), its forward direction, and its intensity.

To detect interactions with these sources, the player body carries eight sphere colliders acting as virtual sensors: six corresponding to the fan actuators and two to the compressed-air actuators, positioned to mirror the layout of the physical prototype, as shown in fig. 3.12. When the user moves through the scene, these virtual sensors enter and exit trigger volumes. An activation only occurs when a sensor and a source overlap, meaning that haptic feedback is only produced when

the user's body is physically within range of a virtual airflow event. This design allows scene authors to compose haptic experiences modularly, by placing and configuring trigger volumes in the Unity Editor without modifying any underlying code.

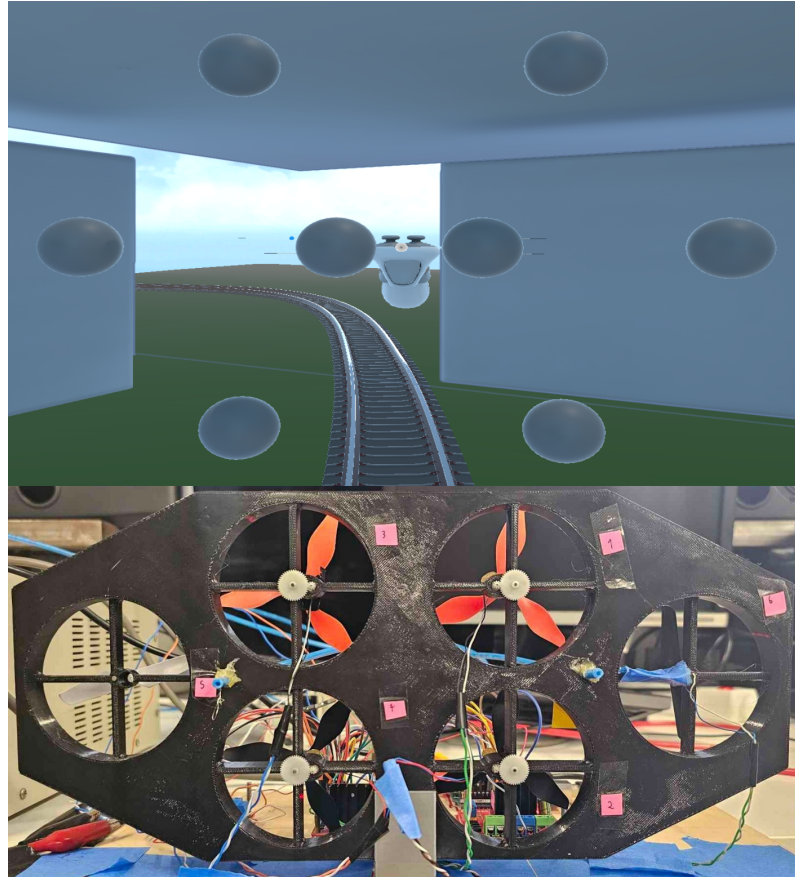


Figure 3.12: The prototype compared to its virtual proxies. The compressed air proxies are positioned closer to the centre than in the physical prototype to ensure more consistent activation.

3.5.5.2 Mid-Level Layer: Parameter Mapping

When a virtual sensor enters a trigger volume, the script attached to that volume communicates with the player body's `ArduinoInterface` script, which is responsible for translating the source's parameters into a concrete control value.

For fan trigger volumes, the `ForceDetection` script computes the alignment between the virtual source's forward direction and the player's forward direction using a dot product. Only the component of the airflow that faces the player directly contributes to the output, ensuring that haptic feedback reflects the user's orientation relative to the source. The resulting value is mapped to a speed in the range 0–60, which is passed to the communication layer.

For compressed-air trigger volumes, the `ImpactDetection` script sends a binary value, either 0 or 255, as the electric valve is only on/off. No directional computation is needed, as the compressed-air jets are either fully active or fully inactive.

3.5.5.3 Communication Layer: Serial Interface

Control values are transmitted to the Arduino via a USB serial connection, managed by the `ArduinoInterface` script using `System.IO.Ports`. Each command is formatted as a comma-separated string encoding the actuator identifier, the target pin, and the speed value, and is written to the serial port using `SendSpeed`, as shown in listing 3.1

Listing 3.1: `SendSpeed` method from `ArduinoInterface`. Called on trigger entry and exit to update the output value for each actuator.

```
1     private void SendSpeed(int fanId, int speed)
2     {
3         if (_serialPort == null || !_serialPort.IsOpen)
4         {
5             Debug.LogWarning("Serial port is not open.");
6             return;
7         }
8
9         if (!pinById.TryGetValue(fanId, out int pin))
10        {
11            Debug.LogWarning("No configured pin for fan ID: " + fanId);
12            ;
13            return;
14        }
15
16        try
17        {
18            string message = fanId + "," + pin + "," + speed;
19            _serialPort.WriteLine(message);
20        }
21        catch (Exception ex)
22        {
23            Debug.LogError("Failed to send command: " + ex.Message);
24        }
25    }
```

3.5.5.4 Firmware Layer: Arduino Command Processing

The Arduino processes each incoming serial message individually within its main loop. Each line is parsed into its three fields: actuator identifier, pin, and speed; with the appropriate write operation being selected based on whether the target pin supports **PWM**. Fan pins receive an `analogWrite` call with a value clamped to 100, as higher values did not produce additional

speed and risked motor damage. Valve pins receive a `digitalWrite` call, interpreting 0 as LOW and any non-zero value as HIGH, as shown in listing 3.2

Listing 3.2: `processLine` method from the Arduino firmware. Called iteratively while messages remain in the serial buffer.

```
1 void processLine(char* line) {
2     char* tokFan = strtok(line, ",");
3     char* tokPin = strtok(nullptr, ",");
4     char* tokSpeed = strtok(nullptr, ",");
5
6     if (tokFan == nullptr || tokPin == nullptr || tokSpeed ==
7         nullptr) {
8         Serial.println("ERR,FORMAT");
9         return;
10    }
11
12    int fanId = atoi(tokFan);
13    int pin = atoi(tokPin);
14    int speed = atoi(tokSpeed);
15    pinMode(pin, OUTPUT);
16
17    if (!isPwmPin(pin))
18        digitalWrite(pin, speed);
19    else
20        analogWrite(pin, speed);
21 }
```

The building blocks described in this chapter: virtual air sources, sensor proxies, the parameter mapping backend, and the Arduino firmware; together form a modular framework that allows a scene designer to populate a VR environment with configurable airflow events without requiring changes to the underlying system¹. Any combination of fan-based and compressed-air sources can be placed and parameterized directly in the Unity Editor, and the remaining layers handle the translation to physical actuation automatically. This framework was used to construct the experimental scene used for evaluation in this work, as described in the following chapter.

¹The Github repository that holds all the code is in chapter B.

Chapter 4

Tests and Results

This chapter describes the experimental evaluation conducted to assess the effectiveness of the proposed haptic feedback device. Given that the primary objective of the system is to enhance the sense of immersion through facial haptic stimulation, a structured user study was designed to measure both the perceptibility of the feedback and its impact on the overall **VR** experience.

4.1 Goal of the tests

Since our device is focused on applying forces on the user, the goal of the experimental evaluation was to assess the effectiveness and usability of the proposed haptic feedback prototype in virtual reality environments. Specifically, the tests aimed to determine:

- Whether the effectiveness of facial haptic feedback differs depending on the type of virtual interaction or environmental scenario.
- Whether the proposed device can provide haptic feedback while maintaining acceptable levels of user comfort during short **VR** sessions.
- Whether participants are capable of perceiving and distinguishing the presence or absence of the facial haptic feedback system under different actuation conditions (e.g., fan-based airflow and compressed-air stimuli).

4.2 Prototype

A key constraint of the current prototype is that its actuators are mounted on a fixed tripod in the physical environment, meaning the direction of stimulation remains constant in real-world space regardless of the user's head orientation. To ensure that all actuators could be evaluated within a single coherent experience, the user study was conducted within a virtual roller coaster environment. This scenario was chosen deliberately: by constraining the user's trajectory through a scripted path, it becomes possible to control the user's facing direction at any given moment. Actuators were positioned such that each one aligns with the user's forward direction at a specific

segment of the track, allowing stimulation events to occur naturally and organically as the ride progresses. This approach eliminates the need for participants to reorient themselves and ensures that each actuator is activated under consistent and reproducible conditions across all trials.

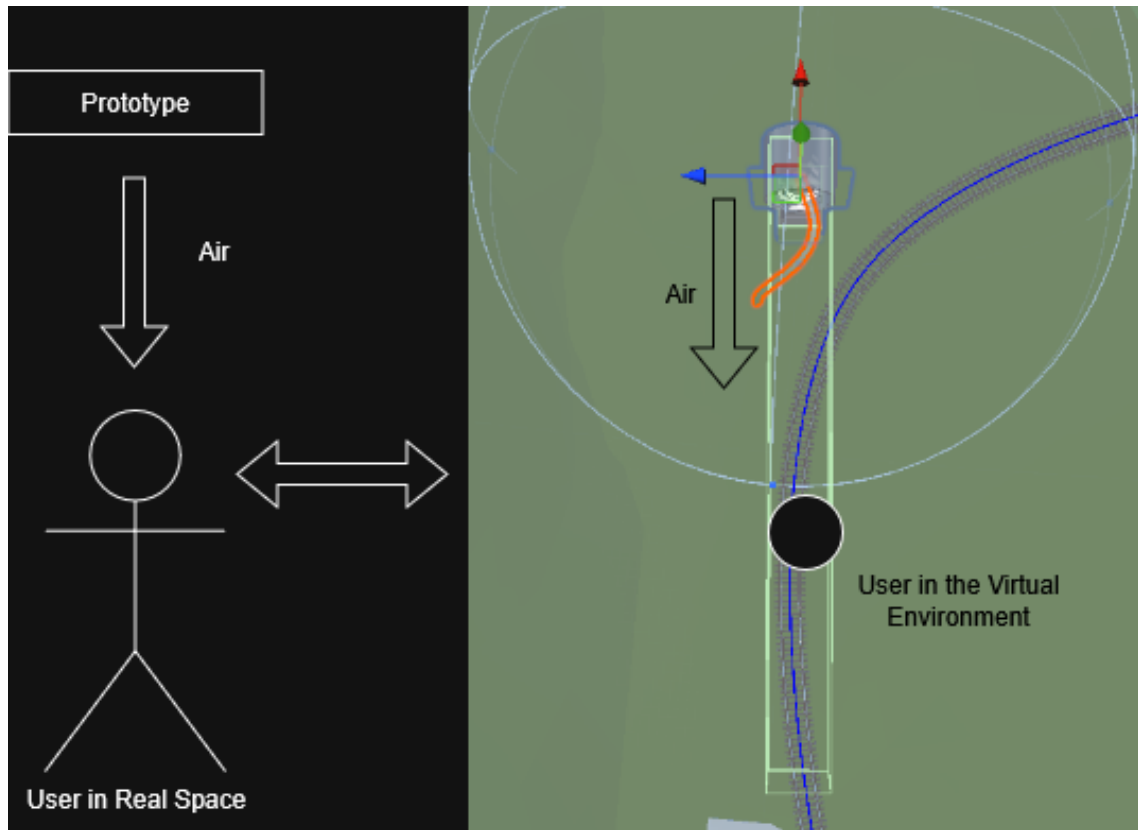


Figure 4.1: Actuator activation points were positioned along the track to align with the user's direction of travel at each stimulus event

Each experimental session begins in a largely empty introductory scene, in which participants are presented with a message explaining the evaluation procedure. They were informed that, following each actuator activation event during the ride, they would be asked to verbally rate the perceived realism of the haptic stimulus on a scale of 1 to 5, where 1 corresponds to *unrealistic* and 5 to *realistic*. Responses were recorded by the observer.

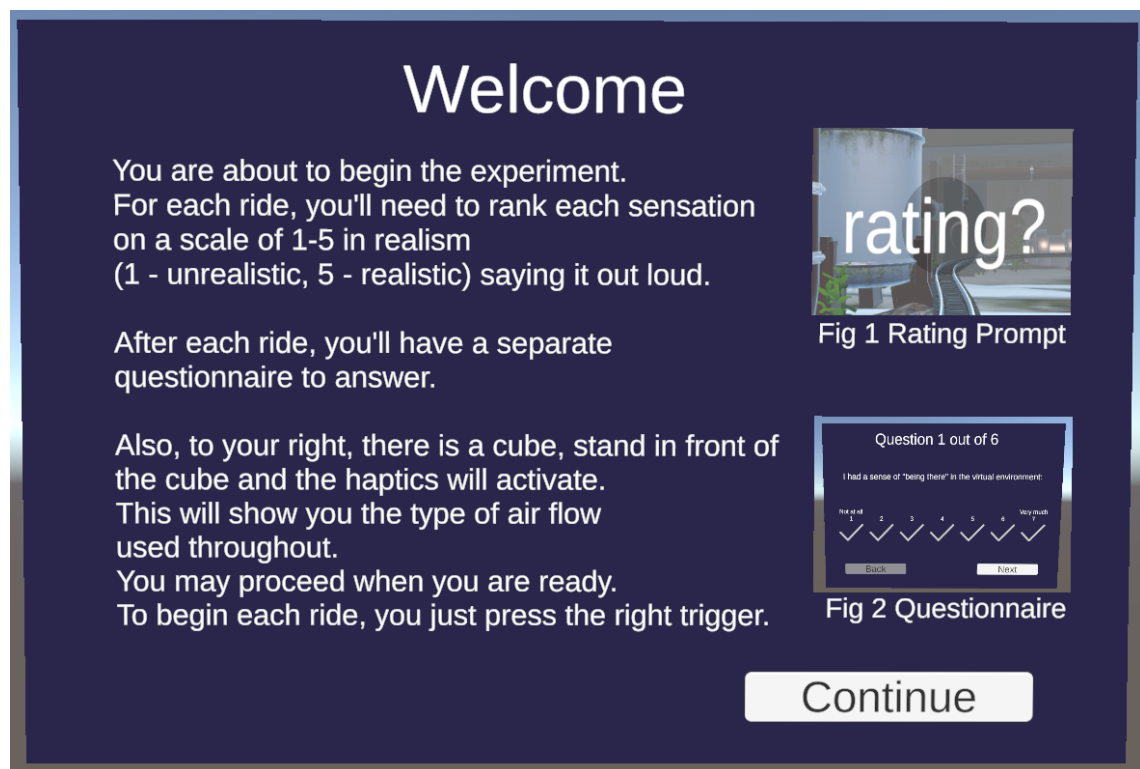
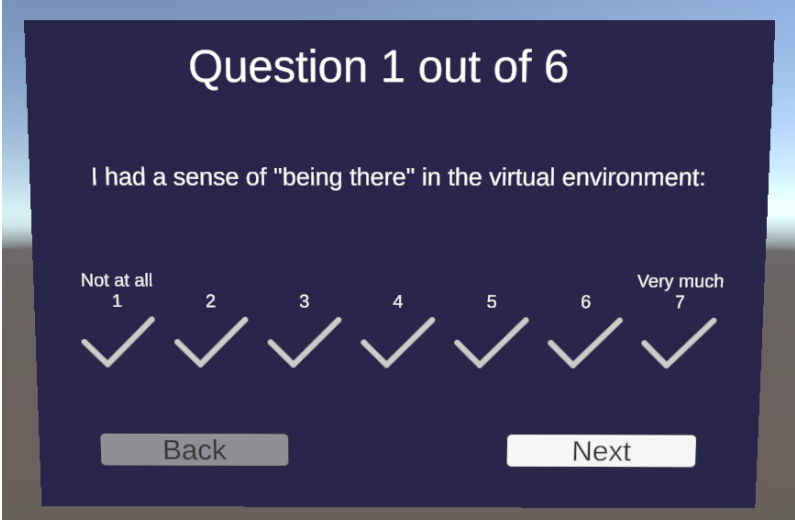


Figure 4.2: Introductory message displayed to participants at the start of each session. The Moderator also explains it out loud and adds on to it

The introductory scene also contains a cube in the virtual environment that, when approached, triggers the fan-based actuators. This element serves exclusively as a familiarization tool, allowing participants to experience the intensity of the airflow stimulation in a neutral context, without any associated virtual scenario that could introduce expectation bias. Notably, the compressed-air actuators are not included in this warm-up step, as the limited capacity of the air tank makes extended or repeated activation impractical. Once the participant has familiarized themselves with the device, they press the *Continue* button to proceed to the first test condition. Each of the four test scenes is nearly identical in structure. The participant is seated in a virtual minecart and initiates the ride by pressing the right trigger on the controller. The ride proceeds at a deliberately slow pace to minimize motion-related discomfort unrelated to the haptic stimuli. The test scenes only differ in what Haptic actuators are turned on:

1. All haptics off
2. Only Fans on
3. Only Compressor on
4. Fans and Compressor on

Note that we created a 4 sized latin square [73] to ensure an even spread of 4 different random orderings of the tests so as to not incite any expectancy effect. After each test there is a Slater–Usch–Steed (SUS) questionnaire, as shown in fig. 4.3.



The image shows a digital interface for the SUS questionnaire. At the top, it says "Question 1 out of 6". Below that is the statement "I had a sense of 'being there' in the virtual environment:". Underneath the statement is a horizontal scale from 1 to 7. Above the numbers 1 and 7 are the labels "Not at all" and "Very much" respectively. Each number has a white checkmark below it, indicating that all options are available for selection. At the bottom of the interface are two buttons: "Back" on the left and "Next" on the right.

Figure 4.3: SUS questionnaire

4.3 Main conditions and setup

The tests were carried out at the Sound and Music Computing Lab at DEI/FEUP during the month of June. The Physical environment, as seen in fig. 4.4, shows the prototype on the camera tripod.



Figure 4.4: Example of a test setup

Attached to the wooden board is 4 L298N motor controllers, 3 to 2 fans each and 1 for the electric valve. Each motor controller is then connected to the power supply sitting on the table and the Arduino as shown in fig. 3.10 . The Arduino is plugged into the pc also sitting on the table. Underneath the table is the air compressor. Unfortunately before the first test, one of the fans malfunctioned and we were unable to fix, but every test was equally conducted with one less fan than originally planed.

4.4 Initial State

Prior to each session, the haptic hardware was powered on and verified to be in a functional state. The compressed air tank was filled to 5 Bar before the participant arrived or during the initial form, ensuring sufficient pressure for all compressed-air activation events across the full duration of the session.

4.5 Coordinator / observer / facilitator

All experimental roles (coordinator, observer, and facilitator) were performed by the same operator. To maintain consistency, all actions were carried out following a predefined protocol, with strict separation of responsibilities across functional roles.

4.5.1 Coordinator function

In the coordinator role, the operator was responsible for monitoring and controlling both the experimental software running on the host computer and the haptic prototype device. And as a limitation of the air compressor's tank, would need to turn on (right before a section where it was needed) and off (when no longer needed) the master valve in the compressor itself because of an air leak we were unable to fix.

4.5.2 Observer function

In the observer role, the operator recorded observations regarding participant difficulties, unexpected behaviors, and potential technical issues not explicitly reported through questionnaires.

4.5.3 Facilitator function

In the facilitator role, the operator guided participants through the setup process, including fitting of the VR headset and provided standardized instructions prior to task execution.

4.6 Participants

20 participants were recruited from a general adult population with no strict demographic restrictions beyond basic safety and usability considerations. Individuals with prior VR experience as

well as first-time users were included in the study. Participant familiarity with VR systems was recorded, as it was expected that lower levels of VR experience could influence perceived discomfort and immersion.

4.7 Test methods

The evaluation methodology primarily consisted of user-based testing focused on immersion and comfort. Participants completed a series of VR tasks under different haptic conditions, followed by subjective evaluation questionnaires. Comparisons were performed between scenarios with and without fans and compressed air.

4.8 Data to collect

For every user, the information obtained was:

- Age
- Gender
- Vr Experience
- SUS questionair per experiment
 - 6 questions
- Realism ratings per experiment
 - 5 ratings / 1 rating per haptic trigger
- User Comments
 - Most of these touched on how comfortable or not the experience was

SUS Presence questionnaire questions:

- I had a sense of "being there" in the virtual environment:
 - 1 Not at all, 7 Very much.
- There were times during the experience when the virtual environment was the reality for me...
 - 1 At no time, 7 Almost all the time
- The virtual environment seems to me to be more like...
 - 1 Images that I saw, 7 Somewhere that I visited.

- I had a stronger sense of...
 - 1 Being elsewhere, 7 Being in the virtual environment
- I think of the virtual environment as a place in a way similar to other places that I've been today...
 - 1 Not at all, 7 Very much so.
- During the experience, I often thought that I was really standing in the virtual environment..
 - 1 Not at all, 7 Very much so.

4.9 Help resources, Facilitator help

Limited facilitator assistance was permitted during the experiments, as the purpose of the study was not to evaluate the participant's ability to understand the system interface. Assistance was restricted to clarification of controls, task objectives, and procedural instructions.

4.10 Test completion criteria

A test session was considered complete once the participant had attempted all assigned **VR** tasks, regardless of task success. The primary objective was exposure to the haptic system across multiple interaction scenarios rather than task performance accuracy.

4.11 Success criteria

The experiment was considered successful if participants reported high levels of immersion and presence while maintaining low reported levels of discomfort and fatigue associated with the haptic device. Additionally, successful differentiation between haptic actuation conditions was considered an indicator of perceptual effectiveness of the proposed system.

4.12 Experiment Protocol

Prior to data collection, a standardized script was prepared for the coordinator to introduce the test to the participant at the start of each session. This script is reproduced in chapter **C**. The pre-test questionnaire collected demographic information including age, gender, and prior **VR** experience. A Latin square design was applied to evenly distribute the participants in between 4 different orderings of the 4 test conditions, ensuring that no particular test ordering could bias the results.

4.12.1 Procedure

Each session followed a fixed sequence. Upon arrival, the participant read and signed the consent form and completed the pre-test questionnaire. Preferably the coordinator would put the air compressor accumulating before the tester even arrived but if it wasn't possible, during the consent and pre-test questionnaire is when they'd leave it accumulating. The facilitator then delivered the standardised verbal interlocation and guided the participant through fitting of the **VR**. Before the first test began, the user was to read a message in the introductory scene explaining the verbal rating they were to give and the **SUS** questionnaire after each test condition. The facilitator would point out the important parts of the message as well, to ensure the participant understood it well. The participant was then directed to approach a cube in the introductory scene, which triggered the fan actuators, allowing familiarization with the haptic device without any associated virtual context that could introduce expectation bias. Once ready, the participant pressed the Continue button to proceed to the first test condition.

Each condition followed the same structure: the participant initiated the ride by pressing the right trigger, experienced the five haptic activation events along the track, and provided a verbal realism rating following each event. Ratings were recorded by the observer. After completing the ride, the participant completed the **SUS** questionnaire still in a **VR** scene before proceeding to the next condition. This sequence was repeated for all four conditions in the order determined by the Latin square. Upon completion of the final condition, the session concluded. Each session lasted approximately 15 minutes in total.

4.13 Tasks

The primary task assigned to each participant consisted of experiencing the virtual roller coaster ride and providing a verbal realism rating following each of the five actuator activation events encountered along the track. Participants were instructed to rate each stimulus on a scale of 1 to 5, where 1 corresponded to unrealistic and 5 to realistic, immediately after leaving each activation zone. Ratings were recorded by the observer. This task was repeated across all four experimental conditions. Following the completion of each ride, participants were additionally asked to complete the Slater–Usoh–Steed presence questionnaire before proceeding to the next condition. The five actuator activation events that participants were asked to evaluate were:

1. **Base Fan:** Activates the fan actuators alone, serving as the baseline airflow stimulus with no additional effects.
2. **Branch Impact:** As the user collides with a virtual branch, the compressed-air actuator is triggered, delivering a sharp burst of air to simulate the physical impact. A branch collision sound effect accompanies the stimulus.

3. **Obstructed Fan:** Functions similarly to the Base Fan, but the virtual fan is partially obstructed. As the user shifts laterally with the spline path, the corresponding physical fan actuators activate accordingly, simulating directional airflow around an obstacle.
4. **Soft Leaves:** Triggered when the user contacts the tip of a virtual branch, activating the fan actuators at low intensity. This event is designed to simulate a gentle tactile sensation, deliberately exploiting the fans' relatively slow spin-up time to avoid producing an abrupt or strong airflow.
5. **Pebble Impact Fan:** The fan actuators activate as in the Base Fan event, but the compressed-air actuator additionally fires at randomised intervals to simulate the sensation of small projectiles striking the user's face. This is reinforced by a dedicated pebble impact sound effect and a particle effect in which virtual pebbles are visually seen flying towards the user.

The spatial layout of these activation events along the track is illustrated in fig. 4.5.



Figure 4.5: The 5 actuator activation events. As the user leaves each event is when they are prompted to rate them out loud on realism

4.14 Pilot tests

A set of pilot sessions was conducted prior to the main study to validate the experimental procedure and identify issues requiring correction before data collection began.

Several refinements emerged from this process. Some were minor adjustments to improve clarity and consistency, such as rewording the introductory message to ensure participants understood

the rating task, and repositioning the virtual branches along the track to more reliably align with the user's face height. Others addressed more critical functional issues: a clamping mechanism was added to constrain the participant's position during the ride to prevent them from sliding off the minecart, and a trigger volume attached to the user's head was introduced to more consistently activate the branch impact and leaf rustling sound effects, which had previously been unreliable.

These adjustments were incorporated into the final experimental setup prior to the start of the main data collection.

4.15 Result and analysis

The main focus of the results then is the SUS questionnaire answers and the Realism ratings. All relevant data and tables are in chapter D.

4.15.1 Realism ratings

An initial inspection of the mean perceived realism ratings across experiment conditions reveals a consistent pattern. Fan-based conditions (Fans only, Both) produced noticeably higher ratings than the no-haptics baseline, while compressed air alone yielded only a modest improvement and remained substantially below fan-based conditions, as illustrated in fig. 4.6.

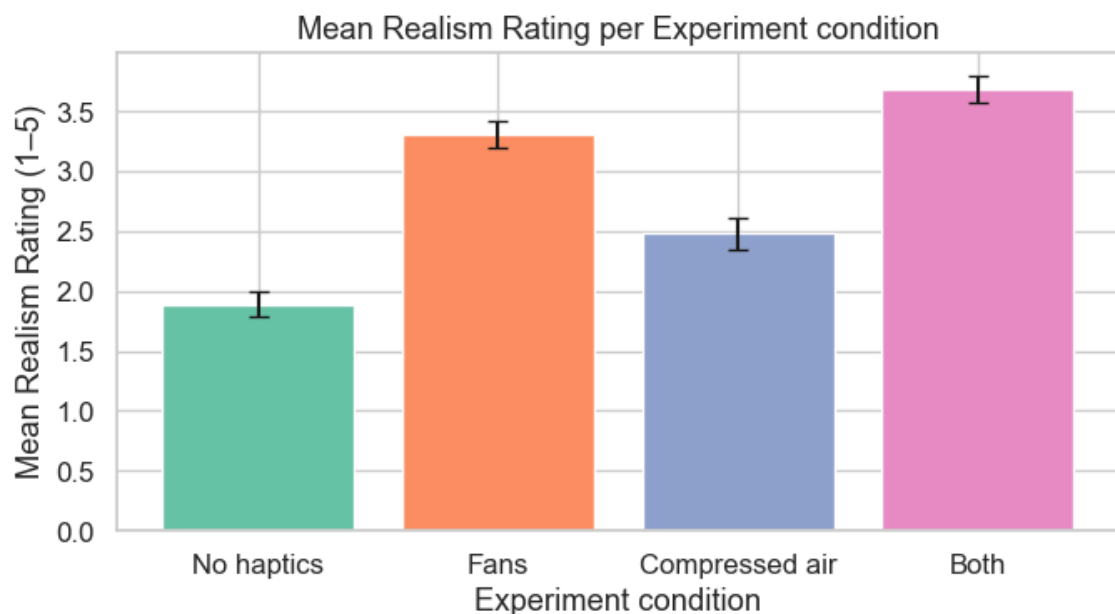


Figure 4.6: Mean perceived realism rating per experiment condition (1–5 scale). Error bars represent standard error of the mean.

Looking at fig. 4.7, across haptic event types, Fan with pebbles (H5) received the highest mean rating overall, which is expected, with it being the only event type that engages at least one actuator modality in 3 out of 4 tests.

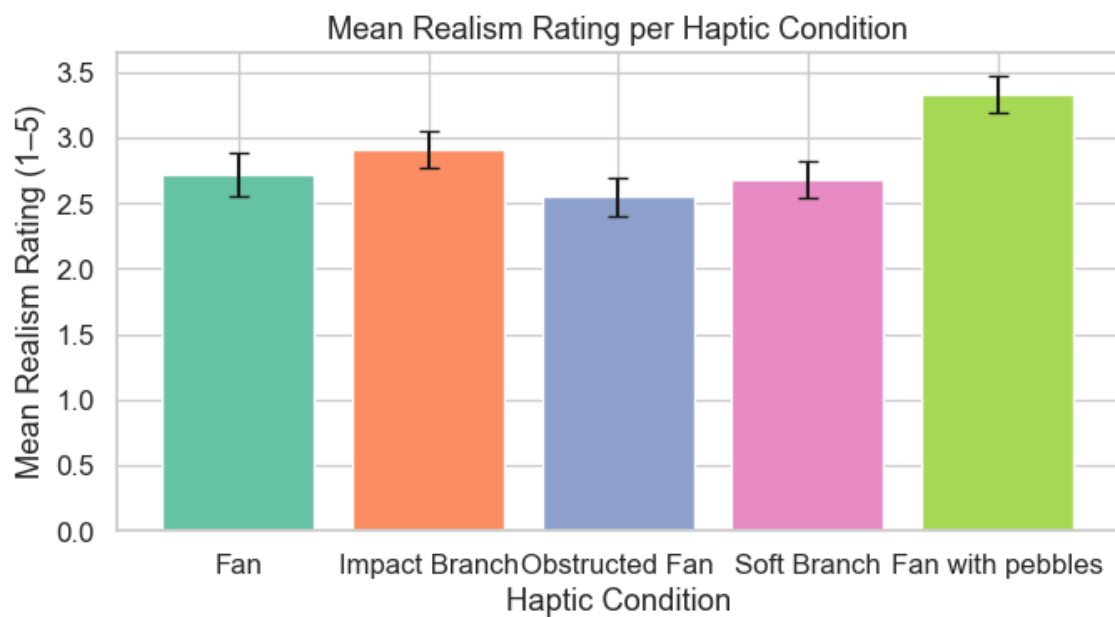


Figure 4.7: Mean perceived realism rating per haptic event type, averaged across all experiment conditions. Error bars represent standard error of the mean.

To evaluate whether haptic feedback influenced participants' perceived realism of individual haptic events, a two-way repeated measures ANOVA was conducted with Experiment condition (4 levels: no haptics, fans only, compressed air only, both) and Haptic event type (5 levels: H1–H5) as within-subjects factors. Prior to interpreting the results, Mauchly's test of sphericity was examined. Sphericity was satisfied for the Experiment factor ($W = .764$, $p = .444$) and the Experiment $\times$ Haptic interaction ($W = .006$, $p = .634$), so uncorrected degrees of freedom were used for those effects. Sphericity was violated for the Haptic factor ($W = .223$, $p = .002$), and therefore Greenhouse-Geisser corrected values are reported for that effect.

4.15.1.1 Main Effect of Experiment

A significant main effect of Experiment condition was found, $F(3, 57) = 41.519$, $p < .001$, $\eta^2 p = .686$, indicating that perceived realism ratings differed substantially across haptic configurations. This represents a large effect, with the Experiment condition accounting for 68.6% of the variance in perceived realism. Bonferroni-corrected pairwise comparisons revealed that both the fans-only condition (Exp2, $M = 3.31$) and the combined condition (Exp4, $M = 3.69$) produced significantly higher ratings than the no-haptics baseline (Exp1, $M = 1.89$; both $p < .001$). Similarly, both Exp2 and Exp4 significantly outperformed the compressed-air-only condition (Exp3, $M = 2.48$; $p < .001$ for both). Notably, the difference between fans-only and both-together did not reach significance ($p = .116$), suggesting that fan-based airflow is the primary driver of perceived realism, with compressed air contributing less when fans are already active. Compressed air alone (Exp3) also did not differ significantly from the no-haptics baseline ($p = .057$), indicating that compressed

air in isolation produced only a marginal and statistically unreliable improvement in perceived realism overall.

4.15.1.2 Main Effect of Haptic Event Type

A significant main effect of Haptic event type was also found, $F(2.205, 41.897) = 8.196$, $p < .001$, $\eta^2 p = .301$ (Greenhouse-Geisser corrected), indicating that perceived realism differed across the five haptic event types regardless of experimental condition. H5 (Fan with pebbles, $M = 3.34$) received the highest overall ratings, differing significantly from H1 (Fan, $M = 2.73$; $p < .001$), H3 (Obstructed Fan, $M = 2.55$; $p < .001$), and H4 (Soft Branch, $M = 2.69$; $p < .001$). H2 (Impact Branch, $M = 2.91$) did not differ significantly from any other haptic event type after correction. These differences reflect the varying complexity of the simulated events, with a events such as H5 that combines both haptic modalities consistently perceived as more realistic than single-modality events.

4.15.1.3 Experiment $\times$ Haptic Interaction

Critically, a significant Experiment $\times$ Haptic interaction was found, $F(12, 228) = 14.173$, $p < .001$, $\eta^2 p = .427$, indicating that the effect of haptic configuration on perceived realism was not uniform across haptic event triggers. This interaction is illustrated in the estimated marginal means profile plot fig. 4.8. As shown, lines for the four experiment conditions are crossing, confirming that different actuator combinations benefit different haptic events to different degrees and it's not always an improvement in every situation. Fan-dependent event triggers (H1, Fan; H3, Obstructed Fan) show a sharp increase in perceived realism when fans are active (Exp2: $M = 3.90$ and $M = 3.45$, respectively) relative to no haptics (Exp1: $M = 1.55$ and $M = 1.40$), but gain comparatively little from compressed air alone (Exp3: $M = 1.60$ and $M = 1.80$). This is consistent with the physical design of the system, in which fan actuators are specifically responsible for simulating sustained airflow events. Impact events (H2, Impact Branch; H4, Soft Branch) show a more moderate and distributed pattern of gains across conditions, with compressed air contributing more noticeably to their realism relative to its effect on fan-dependent events. Most notably, H5 (Fan with pebbles) reached its peak rating under the combined condition (Exp4, $M = 4.35$), the highest mean rating observed across the entire dataset, whereas its rating under fans-only (Exp2, $M = 3.75$) and compressed-air-only (Exp3, $M = 3.25$) conditions were both lower. This suggests a genuine synergistic effect for compound haptic events, where the simultaneous activation of both actuator types produces a perceived realism that neither modality achieves on their own.

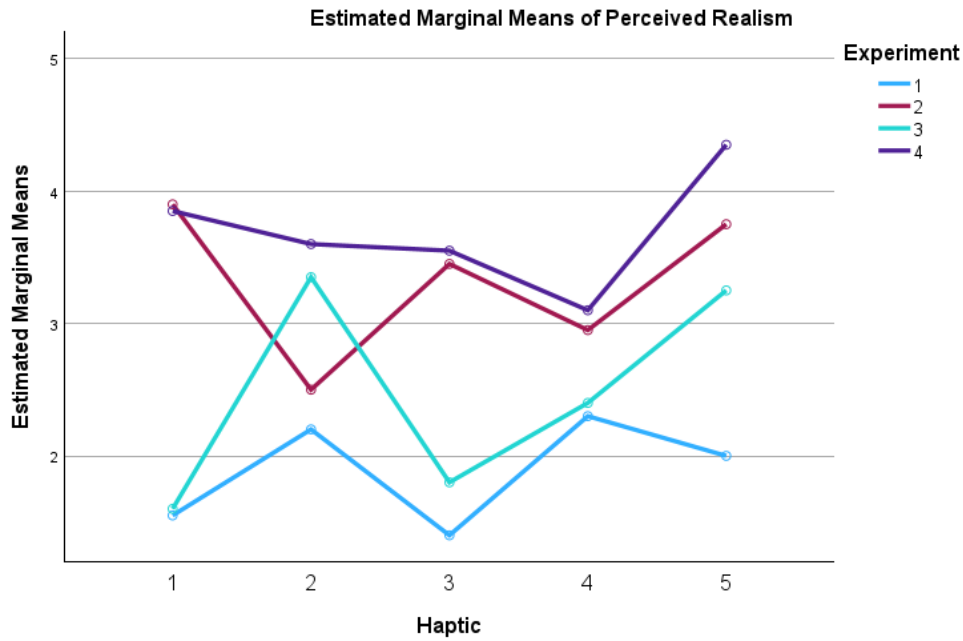


Figure 4.8: Estimated Marginal Means of Perceived Realism by Haptic Event Type and Experiment Condition

Considering then that there was a significant Experiment $\times$ Haptic interaction found, more friedman and Wilcoxon tests were done. A first Friedman test assessed whether experiment conditions differed within each haptic event type. Significant differences were found for H1 , H2 , H3 , H4 and H5 (all $\chi^2(3)$ and $p < .032$), confirming that the effect of haptic configuration was not uniform and that all five event types were sensitive to at least some manipulation of the actuator configuration. Wilcoxon signed-rank pairwise comparisons across experiment conditions were then conducted for each haptic event type individually.

- For **H1 (Fan)**, ratings were significantly higher under fans-only (Exp2, $Z = -3.810$, $p < .001$) and both-combined (Exp4, $Z = -3.729$, $p < .001$) relative to no haptics (Exp1), whereas compressed-air-only (Exp3) did not differ from no haptics (Exp1) ($p = .942$). The contrast between fans-only (Exp2) and compressed-air-only (Exp3) was also highly significant ($Z = -3.903$, $p < .001$), confirming that airflow from the fan actuator is the sole haptic atuator for this event.
- For **H2 (Impact Branch)**, the only compressed-air event, the pattern reverses: compressed-air-only (Exp3) increased significantly from no haptics (Exp1) ($Z = -2.946$, $p = .003$), while fans-only (Exp2) did not ($p = .207$). The combined condition (Exp4) also increased significantly from no haptics ($Z = -3.500$, $p < .001$), consistent with compressed air being the active modality in both Exp3 and Exp4 for this event.
- For **H3 (Obstructed Fan)**, another fan-driven event, results closely mirrored H1: fans-only (Exp2) ($Z = -3.813$, $p < .001$) and both-combined (Exp4) ($Z = -3.959$, $p < .001$)

increased significantly from no haptics (Exp1), while compressed-air-only (Exp3) did not ($p = .101$). The fans-only (Exp2) vs. compressed-air-only (Exp3) contrast was again significant but decreasing ($Z = -3.902, p < .001$).

- For **H4 (Soft Branch)**, also a fan event, the pattern was weaker: fans-only (Exp2) increased significantly from no haptics (Exp1) ($Z = -2.667, p = .008$), but the both-combined (Exp4) condition did not reach significance relative to no haptics (Exp1) ($p = .056$), and compressed-air-only (Exp3) showed no difference from no haptics (Exp1) ($p = .642$). Compressed-air-only (Exp3) was nonetheless significantly worse than fans-only (Exp2) ($Z = -4.027, p = .010$). The attenuated response for H4 relative to H1 and H3 may reflect the gentler, less salient nature of this event, where the soft branch contact produces a subtler airflow sensation that is more difficult for participants to detect and rate as realistic.
- For **H5 (Fan with Pebbles)**, the only event engaging both modalities simultaneously, all comparisons involving no haptics (Exp1) were significantly better (all $p \leq .003$), and crucially, compressed-air-only (Exp3) showed a significant decrease compared to fans-only (Exp2) ($Z = -1.968, p = .024$) while both-combined (Exp4) showed a significant increase compared to fans-only ($Z = -2.814, p = .005$) tracing a clear incremental realism gain as modalities are added but that most of the positive effect comes from the fans. This confirms the synergistic effect already suggested by the marginal means plot: neither modality alone reproduces the full perceived realism of the combined condition for this event.

A second Friedman test compared the five haptic event types within each experiment condition. Significant differences were found in all four conditions (all $\chi^2(4)$ and $p < .001$), indicating that participants consistently discriminated between haptic events in terms of perceived realism regardless of which actuator configuration was active. Follow-up Wilcoxon signed-rank pairwise comparisons within each condition further characterised these differences, and are interpreted below in light of which actuator each event is associated with: H1, H3, and H4 are fan events; H2 is the compressed-air event; and H5 engages both modalities.

- Within the **Exp1 (no-haptics condition)**, several pairs already differed significantly. H2 (Impact Branch) received higher ratings than H1 ($Z = -2.250, p = .024$) and H3 ($Z = -2.818, p = .005$), and H4 ($Z = -2.491, p = .013$) and H5 ($Z = -2.070, p = .038$) also rated higher than H1, while H3 received the lowest ratings overall. These baseline differences suggest that visual and contextual cues in the coaster scenario already led participants to perceive some events as more plausible than others, even before any haptic feedback was introduced.
- Within the **Exp2 (fans-only condition)**, H1 rated significantly higher than H2 ($Z = -3.134, p = .002$), H3 ($Z = -2.496, p = .013$), and H4 ($Z = -2.728, p = .006$), while H2 rated lower than H3 ($Z = -2.384, p = .017$), H4 ($Z = -1.979, p = .048$), and H5 ($Z = -3.068, p = .002$). H5 also rated significantly higher than H4 ($Z = -2.691, p = .007$). This pattern is consistent with actuator mapping: H1 is the most direct fan event (sustained frontal

airflow) and benefited most from fan activation, while H2 (the compressed-air event) received no matching haptic output and consequently rated lowest among events that do have an associated actuator. H5's advantage over H4 suggests that even with only fans active, the pebble-impact sound and visuals of H5 added perceptual richness beyond the soft branch sensation of H4.

- Within the **Exp3 (compressed-air-only condition)**, the pattern inverted in a manner directly complementary to Exp2. H2 rated significantly higher than H3 ($Z = -3.465$, $p < .001$) and H4 ($Z = -2.669$, $p = .008$), and H1 rated lower than H2 ($Z = -3.660$, $p < .001$), H4 ($Z = -2.584$, $p = .010$), H5 ($Z = -3.716$, $p < .001$), and H5 also rated higher than H3 ($Z = -3.517$, $p < .001$) and H4 ($Z = -2.751$, $p = .006$). H1 and H3, the two fan-only events most dependent on sustained airflow, received the lowest ratings in this condition, as their corresponding actuator was inactive. H2, now receiving its matched haptic output, rated comparatively higher, validating the modality-specificity of the actuator design. Notably, H2 and H5 did not differ significantly ($p = .644$), which is consistent with H5 including compressed air as one of its two modalities.
- Within the **Exp4 (both-combined condition)**, H5 consistently stood out as the highest-rated event, differing significantly from H1 ($Z = -2.183$, $p = .029$), H2 ($Z = -2.803$, $p = .005$), H3 ($Z = -3.087$, $p = .002$), and H4 ($Z = -3.309$, $p < .001$). By contrast, H1, H2, and H3 did not differ significantly from one another, and neither did H2 vs. H4 ($p = .079$) or H3 vs. H4 ($p = .100$). The convergence of H1, H2, H3, and H4 under the combined condition suggests that when all actuators are simultaneously active, most individual events reach a similar realism ceiling, and it is only H5 — the event specifically designed to engage both modalities at once — that continues to stand apart, benefiting uniquely from the full actuator configuration.

4.15.2 SUS Questionnaire

An initial interpretation of the **SUS** scores across experiment conditions on fig. 4.9 on the other hand revealed a similar pattern but not as clear as the realism ratings.

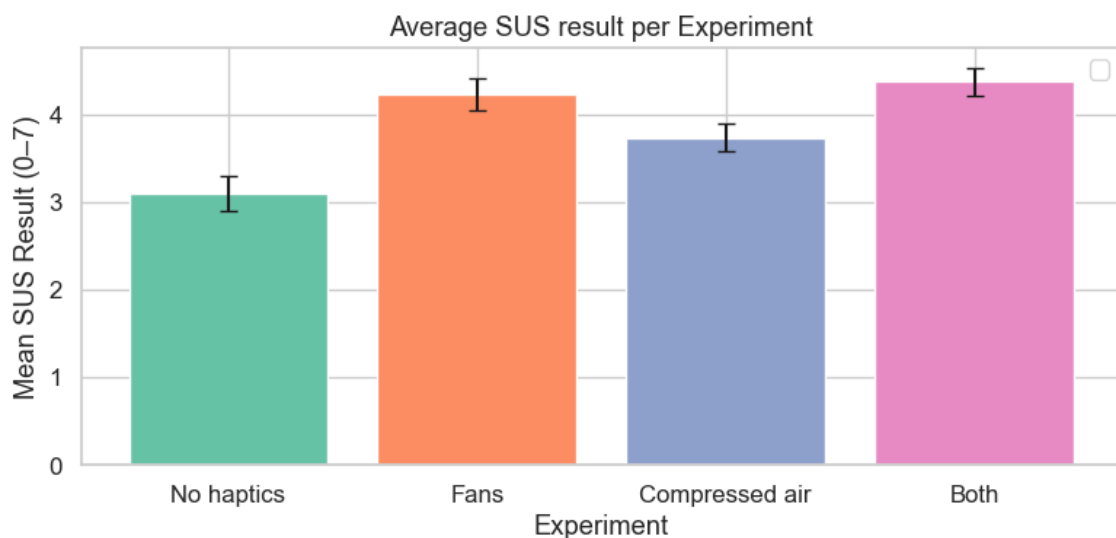


Figure 4.9: Mean Slater–Usoh–Steed score per experiment condition

4.15.2.1 Overall SUS Composite Score

The Friedman test across all four experiment conditions revealed no statistically significant difference in overall presence scores, $\chi^2(3) = 5.824$, $p = .121$. This indicates that, taken as a whole, the haptic configuration did not produce a reliably different sense of presence across conditions, despite a descriptive trend toward higher presence scores in the full-haptics condition.

4.15.2.2 Comparison by SUS Question

Given the non-significant composite result, Friedman tests were conducted on each of the six individual SUS questions to examine whether specific dimensions of presence were sensitive to the experimental manipulation. Five of the six questions showed statistically significant differences across conditions: Q1 ($p < .001$), Q2 ($p < .001$), Q3 ($p < .001$), Q5 ($p < .001$), and Q6 ($p = .004$). Q4 alone was non-significant ($p = .291$). This is likely attributable to a systematic misinterpretation of Q4's response scale by a majority of participants. Q4 asks respondents to locate themselves on a spectrum between "*being elsewhere*" and "*being in the virtual environment*"; however, several participants reported interpreting the scale in the reverse direction, so "*being elsewhere*" being a positive sign of immersion. This wording ambiguity likely introduced some error into Q4 responses, reducing its sensitivity to the changes in the experiments. Wilcoxon pairwise comparisons revealed a consistent pattern across the five significant questions: differences were predominantly driven by comparisons involving Experiment 1 (no haptics) against fan-based conditions. Specifically:

- Exp1 vs Exp2 was significant and positive across Q1, Q2, Q3, Q5, and Q6 (all $p \leq .023$), indicating that introducing fans alone produced a meaningful increase in perceived presence across most dimensions.

- Exp1 vs Exp4 was significant and positive across Q1, Q2, Q3, Q5, and Q6 (all $p \leq .008$), confirming that the full-haptics condition similarly elevated presence relative to baseline.
- Exp3 vs Exp4 was significant and positive across Q1, Q2, Q3, Q5, and Q6 (all $p \leq .027$), confirming that the full-haptics condition elevated presence relative to only compressed air.
- Exp1 vs Exp3 was significant and positive across Q1, Q2, Q3 (all $p \leq .003$), but failed to show a significant difference in Q5 and Q6. This shows the small improvement of compressed air in relation to no haptics.
- Exp2 vs Exp4 were largely non-significant across questions, suggesting fans-only vs fans with compressed air are not reliably distinguishable in terms of presence, mirroring the pattern found in the perceived realism ratings.
- Exp2 vs Exp3 produced the only consistently red (negative significant) result, which shows that only compressed air performed worse in relation to only fans.

4.16 Discussion

The results across both outcome measures point to a consistent and interpretable pattern, though the two metrics differ notably in their sensitivity to the experimental manipulation. The most clear-cut finding concerns perceived realism. The two-way repeated measures ANOVA revealed a large and highly significant main effect of haptic configuration, with fan-based conditions driving the bulk of perceptual gains. Ratings rose substantially from the no-haptics baseline when fans were active, while compressed air in isolation produced only a marginal improvement that did not reach statistical significance relative to no haptics. The significant Experiment $\times$ Haptic interaction further supports this interpretation. Fan-dependent events showed sharp realism gains exclusively when fans were active, while impact events showed a more distributed pattern of improvement across conditions, with compressed air contributing more noticeably in those contexts. Most strikingly, the compound event H5 (Fan with pebbles) reached its peak mean rating only under the combined condition, suggesting a genuine synergistic effect when both actuator types are simultaneously engaged. This implies that the two modalities are not simply additive, but interact in a way that produces a qualitatively richer perceptual experience for sufficiently complex haptic events. The presence findings are more nuanced. The Friedman test on composite SUS scores did not reach significance, and the planned Wilcoxon comparison between the no-haptics and full-haptics conditions was similarly non-significant. This stands in apparent tension with the strong realism effects, and warrants some reflection. One plausible explanation is the confusion in question 4: Most testers reported an opposite interpretation of the scale, where they interpreted "being elsewhere" as a positive indicator of immersion rather than its opposite, introducing noise into that item specifically. This could have been enough to reduce the significance of the overall SUS questionnaire. That said, item-level Friedman tests revealed significant differences on the other five of the six SUS questions, with pairwise comparisons indicating that these effects were

predominantly driven by differences between the no-haptics condition and fan-based conditions. Taken together, the two measures tell a coherent story. Fan-based airflow is the primary perceptual driver in this system, producing robust improvements in both moment-to-moment realism and, at the item level, multiple dimensions of presence. Compressed air contributes meaningfully to specific event types, and its combination with fan-based stimulation produces synergistic effects for compound haptic scenarios. The absence of a significant global presence effect likely reflects the constraints of the measurement approach and the study design rather than a genuine null effect of haptic feedback on immersion.

A further detail worth noting in the realism data is the convergence pattern observed under the combined condition: when both actuators were simultaneously active, ratings for H1, H2, H3, and H4 clustered at a similar level, suggesting a shared perceptual ceiling for single-modality events under full haptic stimulation. Only H5 — the event specifically designed to engage both modalities — continued to stand apart, uniquely benefiting from the complete actuator configuration. This reinforces the interpretation that the two modalities are not simply redundant but contribute differentially based on the structural complexity of each haptic event, a finding that validates the design decision to incorporate both rather than committing to a single actuation approach. Regarding presence, it is also worth noting that a planned direct comparison between the no-haptics and full-haptics conditions using a Wilcoxon signed-rank test similarly yielded no significant difference ($Z = -1.114$, $p = .265$), further confirming the non-significance of the composite SUS result. Descriptively, however, scores followed a consistent directional trend across conditions — no haptics ($M = 3.09$), fans only ($M = 4.23$), compressed air only ($M = 3.73$), both combined ($M = 4.37$) — which aligns with the realism findings and suggests the null composite result is more likely a power and measurement artefact than evidence against a genuine presence effect.

4.17 Summary

This chapter described the experimental evaluation of the facial haptic feedback prototype across four haptic configurations — no haptics, fans only, compressed air only, and both combined — with 20 participants in a virtual roller coaster scenario. The study design, procedure, participant roles, and data collection instruments were outlined, followed by a presentation and analysis of the two primary outcome measures. Perceived realism ratings showed a strong and significant response to haptic manipulation, with fan-based conditions producing the largest gains and a synergistic benefit identified for compound events engaging both actuator types simultaneously. Presence scores, as measured by the Slater–Usuh–Steed questionnaire, did not reach significance at the composite level, though item-level analyses revealed a pattern consistent with the realism findings. The following chapter presents the conclusions drawn from these results and discusses directions for future work. Within the presence analysis, a notable caveat was the systematic misinterpretation of Q4's response scale by several participants, which likely reduced that item's sensitivity and may have contributed to the non-significant composite result. Beyond the main ANOVA findings, Friedman and Wilcoxon follow-up tests confirmed that the effect of haptic configuration was not

uniform across event types, with all five haptic events showing sensitivity to at least some actuator manipulation. A further notable pattern was the convergence of realism ratings for H1 through H4 under the combined condition, with only H5 continuing to stand apart, uniquely benefiting from the full actuator configuration.

Chapter 5

Conclusions

This chapter synthesises the work presented in this dissertation, summarising the contributions of each chapter before reflecting on the main findings, limitations, and directions for future work.

Chapter 1 introduced the research context and motivation for this work, establishing that while visual and auditory realism in virtual reality have advanced considerably, haptic feedback remains predominantly confined to handheld vibration actuators, and the face — despite its high tactile sensitivity — has received comparatively little attention as a target for haptic stimulation. From this gap, three research questions were formulated concerning the perceived realism of facial haptic events, their effect on presence, and their impact on user comfort. Chapter 2 surveyed the state of the art in haptic interface design, categorising prior work into graspable, wearable, and touchable devices, and confirmed that airflow-based facial stimulation represents an underexplored yet promising direction, motivating the design choices pursued in this work.

Chapter 3 described the design and implementation of the proposed prototype, a low-cost facial haptic feedback system combining fan-based airflow actuators and compressed-air jets mounted on a fixed external tripod. The chapter detailed the hardware components — including the drone motors, fans, solenoid valve, electronic layout, and Arduino Uno microcontroller — alongside the layered software architecture bridging the Unity virtual environment to the physical actuators via a serial interface.

Chapter 4 presented the experimental evaluation of the prototype across four haptic configurations (no haptics, fans only, compressed air only, and both combined) in a roller coaster VR scenario. Twenty participants provided perceived realism ratings for five haptic event types and completed the SUS questionnaire following each condition. Statistical analysis using a two-way repeated-measures anova revealed a significant main effect of haptic configuration on perceived realism, as well as a significant interaction between configuration and event type. Analysis of individual SUS items via Wilcoxon signed-rank tests identified significant differences on five of the six presence questions, predominantly driven by comparisons between the no-haptics and fan-based conditions.

5.1 Limitations

A recurring issue throughout testing stemmed from the imprecision inherent in the fan assembly. The drone motors and fans were repurposed components mounted in 3D printed housings, and beyond the motor quality in itself, the tolerances required for a consistent fit proved difficult to achieve reliably across all six units. As a result, individual fans exhibited significantly different levels of mechanical resistance, making it impossible to guarantee uniform airflow across the user's facial surface. This inconsistency had three notable downstream effects: in certain conditions, one or more fans would cut out entirely when all channels were activated simultaneously, likely due to uneven current draw across the L298N drivers; granular speed control proved largely ineffective, as intermediate PWM values amplified the perceptible differences between fans, while lowering it too much did not produce airflow strong enough to be noticeable; and fan noise was near impossible to reduce, even with proper noise canceling headphones, which affected certain users' immersion. A further structural limitation was the prototype's dependence on a fixed tripod mount. By constraining the direction of haptic stimulation to a single fixed orientation in physical space, the range of virtual scenarios that could be meaningfully evaluated was significantly restricted, ultimately necessitating a constrained interaction paradigm — the roller coaster scenario — in which the user's head remains oriented toward the prototype throughout the experience.

5.2 Future Improvements

The most immediate area for improvement concerns the fan assembly. Several more cost-effective alternatives exist, for instance brushless motors or small strong pc fans that could eliminate most of the mechanical issues as discussed in the limitations section section 5.1. Perhaps the most impactful change though, would be of transitioning the prototype from a fixed tripod to being attached to the HMD. The current design constrains the haptic simulation to only one direction in physical space and required the roller coaster testing paradigm as a workaround. This transition is not straightforward, as weight becomes a big concern for comfort, given most HMD's already heavy weight. It would also additionally require other changes as the need for more compact and safer circuitry, or even for the need of placing the compressed air tube in a manner that wouldn't affect the user. Another possibility would be of surrounding the user with fans in all directions. This would possibly make the sensations much more realistic and less intrusive but would introduce their own constraints, namely the need for much stronger fans, as they'd need to be much further away from the user. Beyond fixing issues felt during testing, the prototype has the potential to expand to other haptic modalities, for example, temperature or humidity in conjunction with the fans, as discussed in table 3.2

5.3 Closing Remarks

This work demonstrates that a low-cost, fixed-tripod facial haptic feedback system is capable of producing meaningful and statistically robust improvements in the perceived realism of haptic events in virtual reality, with fan-based airflow emerging as the primary driver of perceptual gains and a clear synergistic benefit identified for compound haptic events engaging both actuator modalities simultaneously. While the effects on global presence and usability composites did not reach statistical significance in this study, item-level analyses and descriptive trends are consistent with a positive directional influence of haptic feedback on the VR experience. These findings provide a foundation for the continued development of accessible, low-cost haptic hardware as a viable means of enhancing perceptual fidelity in consumer virtual reality.

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Appendix A

Literature Review methodology

The literature review was conducted following a Scoping Review approach. The sources stemmed from Elicit, Google Scholar, IEEE and ACM.

A.1 Search terms

To identify relevant literature, a set of targeted search terms was defined to capture research related to haptic interfaces, virtual reality interaction, and wearable feedback technologies. The terms were selected to balance breadth and specificity, ensuring coverage of foundational concepts as well as emerging applications.

Search queries were iteratively refined during the review process to incorporate terminology commonly used in the haptics and VR communities. This approach enabled the inclusion of diverse device types relevant to the scope of this dissertation.

- "Haptic hardware for VR" (Elicit - Broad initial search)
- "How do different haptic feedback technologies impact user immersion and interaction accuracy in virtual reality environments?" (Elicit)
- "virtual reality inside out tracking" (Google Scholar)
- "Graspable haptic devices" (Google Scholar)
- "Wearable haptic devices" (Google Scholar)
- "Touchable haptic devices" (Google Scholar)
- "Tactile display" (Google Scholar)
- "How do cable configurations affect immersion in virtual reality experiences for users?" (Elicit)
- "face haptics for vr" (Google Scholar)
- "facial haptic device" (Elicit)

A.2 Selection Criteria

The articles were chosen primarily on research published from 2015 onwards, a period that coincides with increased accessibility and adoption of consumer virtual reality systems following the introduction of early development kits such as the Oculus DK1 and DK2 ([29, 68]). This timeframe marks a broader expansion of VR as a research and application domain, resulting in a significant increase in studies exploring immersive interaction techniques, including haptic feedback.

However, this review is not restricted exclusively to VR-specific publications or to this temporal window. Foundational and influential work in haptic interfaces—particularly research addressing force feedback, tactile rendering, and interaction paradigms that later informed VR applications—has also been included, even when predating 2015 or originating outside of VR-focused contexts.

Selection criteria prioritized wearable, graspable, or haptic surfaces. Both experimental prototypes and conceptual systems were considered, provided they contributed meaningful insights, with priority to the former tables A.1 and A.2.

Device Category	Graspable	Wearable	Touchable	Other papers
Papers selected	32	30	10	17

Table A.1: Summary of selected papers, categorized by their device. "Other papers" refer to supports for certain statements or were States of the Art used as basis

Type of Articles	Conference Paper	Journal Article	Thesis	Preprint
Papers selected	54	31	3	1

Table A.2: Summary of selected papers, categorized by their article type

A.3 Closing Remarks

This literature review established a structured overview of contemporary research in haptic interfaces relevant to immersive virtual reality. By applying a scoping review methodology, a diverse set of publications was identified and categorized according to device form factor and research focus. The resulting body of literature reflects the rapid expansion of haptic technologies in recent years, particularly in wearable and graspable systems aimed at enhancing interaction realism.

Analysis of the selected works reveals a strong emphasis on hand-centered haptic feedback, with comparatively fewer investigations targeting alternative body regions. While this focus aligns with traditional interaction paradigms in virtual reality, it also highlights opportunities for exploring underrepresented modalities of tactile feedback.

The categorization and selection process presented in this chapter provides the foundation for a more detailed examination of representative systems. The following chapter builds upon this groundwork by reviewing the state of the art in graspable, wearable, and touchable haptic devices, with particular attention to how these systems address immersion, realism, and perceptual engagement. This progression enables a clearer identification of design trends, limitations, and research gaps that inform the proposed approach.

Appendix B

Github Repo

link: <https://github.com/dratomitoma/Thesis>

B.1 Assets used

Table B.1: All assets used, including third-party Unity assets, models, textures, audio files, and other external resources used during the development of the project. Each entry includes the asset name, its purpose in the project, the source, author or publisher, and the applicable licence where available.

Asset Name	Use in Project	Source/URL	Author / Publisher	Licence
Abandoned Factory	Used as environment prop and the included metal material was used in the test fans	sketchfab	Rixael	CC BY 4.0
Train Track	Used for the spline path	sketchfab	timblewee	CC BY 4.0
Falling branch	Test branch impact sound	Pixabay	marcolo91 (Freesound)	Pixabay Content License
Forest Ambience	Background ambient sounds	Pixabay	SoundReality	Pixabay Content License
Wind Lake SFX	Test Fan noises	Pixabay	SoundReality	Pixabay Content License
Leaves	Test branch leaves rustling sound	Pixabay	SOUNDSCAPE_HUMFAK (Freesound)	Pixabay Content License

Fan for Metro #2	Used as prop for the test fans	Unity Asset Store	Abandoned World	Unity Asset Store EULA
True Track System - Spline Merger	Used the minecart prop	Unity Asset Store	Joshabyte	Unity Asset Store EULA
[Free Asset] Fan Spin Effect: Wind Particles	Used for the test fans effects	Unity Asset Store	SOLODREAM CREATION	Unity Asset Store EULA
Low-Poly Simple Nature Pack	Used for the environment: ground and test branch's tree	Unity Asset Store	JustCreate	Unity Asset Store EULA

Appendix C

Experiment script

- Introduction:
 - Prior to the first test session, participants received a standardized verbal introduction delivered by the facilitator. The script read as follows:
 - * "Hello I am a Master's student in Informatics and Computing Engineering at the Faculty of Engineering of the University of Porto. This thesis project is titled 'Enhancing Immersion in Virtual Reality Through Facial Airflow Haptic Feedback'. The focus was the development of this device (i point over to the prototype). Now it may seem like a lot but all it's gonna do is blow air to your general face area through fans and compressed air. We assure you that the forces are fully within reasonable limits but even so you need to give us consent in the forms to run this test. Another thing to note, you need to, after each haptic post, give me a rating from 1 to 5 during each experiment."
- Pre-Test Questionnaire:
 - Consent
 - Age?
 - How much experience with VR
 - What kind of experience with VR
- VR Setup:
 - Let them move around and try out an example of the haptic hardware Without any virtual representation as to not insert any bias into the tests
- Tests

Appendix D

Full results

D.1 two-way repeated measures ANOVA

Table D.1: Mauchlys Test of Sphericity

Within Subjects Effect	Sig.
Experiment	0.444
Haptic	0.002
Experiment * Haptic	0.634

Table D.2: Tests of Within Subjects Effects

Source	Sphericity Correction	F	Sig.	Partial Eta Squared
Experiment	Sphericity Assumed	41.519	<.001	0.686
Haptic	Greenhouse-Geisser	8.196	<.001	0.301
Experiment * Haptic	Sphericity Assumed	14.173	<.001	0.427

Table D.3: Pairwise Comparisons

(I) Experiment	(J) Experiment	Mean Difference (I-J)	Std. Error	Sig.
1	2	-1.420	0.161	<.001
1	3	-0.59	0.204	0.057
1	4	-1.800	0.205	<.001
2	3	.830	0.152	<.001
2	4	-0.38	0.149	0.116
3	4	-1.210	0.189	<.001

D.2 Ratings Wilcoxon signed-rank comparison

Table D.4: Overall Perceived Realism Across Conditions

Between all experiments	df	Asymp. Sig.
Exp1,Exp2,Exp3,Exp4	3	<.001

Table D.5: Perceived Realism by Haptic Event Type

Haptic actuator trigger	df	Asymp. Sig.
H1	3	<.001
H2	3	<.001
H3	3	<.001
H4	3	0.032
H5	3	<.001

Table D.6: Wilcoxon Signed-Rank Tests — Pairwise Comparisons of Overall Perceived Realism

Experiment Pairs	Z	Asymp. Sig. (2-tailed)
Exp1 - Exp2	-3.815b	<.001
Exp1 - Exp3	-2.578b	0.01
Exp1 - Exp4	-3.873b	<.001
Exp2 - Exp3	-3.571c	<.001
Exp2 - Exp4	-2.279b	0.023
Exp3 - Exp4	-3.732b	<.001

Table D.7: Wilcoxon Signed-Rank Tests — Pairwise Comparisons by Haptic Event Type (H1-H3)

Experiment Pairs	H1 Rating		H2 Rating		H3 Rating	
	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Exp1 - Exp2	-3.810b	<.001	-1.261b	0.207	-3.813b	<.001
Exp1 - Exp3	-.073b	0.942	-2.946b	0.003	-1.642b	0.101
Exp1 - Exp4	-3.729b	<.001	-3.600b	<.001	-3.959b	<.001
Exp2 - Exp3	-3.935c	<.001	-2.402b	0.016	-3.509c	<.001
Exp2 - Exp4	-.034c	0.973	-3.114b	0.002	-.440b	0.66
Exp3 - Exp4	-1.643b	0.1	-1.115b	0.265	-3.775b	<.001

Table D.8: Wilcoxon Signed-Rank Tests — Pairwise Comparisons by Haptic Event Type (H4-H5)

Experiment Pairs	H4 Rating		H5 Rating	
	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Exp1 - Exp2	-2.667b	0.008	-3.796b	<.001
Exp1 - Exp3	-.465b	0.642	-3.020b	0.003
Exp1 - Exp4	-1.911b	0.056	-3.893b	<.001
Exp2 - Exp3	-2.057c	0.04	-1.968c	0.049
Exp2 - Exp4	-.111b	0.912	-2.814b	0.005
Exp3 - Exp4	-1.852b	0.064	-3.331b	<.001

- a - The sum of negative ranks equals the sum of positive ranks.
- b - Based on positive ranks. = score increase.
- c - Based on negative ranks. = score decrease.

D.3 SUS Wilcoxon signed-rank comparison

Table D.9: Friedman Test — Overall SUS Scores Across Conditions

Between all experiments	df	Asymp. Sig.
Exp1,Exp2,Exp3,Exp4	3	0.121

Table D.10: Friedman Test — SUS Scores by Individual Question

Question Number	df	Asymp. Sig.
Q1	3	<.001
Q2	3	<.001
Q3	3	<.001
Q4	3	0.291
Q5	3	<.001
Q6	3	0.003

Table D.11: Wilcoxon Signed-Rank Pairwise Comparisons — SUS Scores by Question and Experiment Pair (Q1-Q3)

	Q1 SUS		Q2 SUS		Q3 SUS	
Experiment Pairs	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Exp1 - Exp2	-3.275b	0.001	-3.324b	<.001	-3.221b	0.001
Exp1 - Exp3	-2.710b	0.007	-2.745b	0.006	-1.997b	0.046
Exp1 - Exp4	-3.866b	<.001	-3.729b	<.001	-3.001b	0.003
Exp2 - Exp3	-2.039c	0.041	-0.709c	0.478	-2.543c	0.011
Exp2 - Exp4	-1.231b	0.218	-1.776b	0.076	-0.378c	0.705
Exp3 - Exp4	-2.961b	0.003	-2.215b	0.027	-2.489b	0.013

Table D.12: Wilcoxon Signed-Rank Pairwise Comparisons — SUS Scores by Question and Experiment Pair (Q5-Q6)

	Q5 SUS		Q6 SUS	
Experiment Pairs	Z	Asymp. Sig. (2-tailed)	Z	Asymp. Sig. (2-tailed)
Exp1 - Exp2	-3.126b	0.002	-2.271b	0.023
Exp1 - Exp3	-1.889b	0.059	-1.448b	0.148
Exp1 - Exp4	-2.785b	0.005	-2.740b	0.006
Exp2 - Exp3	-2.754c	0.006	-2.511c	0.012
Exp2 - Exp4	-0.122b	0.903	-.997b	0.319
Exp3 - Exp4	-2.169b	0.03	-2.442b	0.015

- a - The sum of negative ranks equals the sum of positive ranks.
- b - Based on positive ranks. = score increase.
- c - Based on negative ranks. = score decrease.