HUMAN-CENTRIC HAPTICS

AXON

DESIGNING A WEARABLE HAPTIC SYSTEM TO SUPPORT INTUITIVE SITUATIONAL AWARENESS IN COMBAT AVIATION

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ABSTRACT

Fighter pilots operate in high workload environments, where critical information is mostly communicated through visual displays and auditory alerts. As these channels become increasingly saturated due to new technologies, alternative sensory channels can provide other forms of intuitive communication. This project investigates how wearable haptic feedback can support situational awareness by communicating directional information through the tactile channel.

Using a Data-Enabled Design approach, three iterative design loops were conducted involving prototype development, user testing and data-driven refinement. The project focused on understanding how actuator placement and vibration patterns influence the perception and interpretation of vibrotactile cues on the torso. Through a combination of qualitative and quantitative evaluations, design guidelines were developed regarding intuitive haptic communication that requires minimal conscious effort to interpret.

The final design consists of a flight jacket with integrated haptic actuators, capable of communicating directional cues regarding potential threats for left, right, above, below and behind with varying levels of urgency. The project demonstrates how user-centred, data-driven design can inform the development of intuitive wearable haptic systems for high-workload operational contexts.

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CHAPTER 1 - INTRODUCTION

In high performance operational environ¬ments, such as aviation, operators are required to make multiple decisions in rapid succes¬sion while simultaneously processing large amounts of information [28]. Fighter pilots specifi¬cally operate under an extreme cognitive load, where timing and quick interpretation of feed¬back are essential [41]. Currently, information is mostly communicated traditionally, through visual and auditory channels. However, these are often already heavily taxed during flight operations, and with more and more information become increasingly available due to new technologies, additional information through HUDs, speakers or other audiovisual cues risk overloading the pilot's cognitive capacity [20, 40]. A promising additional channel of communi¬cation besides audiovisual channels is using haptic feedback. By including the sense of touch, haptic systems can provide feedback in a way that feels immediate, intuitive and less intrusive than traditional sensory inputs [7]. Since tactile feedback is processed differently from visual and auditory information, it allows cues to be interpreted without competing for attention in often already overloaded sensory channels [5]. This can make haptic feedback par¬ticularly suitable for context in which rapid de¬cision making and high levels of information processing are critical.

Although various haptic feedback systems exist across different markets, many rely on fixed actuator layouts, large grids or generic vibration patterns, offering limited insights into how users actually perceive or interpret tactile feedback on the body [6, 8]. Existing products often lack design-oriented research into how spatial placement, rhythm, and intensity of vi¬brations influence perception, learnability, and comfort when embedded in a wearable form factor [24, 31]. Therefore, a large part of this project will revolve around studying how vibration placement and patterns on the torso influence perception and interpretation of haptic signals. Through iterative prototyping and focusing on user needs, This project aims to take an industrial design approach to exploring how haptic feedback can support intuitive and time-critical deci¬sion-making in combat aviation contexts.

While haptic feedback has shown potential across various domains, limited research has examined how actuator placement and vibration patterns influence perception, interpretation and usability in wearable systems for situational awareness. This limitation becomes partic¬ularly relevant for fighter pilots. As mentioned previously, they operate in conditions that de¬mand rapid decision making and continuous data interpretation while remaining high levels of attention. Although specific research into haptic feedback for aviation has been con¬ducted, for example at TNO, these approach¬es often prioritize system performance, relying on densely populated actuator matrices rather than investigating how the design of specific actuator placements and vibration patterns affect usability and perception [47].
Furthermore, most current studies focus on isolated stimuli or controlled setups, offering limited insights into how other factors might influence the users ability to intuitively inter¬pret the conveyed information [16, 33]. This creates a gap between experimental research and prac¬tical application. What is currently missing is a structured understanding of how findings from research regarding wearable haptic feedback can be translated into concrete design deci¬sions for these systems. This means that design choices are often made based on engineering/testing convenience rather than to maximize perceptual effectiveness. As a result, clear design guidelines for intuitive wearable haptic systems remain limited. Addressing this gap requires an approach that does not aim to optimize a sin¬gle setup, but one that implements a Research through Design and Data-Enabled Design approach through iterative prototyping and user-centred evaluation [44, 48].
My Final Master Project was conducted in collaboration with Touchwaves, a compa¬ny specialized in wearable haptic feedback technology [49]. The project I worked on used their expertise for a new application where their haptic cues are used for situational awareness in combat avi¬ation. Rather than immediately focusing on a finalized product, the project adopted an ex¬ploratory and research-driven approach that emphasizes iterative prototyping and evalua¬tion through both internal and external testing [44].

During this project he following research questions will be adressed:

How does the design of wearable vibrotactile feedback on the torso in¬fluence intuitive and effective situational awareness for combat pilots?
This overarching question is further guided by the following sub-questions:
Which areas of the torso are most suitable for perceiving vibrotactile feed¬back?
How do different spatial positionings of vibration actuators influence the interpretation of haptic cues?
How do vibration patterns (e.g. rhythm, intensity, sequencing) influence perception and interpretability?
How can a wearable haptic system be designed to balance interpretability, comfort, and wearability?
How can iterative prototyping and user testing inform design guidelines for haptic wearables?



figure 1: PROTOTYPE FULL VIEW

GLOSSARY

As this project explores the field of haptic interaction, a number of specific terms are used throughout the report that some readers may not be familiar with. Rather than sending you on a journey through search engines and research papers, a short glossary has been included to provide brief explanations of key terminology used within the project.

Apparent motion

Apparent motion is an illusionary motion and perceived when static stimuli are presented in succession at a specific interval. Haptic apparent motion occurs when two or more separated, discrete points on the skin are stimulated sequentially with specific timing and spacing. Instead of feeling distinct, separate taps or vibrations, the brain perceives a single, continuous, sweeping sensation moving across the skin [12].

Temporal characteristics

Temporal characteristics in haptics define how touch sensations, vibrations, and forces behave and vary over time. Key parameters include frequency (vibrations per second, typically 10 – 300Hz for skin mechanoreceptors), duration (the length of the pulse), rhythm, and latency [20].

Vibrotactile actuator

A vibrotactile actuator is a type of transducer that converts electrical signals into physical vibrations. Commonly used in haptic technology, these devices deliver tactile sensations to the skin. They are often used to provide physical feedback in consumer electronics, virtual reality, and accessibility tools [24]

ERM motor

An ERM (Eccentric Rotating Mass) motor, commonly known as a pager motor, is a DC motor with an offset (non-symmetric) weight attached to its shaft. As the motor spins, the unbalanced weight creates a centripetal force that repeatedly shifts the motor, generating a physical vibration [22].

Haptic Display

A haptic display is an interface that uses physical interactions such as forces, vibrations, and motions, to communicate information through the human sense of touch [33].

CHAPTER 2 - RELATED WORKS

2.1 - Wearable Vibrotactile Feedback

Vibrotactile feedback has been explored wide¬ly as a means of conveying information through the sense of touch. The torso specifically has received attention for the implementation of haptic displays due to its relatively large sur¬face area and its capacity to support 360 de¬gree spatial discrimination of vibrations [8, 17]. Across the literature, two main approaches can be identified when it comes to the posi¬tioning of torso based haptic displays: dense matrix-based actuator layouts and optimally targeted actuator placements.

Matrix-based approaches distribute a large amount of actuators across the torso in a grid like structure such as 5x12, 8x8 or even larg¬er arrays. These systems focus on maximizing spatial resolution (the ability to distinguish be¬tween different points in space on the body) and allow for communicating complex pat¬terns, including apparent motion (the illusion of motion due to rapid switching between static information) and directional sweeps. Dharma et al. (2013) demonstrated that a high-density actuator matrix can convey accurate naviga¬tional cues, allowing users to interpret direc¬tional information through spatial vibration patterns [5]. Similarly, van Erp et al. (2003) em¬ployed a 64-tactor haptic torso display to sup¬port helicopter pilots operating with both night vision goggles and in full vision conditions, by giving haptic feedback while hovering [7]. The study showcased that vibrotactile cues could significantly enhance hover performance by reducing drift, even when visual information was available. However, complex patterns with a large number of active tactors could result in less accurate perception due to "tactile clut¬ter", meaning that cues can become confusing or less effective when too much information is conveyed at a time [7]. This is partly because the torso has a relatively low spatial resolution compared to for example the hands or finger¬tips [5, 15] . matrix based systems also increase hardware complexity, higher power consump¬tion and reduced wearability in uniforms that already include multiple layers [9].

In contrast, targeted placement approach¬es focus on determining actuator position¬ing based on testing and comparing different layouts, often resulting in a smaller number of tactors placed at anatomically meaningful locations on the torso. Instead of maximizng spatial resolution, these designs aim to lever¬age locations where tactile perception is more sensitive, accurate or intuitive [30, 31]. Jones et al. (2004) showed that an array of as low as 9 tactors situated on the lower back can effec¬tively convey directional information, given that vibration frequency and spacing is appro¬priately determined [15]. Targeted approaches typically result in simpler, cost effective sys¬tems that are easy to wear, and may require less training compared to systems with a larg¬er number of actuators. However, reducing the number of actuators also limits the amount of information that can be conveyed. This makes it more difficult to simulate apparent motion or precise directional feedback. These trade-offs highlight the importance of understand¬ing how spatial placement and patterns influ¬ence the effectiveness and intuitiveness of the system. The next section will further highlight findings of potentially meaningful areas on the torso for actuator placement.

2.2 - Spatial perception and pattern recognition on the torso

A significant body of work has examined how individuals perceive haptic feedback on dif¬ferent regions of the body. These studies re¬veal that spatial acuity (the ability to accurate differentiate between different points) on the torso is generally low, with spatial discrimi¬nation thresholds typically ranging between 20 and 40 mm [31]. However, acuity improves near the midsagittal plane of the body, for ex¬ample along the spine or near the navel, where thresholds can decrease to approximately 10 mm [31]. The midsagittal plane also plays a role in users' directional judgements. Van Erp (2005b) stated that users portrayed a sys¬temic directional bias towards the midsagittal plane, often perceiving stimuli as closer to the spine or navel than their actual direction [30]. This suggests that the midsagittal plane may act as mid or anchor points, providing refer¬ence frames for interpreting directional tactile cues. These biases varied across participants, meaning that haptic displays may require indi¬vidual calibration if directional cues need to be interpreted precisely.
Another focal point for ensuring perceptu¬al clarity in haptic displays are the temporal characteristics of vibration patterns. Van Erp (2005a) highlighted that short intervals be-tween two differently placed vibration cues enhance the perception of apparent motion, making directional cues easier to interpret, even with a low number of actuators [31]. Sub¬sequently, longer intervals degraded localiza¬tion accuracy. Kim et al. (2022) similarly com¬pared different types of vibration patterns and found that short bursts, which were named "spot" patterns in the study, were interpreted more intuitively than ramped or multi-burst patterns, particularly leading to faster response times [18].

A recent study by Kim et al. (2023) further shows that the torso is able to accurately recognize spatial patterns up until a certain amount of information. Using a commercial vibrotactile vest, the study demonstrated that recognition accuracy decreases as more actuators are ac¬tivated simultaneously, correlating with the findings of van Erp regarding tactile clutter in dense displays [7, 17].
The placement of tactors also have a signifi¬cant effect on comfort and wearability. However, several studies report conflicting findings about the optimal placement of tactors. Some suggest that bony areas or regions near the spine increase interpretability, whereas users in other studies reported discomfort when ac¬tuators are placed on these areas [18, 31]. Ad¬ditionally, tactor placement on the abdomen is generally seen as less optimal, as it can give an unwanted sensation in the organs or abdomen muscles [5, 36].

Another application of haptic feedback that provides relevant inspiration is its use in assistance for visually impaired us¬ers. These applications focus on multiple types of feedback such as navigation and obstacle avoidance [29]. Prototypes are often made in the form of vibration-based phone navigation and wearable devices that warn about obstacles and convey direction through touch [10, 21, 29]. Other research focuses on more complex haptic interactions for digital interaction. Smartphone studies have explored vibration patterns and touch-accessibility features to help users navigate through interfaces without relying on vision [11]. More recent work extends this further into multimodal interaction, where computer vision triggers tactile cues to guide exploration [25, 32]. This body of literature suggests that haptic feedback is most useful when it delivers simple and immediate spatial information, while multimodal or more complex systems appear more suitable for richer tasks like object recognition and screen interactions. These insights suggest similar potential for communicating spatial information in other domains like combat aviation, where users often must quickly process spatial information outside their field of view.

2.3 - Neurophysiological considerations for design implications

Insights from neuroscience can provide ad¬ditional context for understanding vibrot-actile feedback on the torso. Discriminative touch sensations like vibrations are processed through the dorsal column-medial lemnis¬cal pathway, which supports relatively precise spatial discrimination compared to other so¬matosensory modalities [44]. Sensory inputs on one side of the body get sent to the oppo¬site hemisphere of the brain, meaning path¬ways travel upwards and across the spinal cord [44]. This may be an indicator why spa¬tial acuity is more precise in those areas. An¬other factor that could help guide the design of a haptic torso display is the organization of the body in dermatomes, an area of skin sup¬plied and innervated by a single spinal nerve root [45]. Some argue against applying stimu¬li near dermatome borders as it may be per¬ceived ambiguously [38], while others state that dermatomes overlap and do not have a clear boundary [45]. Even though much of this research focuses on medical contexts, such as locating spinal nerve damage, insights can be applied to haptic design. A study conduct¬ed by Pardo et al. (2022) has already demon¬strated this, by examining haptic interpretabil¬ity across different dermatomes [27]. Although conducted on the arm and shoulder, the study shows that while absolute vibration sensitivity varies across locations, users were equally ca¬pable of perceiving relative changes in vibra¬tion intensity across different dermatomes.

PROJECT ECOSYSTEM

To better understand the context in which the system would operate and develop, a stakeholder analysis was conducted and a value proposition was setup (see figure 2 and 3). The network of actors involved in the development, deployment and use of wearable haptic feedback systems was explored to establish possibilities and limitations during the project. This network includes pilots, aviation/military research organisations, MODs and Touchwaves themselves, several of which were actively involved throughout the project. The value proposition was setup to define key factors for the system to be feasible and create value for the intended user group, highlighting the reduction of visual and auditory workload while supporting situational awareness through vibrations. These analyses helped position the project within a broader system and identify important considerations for successful implementation (Specific company names were kept private to protect Touchwaves and involved parties).

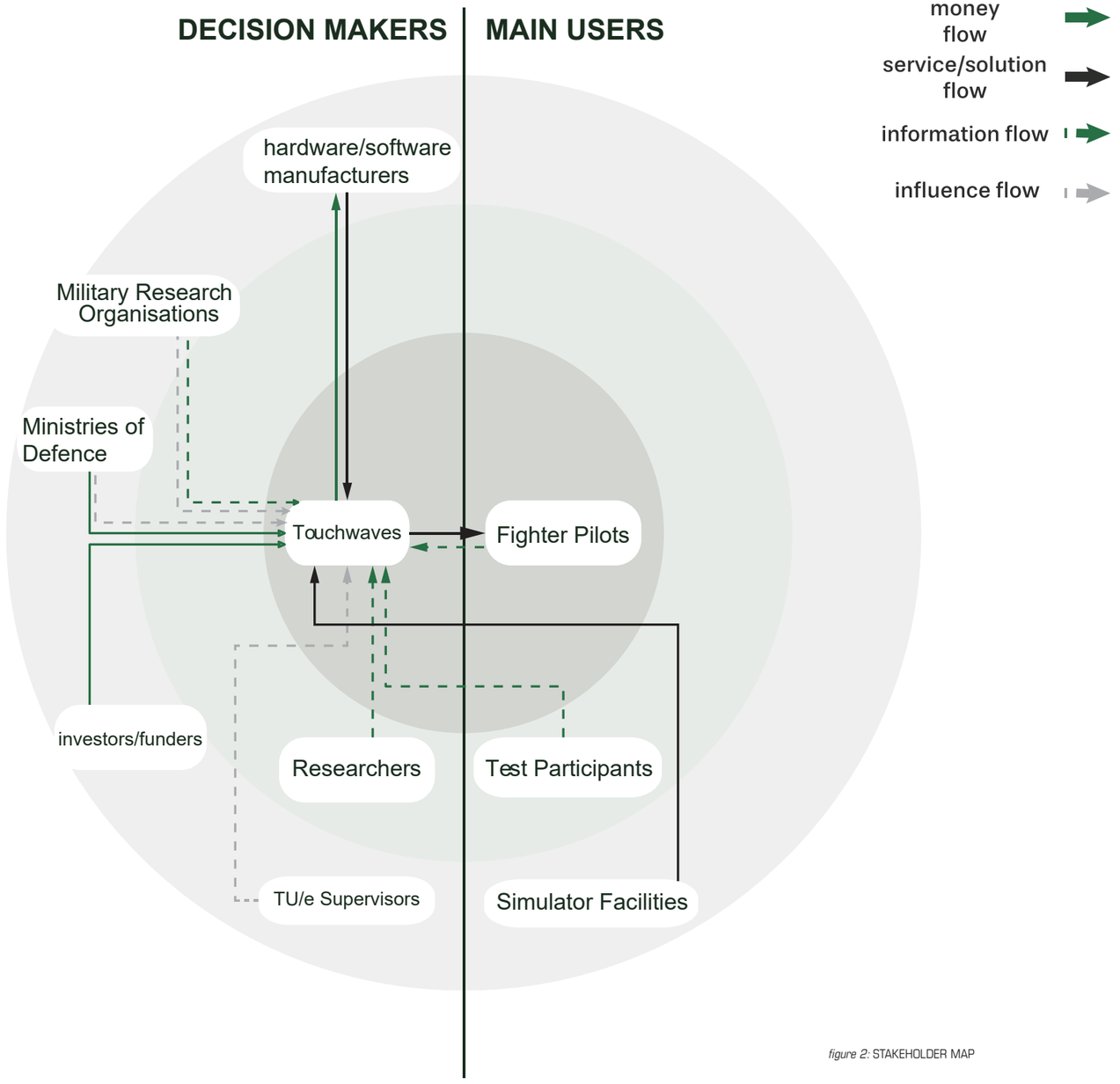


figure 2: STAKEHOLDER MAP

VALUE PROPOSITION

Value Proposition

Products & Services

Flight jacket with integrated haptics
Directional tactile cues
Situational awareness support
Modular actuator panel

Pain Relievers

Reduces visual workload
Reduces auditory overload
Fast directional communication
Minimal training required

Gain Creators

Additional sensory channel
Improved situational awareness
Intuitive spatial information
Compatible with existing workflows

Customer Profile

Users

Pilots / Operators

Gains

Better situational awareness
Faster cue interpretation
Lower cognitive workload

Pains

Cognitive overload
Saturated displays
Missed information

Jobs

Maintain awareness
Detect threats
Make rapid decisions

figure 3: VALUE PROPOSITION CANVAS

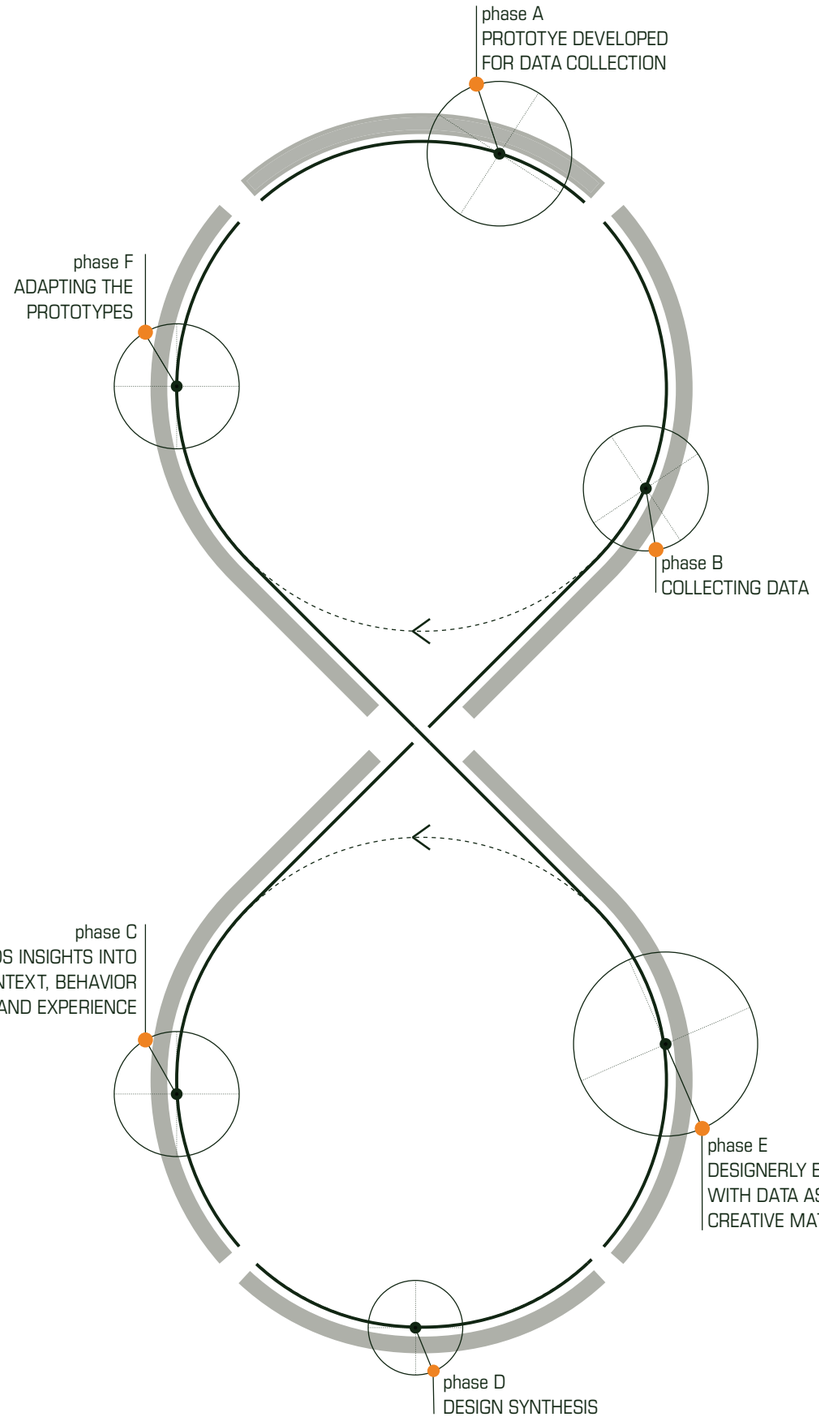


figure 4: DATA-ENABLED DESIGN PROCESS

CHAPTER 3 - METHODOLOGY

3.1 Research Approach

The approach that this project aligns most closely with is that of a Data-Enabled Design (DED) process [53], exploring multiple iterations of wearable haptic displays and gathering data, where each iteration provided a source of insights for the next (see figure 4).

Data-Enabled Design

DED is a design methodology in which data is not solely used to evaluate systems and design solutions, but also to generate insights that actively inform subsequent decisions throughout an iterative design process. Created by Bogers and van Kollenburg, during this approach data is used as a creative design material [54]. Rather than only focusing on validating a final product, DED emphasizes the collection and analysis of data to uncover user needs and opportunities for new design directions. A DED approach is suitable for this project due to the exploratory nature of (wearable) vibrotactile feedback. While previous research mostly provides insights on 1) to what extend the body can interpret haptic feedback and 2) how wearable haptic displays can be developed, there is a limited body of knowledge that explores specific actuator locations and vibration patterns for intuitive communication, especially in the context of supporting situational awareness. Where this project differs from a classic DED approach, is that insights were gathered through structured user tests in controlled settings, opposed to using sensor data gathered while the research probe is being used in the field. Nevertheless, this project still uses data as the primary source for iterative design decisions and therefore aligns closely with DED principles.

The design process during this project was structured around three iterative Data-Enabled Design loops. Each loop consisted of the development of a prototype, the collection of qualitative and/or quantitative data, the analysis of that data to gather design insights, that were then used for design decisions for the subsequent iteration. So, rather than following a linear development process, the system evolved through repeated cycles of designing, building, evaluating and refining. The loops that were conducted each highlight a different phase of the project:

LOOP 1: INITIAL WEARABLE EXPLORATION
LOOP 2: ACTUATOR POSITIONING AND VIBRATION PATTERN EVALUATION
LOOP 3: VALIDATING AN INTEGRATED HAPTIC DISPLAY

Research-through-Design
This project also followed principles of Research-through-Design (RtD), in which knowledge is generated through the creation and evaluation of design artifacts [44]. Within this approach, prototypes and design artifacts not only function as a representation of a potential design solution, but also as an instrument to conduct research that enables the exploration of design questions. Through the act of designing and evaluating those designs, insights can be generated that would otherwise be difficult to obtain with theory alone. These principles are particularly relevant for haptic interaction, where user perception and interpretation play such a large role in how information can be communicated, and are difficult to predict without physical experimentation.

User-Centered Design
In addition to a DED and RtD approach, the project was guided by User-Centered Design (UCD) principles [46]. Throughout every loop of the iterative design process, users were actively involved in evaluating prototypes, and a large part of design decisions were based on user needs, insights and preferences. A focal point of the study was to let users naturally perceive and assign meaning to haptic cues to create a design guideline (framework?) for an intuitive haptic display, rather than instructing them to learn predefined mappings.

3.2 Participants

Participants were recruited multiple times throughout the project to evaluate different aspects of the haptic system. Due to the iterative nature of a Data-Enabled Design process, the level of participants involvement varied throughout the different design loops, with evaluations focusing on different aspects such as wearability, perception, interpretability and usability. Participants were primarily recruited through personal network and consisted of students, Touchwaves employees and employees at the Fashion Tech Farm (office location of Touchwaves). For one part of the final usability test, three military staff persons were recruited through Touchwaves' network. All participants were over 18 years old. The study was structured in multiple stages, each aligned with a specific research goal in mind. For the first two user tests, five participants each were involved. These stages focused on early evaluation and refinement of the wearable prototype, including aspects such as comfort, wearability, and global actuator placement. A smaller sample size was appropriate here, as the goal was to identify major usability issues and inform design iterations rather than to collect a large dataset.
Once a stable and functional prototype was established, the tests regarding the third and fourth research questions involved a larger group of ten participants each. These stages focused on testing of the interpretability and intuitiveness of different actuator placements and vibration patterns, where more consistent and comparable data is required.

For the final usability test, five participants were used for a laptop simulation A/B test, and three participants were recruited for a simulator test. Unlike previous evaluations, which focused on identifying emerging patterns in actuator placement and vibration patterns, the objective of the final evaluation was to assess the usability of the final system.

3.3 Data collection

A combination of qualitative and quantitative data collection methods was used throughout the project. A mixed-method approach was chosen to capture both measurable differences in the perception of haptic cues, as well as the reasoning behind the interpretation of participants. Collecting both forms of data supported the iterative design process by enabling design decisions to be based on objective performance measures of the prototypes as well as subjective user experiences.

Qualitative data was primarily collected through semi-structured interviews and participant observations. Participants were instructed to describe what they perceived, how they interpreted different haptic cues, and whether specific actuator placements or vibration patterns felt intuitive or confusing. These responses provided insights into what happened between the moment of the vibration and when they formed a conclusion regarding the meaning behind the cue.

Quantitative data was collected mainly through Likert-scale questionnaires, directional recognition tasks and response time of cue recognition. Depending on the user test, participants were asked to rate aspects such as comfort, clarity and urgency on a five-point Likert-scale. Additionally, measurements were collected during other tasks, including the accuracy of directional cue interpretation during a task, response time between a given directional cue and direction chosen by the participant, and thresholds of parameters when haptic cues started to decrease in clarity.

The type of data collected varied between design iterations. The decision was made to focus on both quantitative and qualitative data to evaluate vibration patterns and solely on qualitative data to evaluate spatial positionings, which was based on the nature of the research questions. The spatial positioning evaluations included a large number of fundamentally different actuator layouts, each potentially triggering different interpretations and meanings. In this context, qualitative feedback provided richer insights into how participants responded to the cues than numerical ratings. Furthermore, the large number and diversity of cues (33 total) could have made consistent quantitative comparison increasingly demanding for participants. In contrast, the vibration pattern evaluations focused mostly on the comparison of specific parameters across a single motor, making them more suitable for quantitative comparison through ratings.

3.4 Data analysis

Both the collected quantitative and qualitative data were analysed to support design decision-making. Qualitative data was analysed using thematic analysis, in which participant responses, observations, comparisons and preferences were reviewed to identify emerging themes, patterns and explanations regarding the interpretation of haptic cues.
Quantitative data was used mainly to evaluate comparisons between parameters in vibration patterns. Descriptive statistics were used to identify trends and preferences within the collected data, while one-way measured ANOVA was applied where appropriate to evaluate the significance of differences between vibration patterns.

3.5 Ethical considerations

The risks associated with participation were low. Participants may experience mild physical pressure from the vest and low-intensity vibrotactile stimuli on the torso, which could feel unusual or slightly uncomfortable. There was no exposure to extreme stimuli. To mitigate any potential discomfort, vibration intensities were kept within safe, commonly used levels, sessions were relatively short, and participants are seated throughout the test. Participants were informed that they can stop the study at any time without consequences.
The risks to participant privacy were also minimal, as mostly non-identifiable data was collected (except from age and gender). All responses were anonymized using participant codes. Data was stored securely on password-protected devices and is only accessible to the researcher. Any link between participant identity and data was removed after data collection, minimizing the risk of a data breach.

CHAPTER 4 - ITERATIVE DESIGN PROCESS AND EVALUATION LOOP 1 - INITIAL WEARABLE EXPLORATION

DESIGN CONSIDERATIONS

Before the development of any prototypes, several design constraints were introduced by Touchwaves, mainly regarding the possible locations for actuator placement. Since the system is intented for a combat aviation context, not all body locations were suitable for haptic feedback. The following parts of the body were excluded for actuator placement:

The front of the torso was largely avoided due to potential discomfort when vibrations are close to vital organs

The arms were excluded because their position continuously changes during operation, altering spatial meaning of vibration locations.

The head and shoulders were avoided due to the presence of gear including flight helmets and harnesses that could induce uncomfortable pressure on the actuators.

Finally, ***the legs*** were excluded due to the presence of anti-G compression pants that provided blood pooling in the lower extremities. Consequently, the back and sides of the torso were identified as the most suitable regions for actuator placement.

4.1.1 - DESIGN PROCESS ITERATION 1

The initial prototype was developed to explore general actuator placement possibilities. The prototype consisted of an elastic garment with a zipper and modular Velcro-mounted actuators, focusing on rapid repositioning of actuators across different regions of the torso during early experimentation. The prototype was built around a module consisting of an Adafruit Feather 32u4 microcontroller, battery, on/off switch and a custom PCB [14]. The system supported BLE (Bluetooth Low Energy) communication, allowing vibration patterns to be triggered wirelessly through a smartphone. This module was already developed by Touchwaves. Parts that were added were LilyPad Vibe Boards containing ERM vibration motors, that were soldered to the custom PCB using long wiring [45]. The extended wiring enabled the motors to be positioned freely across the body without requiring modifications to the electronics. Additionally, new firmware was coded through the Arduino IDE and uploaded to the microcontroller to control the vibrotactile cues for the corresponding layouts [46].

To support the rapid testing of multiple actuator positions, Velcro strips were attached to both the back/sides of the shirt and the back of the LilyPad Vibe Boards. This allowed the process of quickly removing and repositioning the motors when switching to a different layout. A t-shirt with elastane was used as the base garment for its stretch properties, which were expected to improve actuator-to-skin contact compared to looser or stiffer clothing. Finally, a front zipper was added to simplify taking off and putting on the prototype, particularly when switching between actuator layouts during testing with participants.



figure 5: CONTROL CASE 1

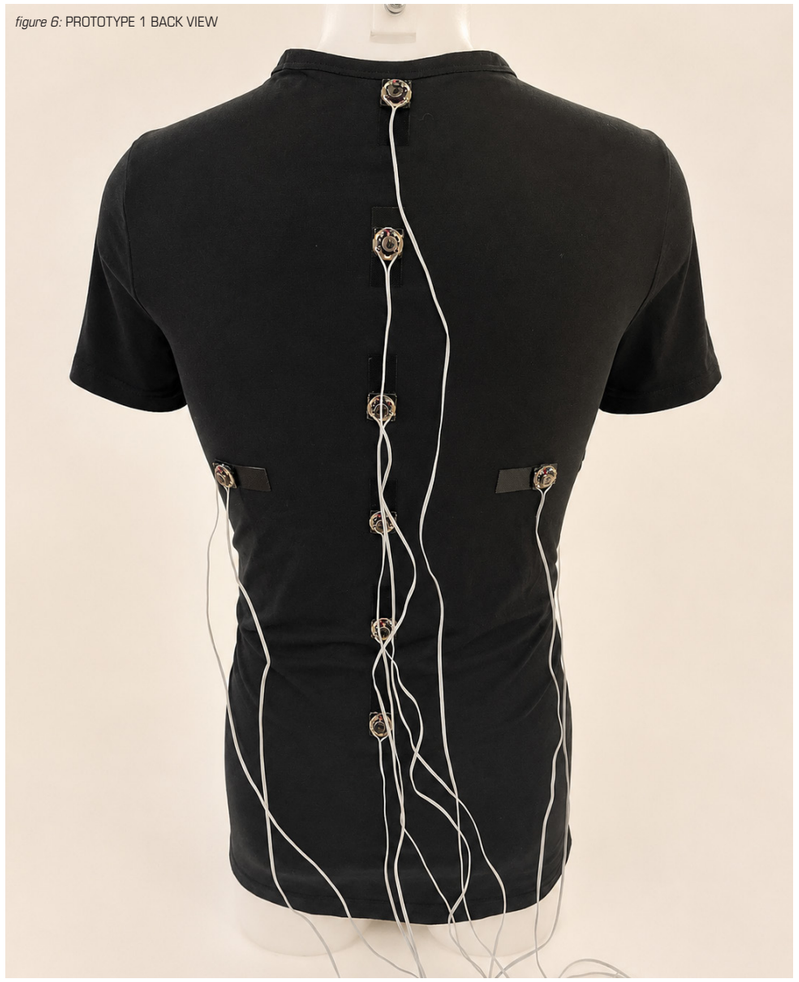


figure 6: PROTOTYPE 1 BACK VIEW



figure 7: BAD UPPER BACK CONTACT

4.1.2 TEST SETUP ITERATION 1

Four distinct initial actuator layouts were developed and compared during this iteration. Rather than comparing individual parameters, these layouts represented different approaches on how haptic displays could generally communicate directional feedback on the back of the torso. The layouts included large apparent motion sweeps, more localized cue placement on the upper/lower back and sides of the torso, using the shoulder blades for cue placement and using a very compact layout located on the midback. The purpose of these layouts was to explore the broader design space of wearable haptic displays and identify possible relevant directions for future iterations. By comparing fundamentally different actuator layouts, initial insights were obtained regarding how actuator distribution, spacing and location on the torso influence the interpretation of haptic cues. Evaluations were done using five Touchwaves and Fashion Tech Farm employees, where Semi-structured interviews were conducted regarding the interpreted direction of a cue and whether it felt intuitive.

4.1.3 RESULTS AND INSIGHTS ITERATION 1

Initial testing revealed that this prototype lacked sufficient stability and actuator-to-skin contact consistency across the torso for reliable results on perception, specifically in the spine, lower back and shoulder blades regions. A tight fit across every region of the back of the torso tended to be very difficult to achieve without tightening mechanisms or additional padding material. Furthermore, the limited adjustability of the garment resulted in only a specific body type and size to receive somewhat accurate results. Additionally, due to the lack of good structure and fit, the actuators tended to shift during movement, further impairing the consistency of vibration localization and interpretability.

Despite these limitations, the prototype highlighted valuable insights regarding the importance of fit, adjustability and consistent perception. The comparison of multiple layout concepts further suggested that actuator positioning has a large impact in how users interpret haptic directional information. These findings directly informed the development of subsequent prototype iterations.

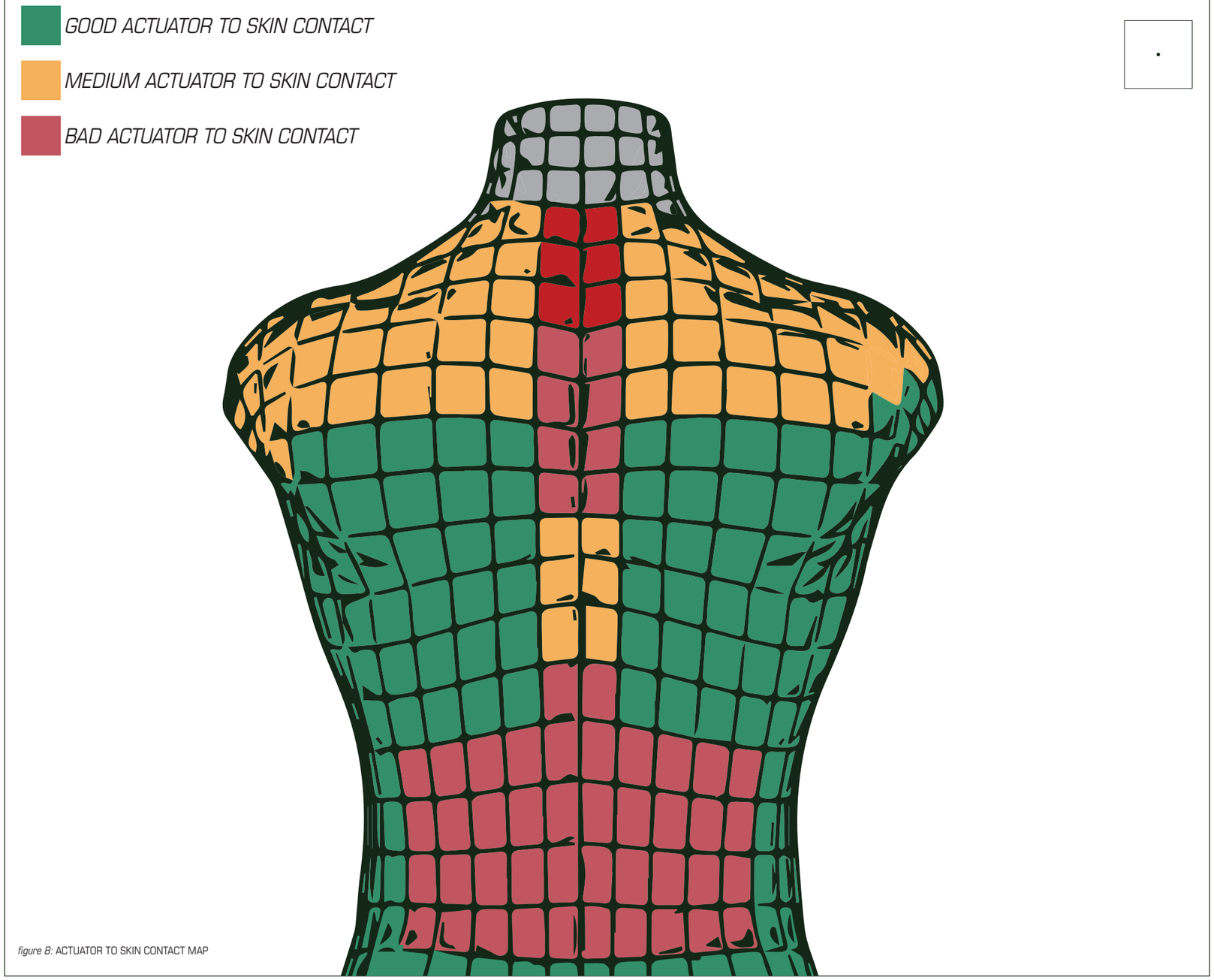


figure 8: ACTUATOR TO SKIN CONTACT MAP

LOOP 2 - ACTUATOR POSITIONING AND VIBRATION PATTERN EXPLORATION

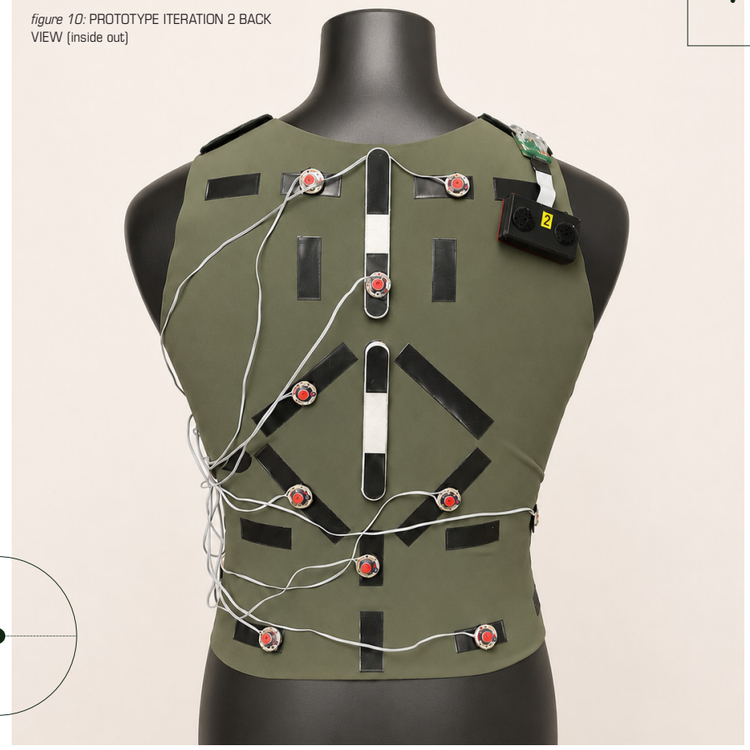
4.2.1 - DESIGN PROCESS LOOP 2

Following the insights from the first prototype iteration, a second prototype was developed with a focal point being to achieve a more reliable system for the evaluation of vibrotactile perception on the torso. In contrast to the initial prototype, this iteration enabled tightening the garment, in the form of adjustable straps that each pulled a different region of the garment closer to the skin: the upper strap was attached to a diagonally cut part of the vest to pull the fabric tight around the shoulder blades, the lower strap was added to the bottom of the garment to tighten around the lower back, and the middle strap was attached more in the center (opposed to the other two straps that were located more on the edge of the fabric) to tighten the fabric around the midback where bunching often occurs due to the natural curve in the spine (see figure 11).

figure 9: PROTOTYPE ITERATION 2 FRONT



figure 10: PROTOTYPE ITERATION 2 BACK VIEW (inside out)



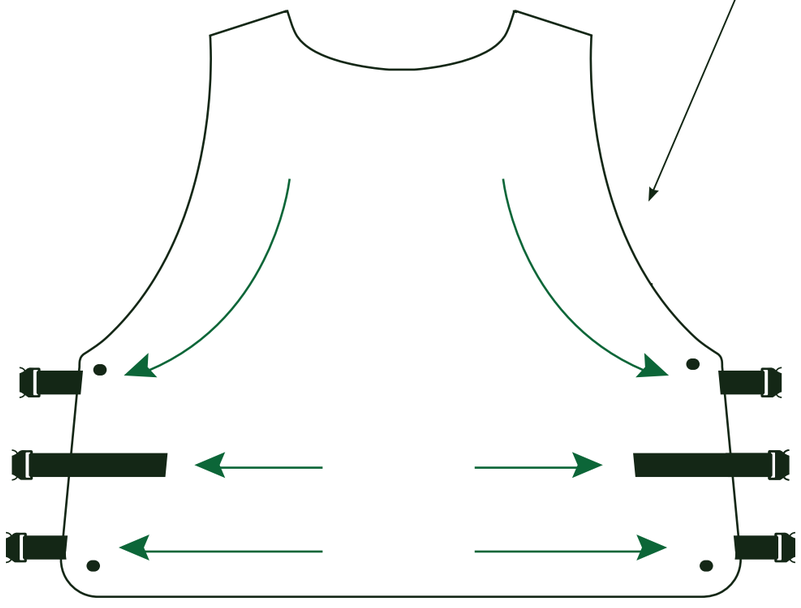


figure 11: PROTOTYPE FIT BUCKLES

Furthermore, 3D printed modules were added to get close actuator-to-skin contact in the spinal groove, since this was an area where maintaining contact was one of the most prominent challenges in iteration one. Mulitple iterations were explored, with varying levels of thickness, curvature and lengths to determine a shape that increased close actuator-to-skin contact in a way that felt most natural to the user. The modules were made out of TPU, a flexible material that was chosen to feel non-intrusive while wearing the garment. By adding the modules to the spinal groove, the actuators were pulled against the skin rather than away from it when the fabric was pulled tight, since the modules protruded out futher than the surface of the shoulder blades (see figure 13).

Finally, extra Velcro patterns were added for more actuator location possibilities, and overall garment improvements such as a removable panel to cover electronics were made.

This iteration was specifically designed to answer the two largest sub research questions, regarding different actuator layouts and vibration configurations on different regions of the torso, with directional interpretation, pattern complexity and localization clarity being of primary focus.



figure 12 TPU MODULE EXPLORATION

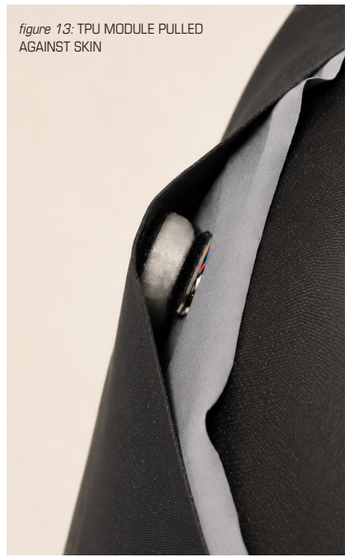
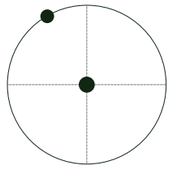


figure 13: TPU MODULE PULLED AGAINST SKIN



figure 14: PROTOTYPE ITERATION 2 INSIDE FLAT



4.2.2 TEST SETUP ITERATION 2

This iteration was specifically designed to answer the two most important sub-research questions, regarding different actuator layouts and vibration patterns on different regions of the torso, with directional interpretation, pattern complexity and localization clarity being of primary focus. Before conducting user tests on university regarding these research questions, internal testing was done once more to evaluate whether the second prototype provided more consistent vibrations than its predecessor. A simple test conducted where actuators were placed on six regions of the torso: upper spine, mid spine, low spine, shoulder blades, mid sides and low sides. Vibrations in these areas where triggered one by one after which participants gave feedback on clarity, comfortability and localization (whether the vibration spread to other parts of the back). Results showed that vibrations were much more consistently interpreted compared to the first prototype, enabling the study to move forward to the next step of user evaluation.

Research question 3: How do different spatial positionings of vibration actuators influence the interpretation of haptic cues?

To evaluate the result of different spatial positionings, multiple actuator layouts were tested across the torso using directional recognition tasks as well as comparative layout testing. The layouts explored aspects such as vertical and lateral apparent motion, different spacing between motors, sweeps across different back regions, spine versus shoulder blade placement, and cues that simulated motion towards or away from the midback. Participants were asked to identify their perceived movement direction, indicate whether vibrations felt like continuous motion or separate points, what type of vibrations felt most intuitive regarding directional cues, and evaluate vibration clarity. The evaluations also explored whether a smaller amount of motors could still effectively communicate directional information intuitively. Five layouts (positioning of motors) with a total of 33 different cues (triggering certain motors within a layout) were tested. The results were analysed using thematic analysis.



figure 15: ACTUATOR POSITION LAYOUTS

Research question 4: How do vibration patterns (e.g. rhythm, intensity, sequencing) influence perception and interpretability?

In addition to spatial positioning, multiple vibration patterns of both individual actuators and multiple actuators in sequence were evaluated, to explore how temporal characteristics influence user perception and interpretability. These evaluations consisted of comparisons between variations in pulse intensities, pulse speeds (durations of pulses), pauses between pulses, ramped vs constant vibrations, and speed of apparent motion sweeps. Participants gave some qualitative but mostly quantitative feedback on the perceived clarity and urgency (1–5 Likert scale rating) and meaning (semi structured interviews) of different characteristics. Other points of attention were given to whether a change in temporal characteristics created a sense of directional movement, and whether low motor intensities or short pulses were perceivable at all.

Qualitative data was analysed using thematic analysis, while quantitative data was analysed using one-way repeated measures ANOVA [2, 3]. The findings acted as guidelines for the final integrated prototype, in which the fixed actuator positions and vibration patterns were embedded directly into a flight-jacket for the final usability evaluation.

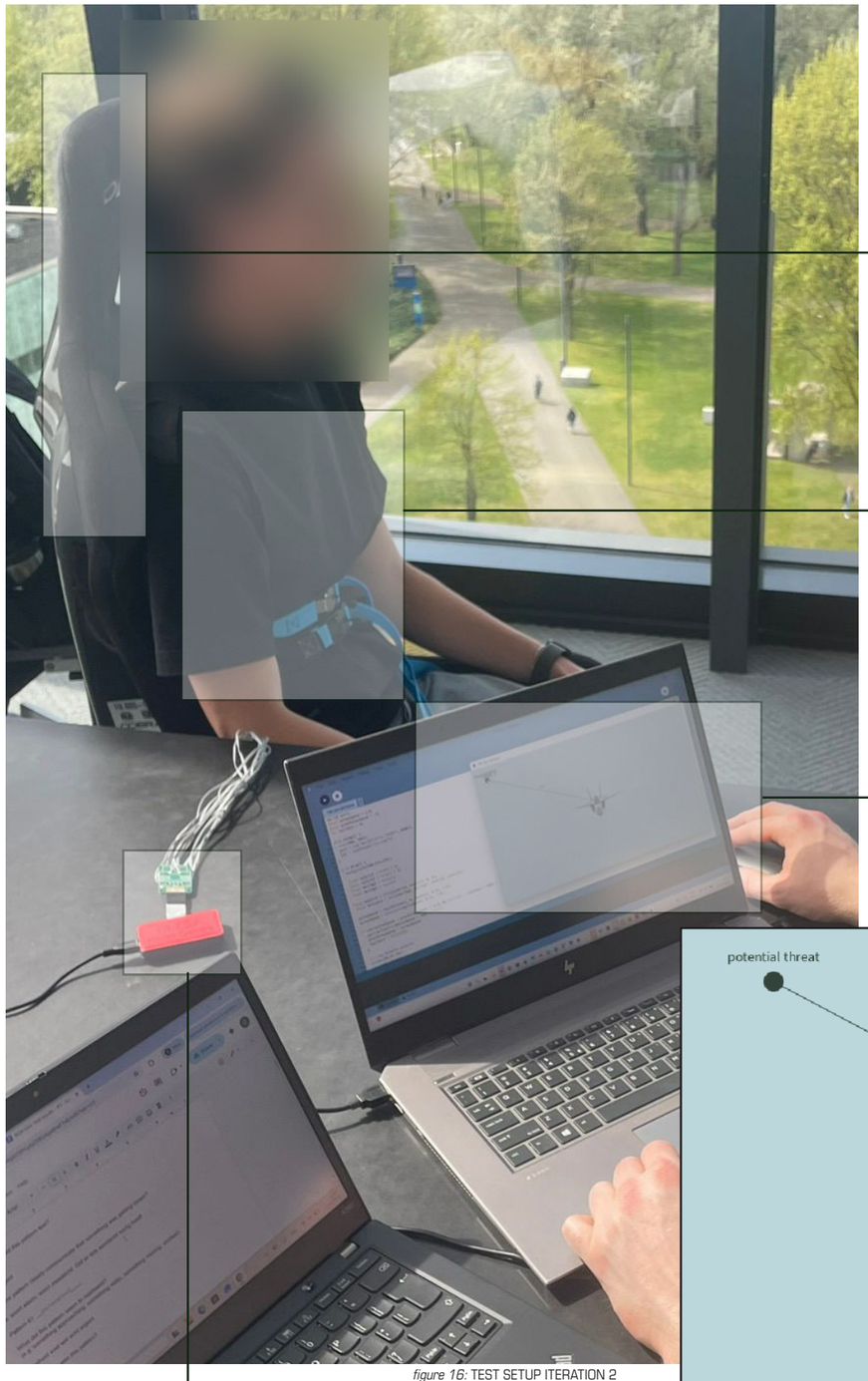


figure 16: TEST SETUP ITERATION 2

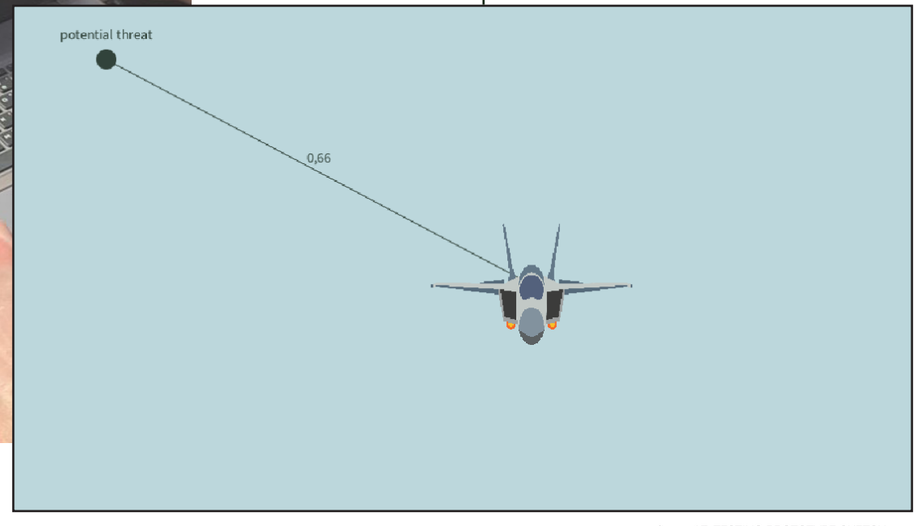


figure 17: TESTING PROTOTYPE SKETCH

4.2.3 RESULTS AND INSIGHTS ITERATION 2

User test RQ3 - Spatial positioning

The results of user test three showed that different actuator layouts have a large impact on both the clarity and interpretation of vibrotactile cues. The following section describes the results regarding how participants interpreted cues across the different layouts.

LAYOUT 1 AND 2. VERTICAL AND LATERAL SWEEPS

Patterns activated in sequence were often described as "movement" rather than separate vibration points, with participants describing cues as "from down to up" (P3), "something is crawling upwards" (P6), and "like something is running up my back" (P10). Even when directional sweeps were reduced from seven to four sequential motors (as long as the distance between actuators is not too large (see figure 17)), most participants did not notice any difference, stating for example that "there is no difference between a full and half sweep" (P1), "I dont feel a difference" (P2), and "there is no noticeable difference between full and half sweep" (P4).

Additionally, differences were observed between lateral and vertical directional cues. Lateral sweeps were often interpreted more consistently and with higher confidence compared to vertical sweeps. Participants often found left and right directional cues to be recognized more easily, compared to up and down directional cues. For example, lateral cues frequently resulted in direct action-oriented responses such as "I would look to the left" (P1), "looking to the right" (P1), and "I would turn to the right" (P7). These lateral cues were perceived as most clear when just one actuator was triggered on the sides of the participants. In contrast, vertical cues sometimes resulted in less clear interpretations and still felt like a presence behind the user, especially when just one actuator was triggered, with participants stating "something straight behind me at that height" (P5), "something is behind me but high behind me" (P8), and "like something is located behind me" (P10).

NOTE: THE COLOUR HIGHLIGHTS THE PERCEIVED VIBRATION STRENGTH, SINCE THE END OF A CUE WAS OFTEN PERCEIVED AS MORE POWERFUL THAN THE START

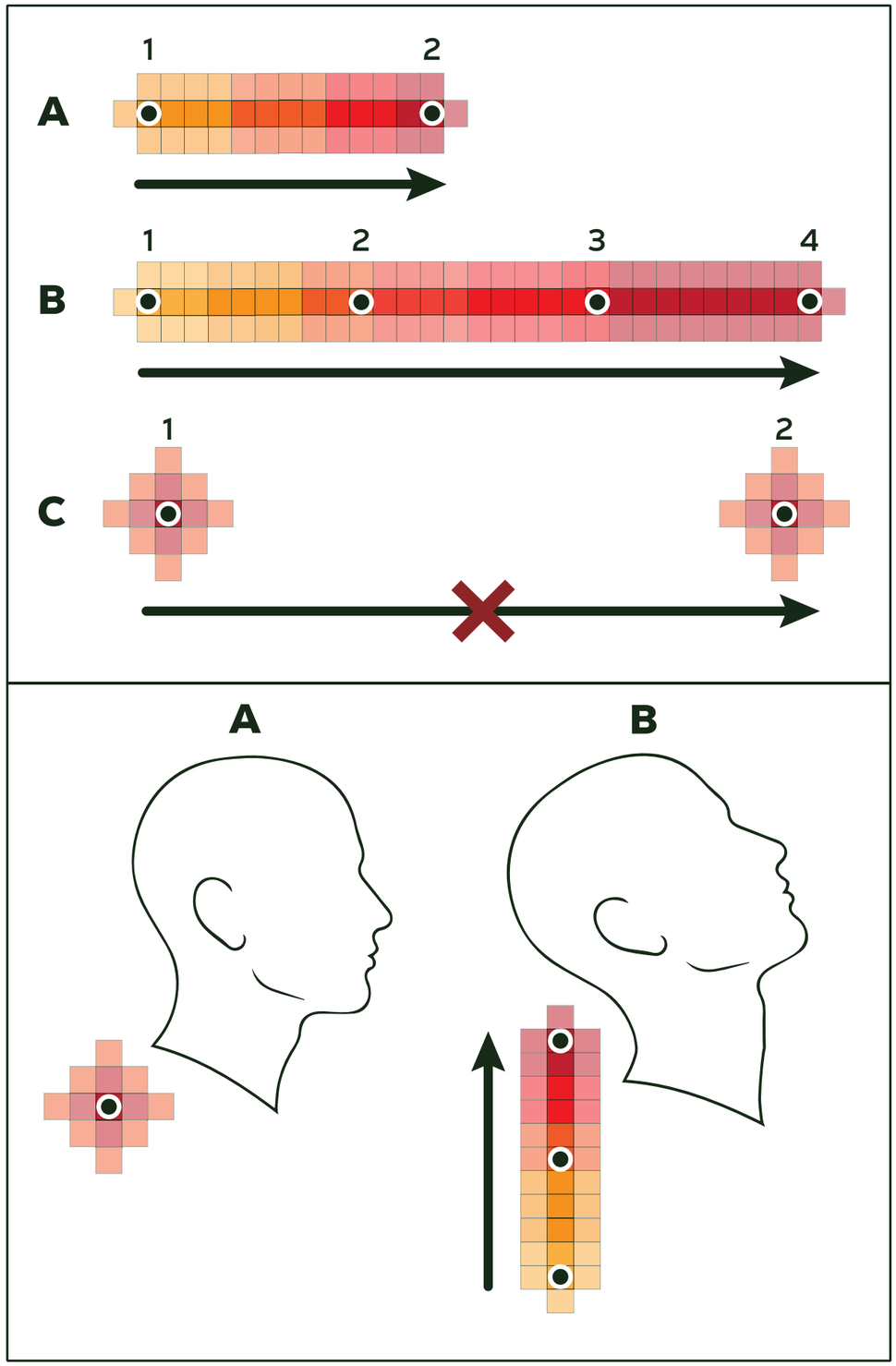


figure 17 & 18: INSIGHTS LAYOUT 1 AND 2

LAYOUT 3. CUES AT DIFFERENT HEIGHTS OF THE BACK

A lateral sweep along the midback was generally more preferred to the same cue located on the lower or upper back. This is reflected in comments such as “The middle is the most intuitive, you feel it the most clearly” (P6). A combination of cues (e.g. upper and middle, lower and middle, or upper, middle and lower) did not increase clarity, and often was perceived as distracting or ‘too much’, stating that “more motors doesn't improve clarity” (P2), “More motors don't really help” (P8), and “I don't get the feeling that more becomes clear” (P6).

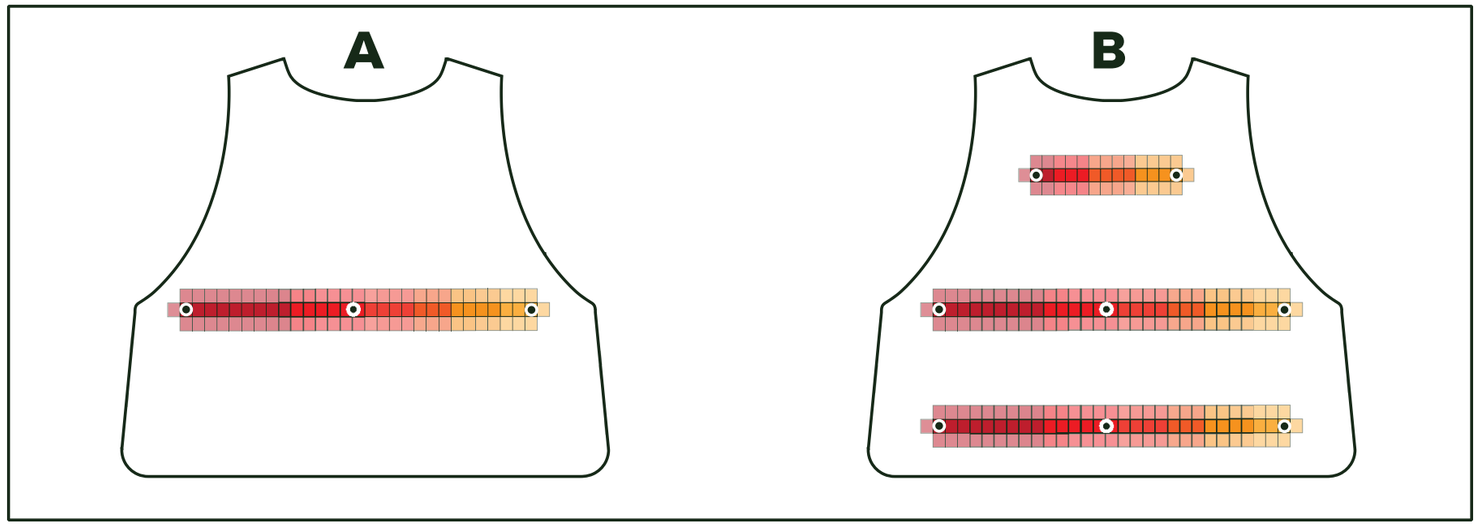


figure 19: INSIGHTS LAYOUT 3

LAYOUT 4. SHOULDER BLADES VERSUS SPINE

When actuators were positioned on the shoulder blades compared to the spine, it did not reduce the participants' ability to describe the cues, but the interpreted meaning varied more as the cues became increasingly complex. For example, where a straight line along the spine was mostly interpreted as “vertical line, feels clear” (P3), “feels clear along one line” (P4), and “line that gives a clear direction” (P7), more complex shoulder blade patterns were often described as “split feels less clear” (P2), “a little confusing” (P6), “feels confusing” (P7),“not clear” (P8), or as a different meaning such as “it feels like there are two things coming towards me now” (P3).

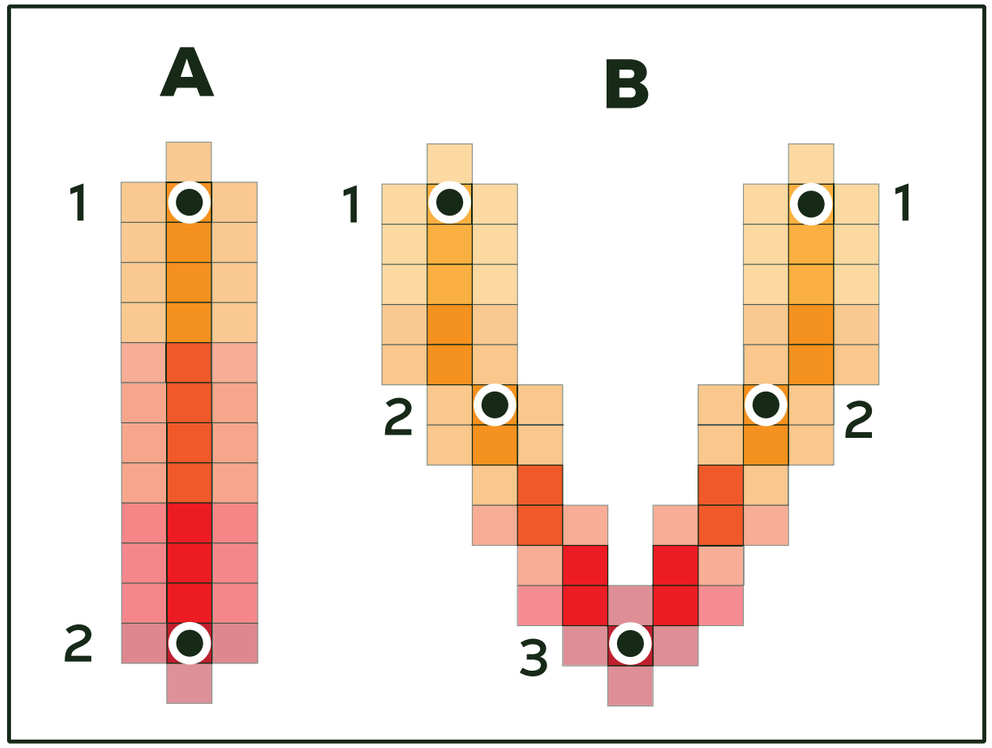


figure 20: INSIGHTS LAYOUT 4

LAYOUT 5. VARYING COMPLEXITY OF MID BACK CUES

To test variation in cue complexity, a single pulsating motor on the mid back was tested, as well as cues that used multiple variations of multiple actuators. Most participants found a single motor pulsating on the midback to be most effective, describing it as "feels like something directly behind me" (P2), "clear central point" (P4), "clear in the mid-dle" (P7), and "clear point behind me" (P10). More complex variants were often perceived as "too many things happening" (P2), "too complex" (P5), "very confusing" (P6), and "too much going on" (P10). Some participants were able to distinguish between more complex and closely space cues that did not spread to other locations of the back, but they required more conscious effort to confidently identify.

OVERALL

Finally, across all layouts participants experienced lower clarity regarding the direction of a cue when they travelled across multiple regions of the back or had overlap with other directions (see figure 21). Participants described these cues as "there is so much stuff happening, it is very confusing" (P1), "it is all a bit confusing" (P1), "it feels like my whole back is turned on" (P4) and "more difficult to understand" (P8). One participant explicitly highlighted the ambiguity between motion and location, stating that the cue "it goes upwards but it starts low" (P8), not being sure about the correct direction (For the full thematic analysis, see Appendix E).

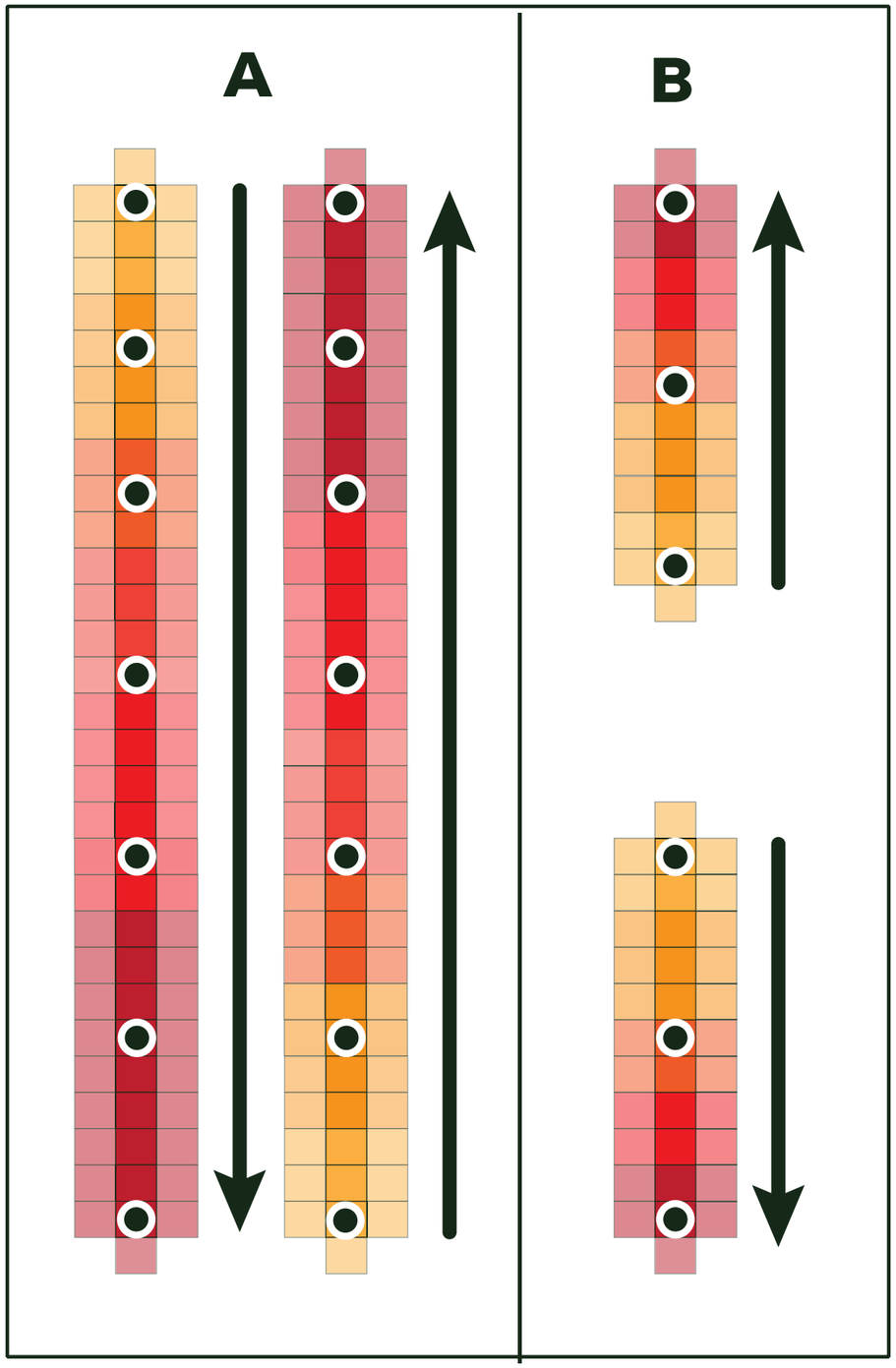


figure 21: INSIGHTS LAYOUT 5

User test RQ4 - Vibration patterns

User test 4 showed that the temporal characteristics such as pulse speed, intensity and rhythm also had a direct effect on how participants interpreted haptic cues.

Overall, faster pulse rates between pulses were often perceived as more urgent or 'dangerous'. Participants often mentioned these patterns to be "similar to parking sensors" (P2), "lock-on systems or countdown warning signals" (P3), describing them as cues that represent 'something is close/getting closer'. Slower, more separated pulses were often perceived as more calm or informational cues. Although differences in vibration intensity were interpreted clearly, often more clearly than differences in pulse speed, the perceived interpretation was mixed among participants. Some related a higher intensity to something getting closer, others interpreted the cue as something larger being near them. lower-intensity cues were generally not preferred for quick informational feedback in general, as they were more difficult to perceive and required greater conscious attention to interpret ('If something is near me I want to be sure that I feel it' (P4)). While a varying intensity in continuous vibration was perceived as more clear, it was also interpreted as annoying and intrusive. Variations in pause duration were generally difficult to distinguish. Combining two parameters, intensity and pulse speed, did not significantly improve interpretability. Participants reported mixed interpretations, with some perceiving increased urgency and others increased cognitive demand. Several participants described the beginning of these patterns as difficult to interpret due to the low initial intensity, after which the pattern suddenly became much more noticeable.

A one-way repeated measures ANOVA revealed a significant effect of vibration pattern on perceived clarity, $F(4,36) = 11.59$, $p < .001$. Pulse duration patterns received the highest clarity ratings ($M = 4.70$), whereas pause-based patterns received the lowest ratings ($M = 2.10$).
A second one-way repeated measures ANOVA revealed a significant effect of vibration pattern on perceived urgency, $F(4,36) = 15.22$, $p < .001$. Intensity-only patterns were perceived as most urgent ($M = 4.35$), while pause-based patterns were perceived as least urgent ($M = 1.80$).

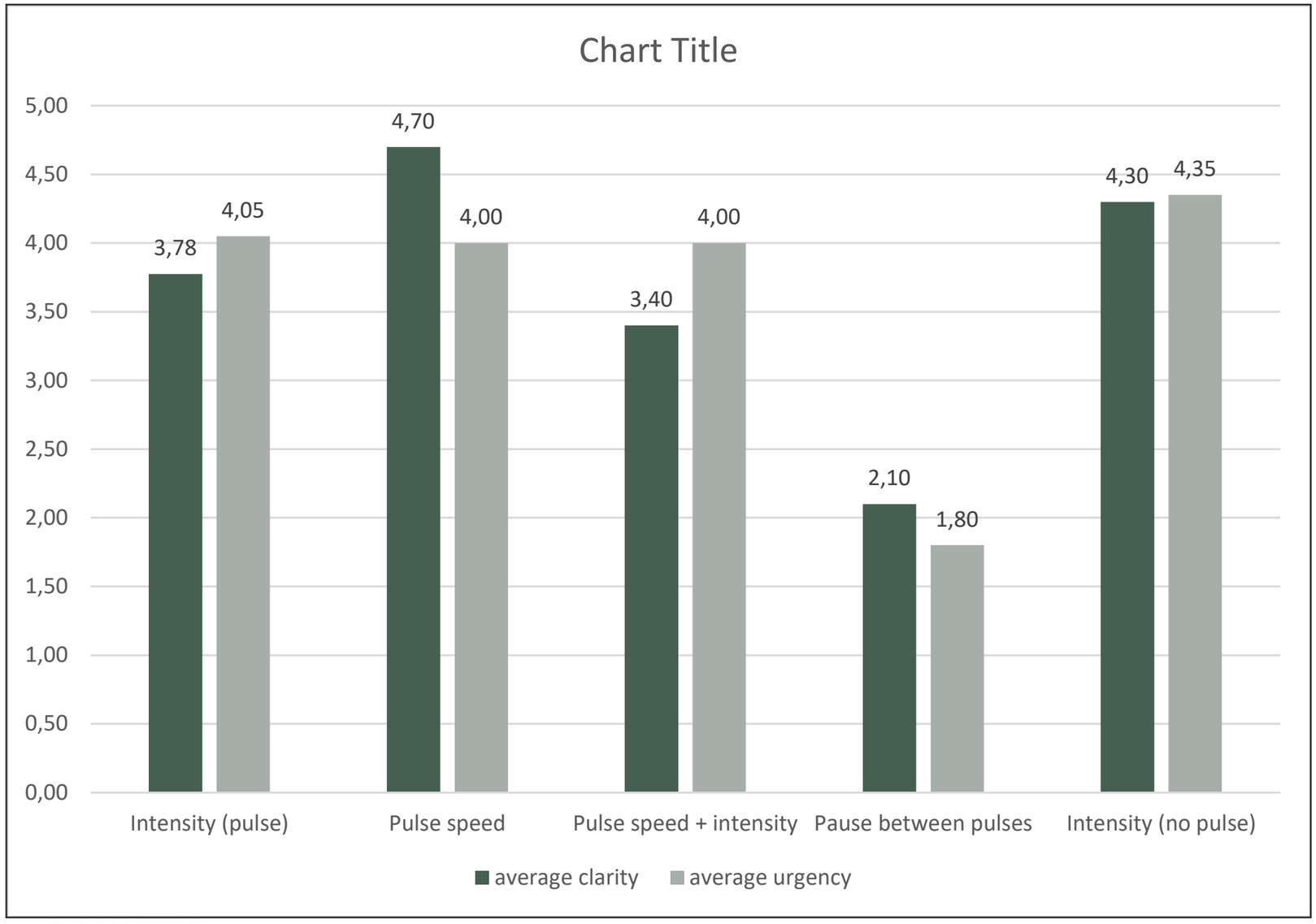


figure 22: RQ4 PULSE TYPE PREFERENCES

Furthermore, the evaluations comparing pulse shapes showed relatively small perceptual differences in a constant pulse versus a ramped fade-in/fade-out pattern, although constant pulses were generally perceived as more urgent, important and clear, whereas ramped patterns were described more as calm, smooth and natural.

The comparison between sequential multiple motor sweeps versus a single motor with a changing vibration pattern showed a consistent distinction between the type of information they were associated with. Multiple motor sweeps were generally perceived as more effective for communicating directional movement, whereas changing the vibration pattern of a single motor (e.g. increasing/decreasing pulse speed) was associated more with a change in distance or urgency. Multiple participants described sweeps as representing an object moving around the body, whereas changing intensity on a fixed location felt more like an object moving closer or farther away from a known position.

Finally, the test evaluated whether multiple motor sweeps could still be effectively communicated when the pulse speed increased. Apparent motion became less clear with higher pulse speeds, eventually often being perceived as disconnected pulses or a single vibration. Reported thresholds for this transition varied between 0.25 and 0.6 seconds, with an average of 0.35 seconds.

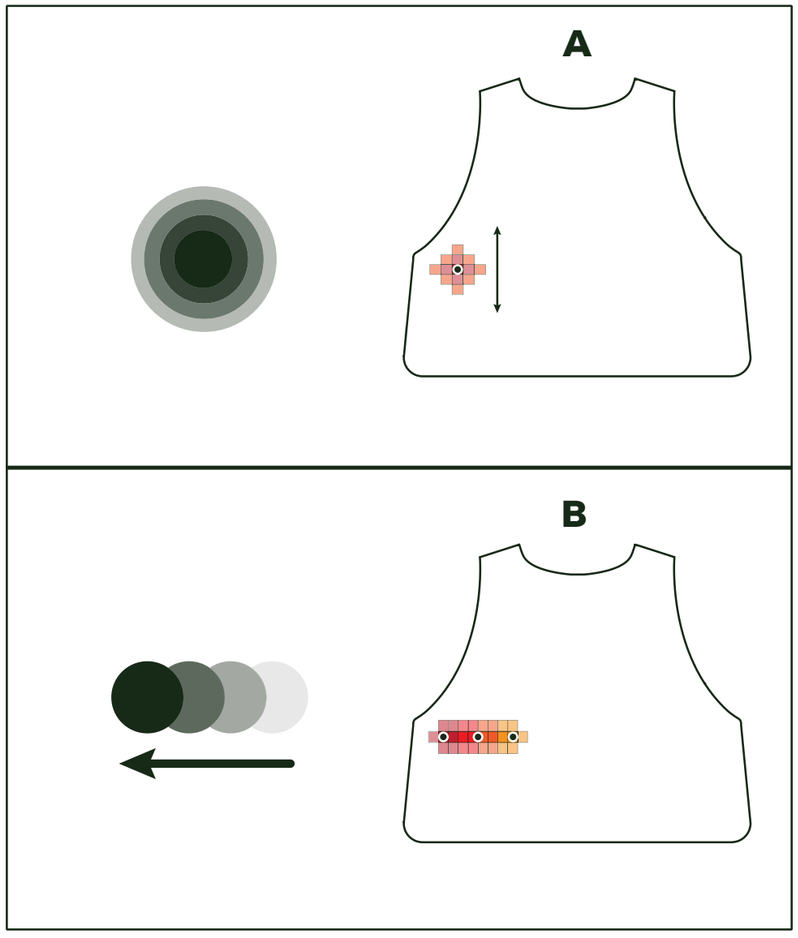


figure 23: INSIGHTS TEST RQ4

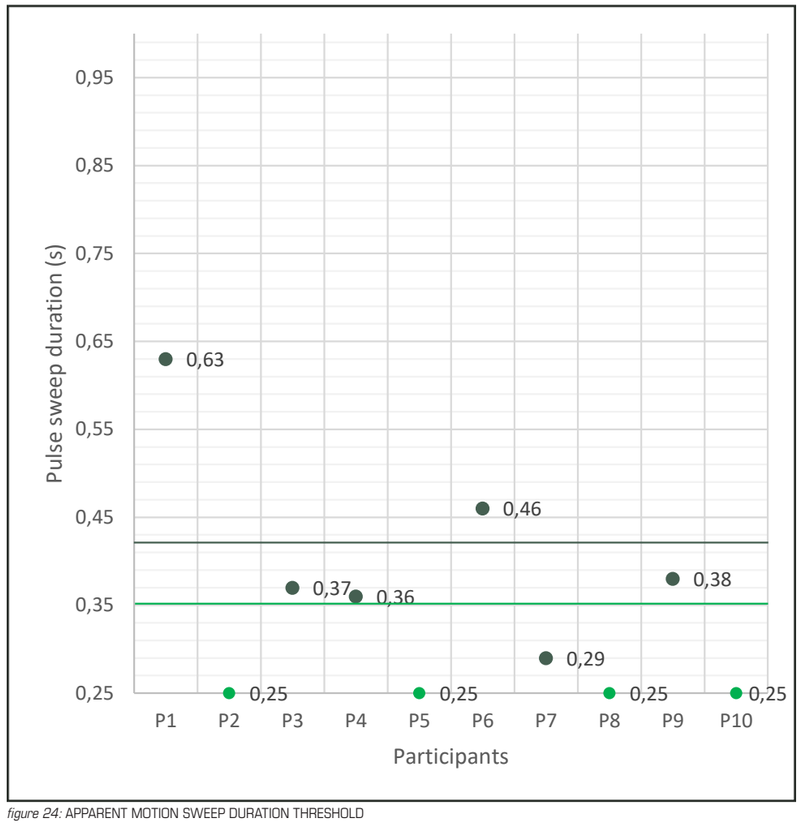
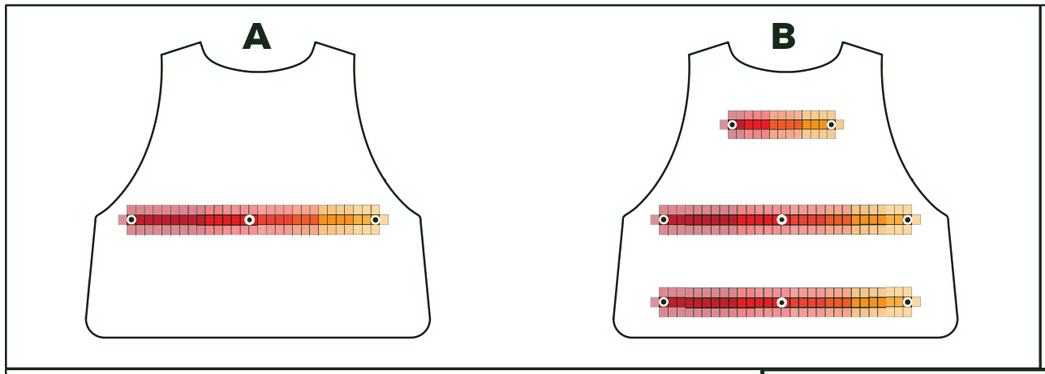
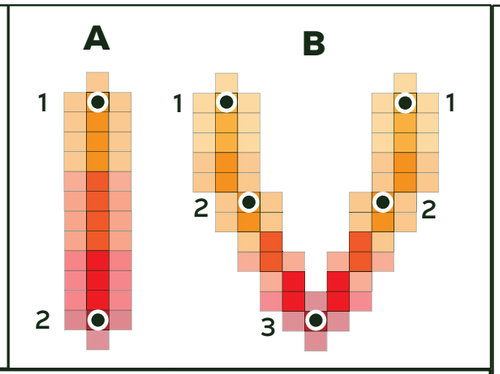
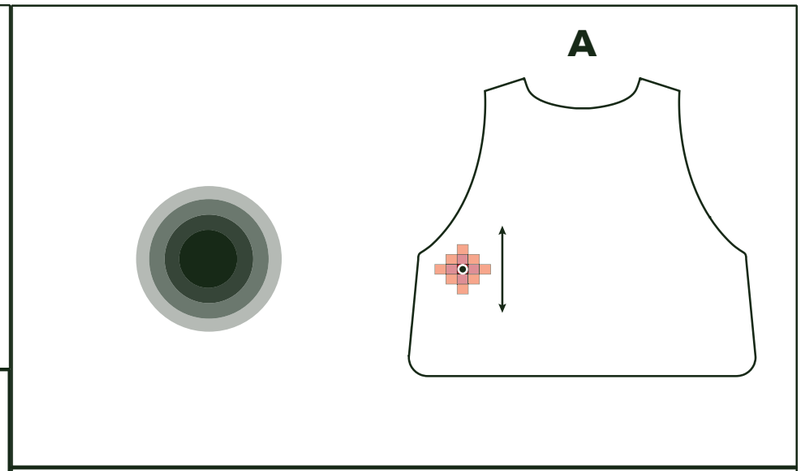


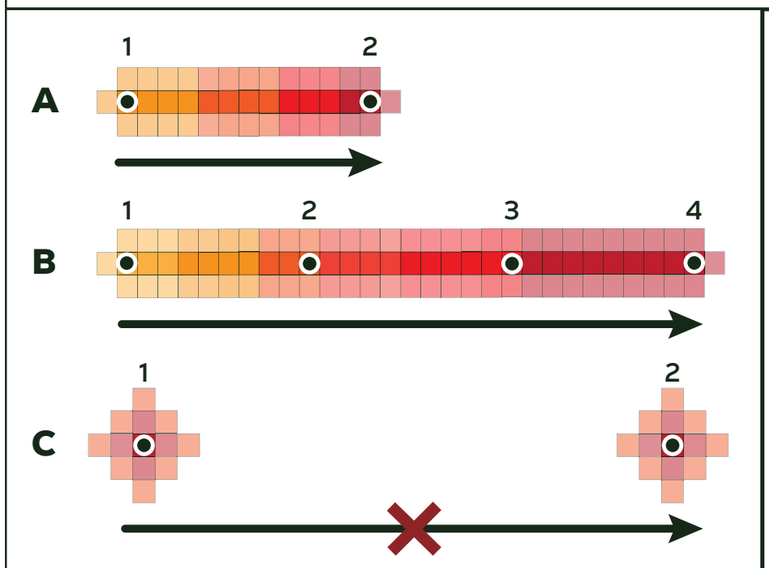
figure 24: APPARENT MOTION SWEEP DURATION THRESHOLD

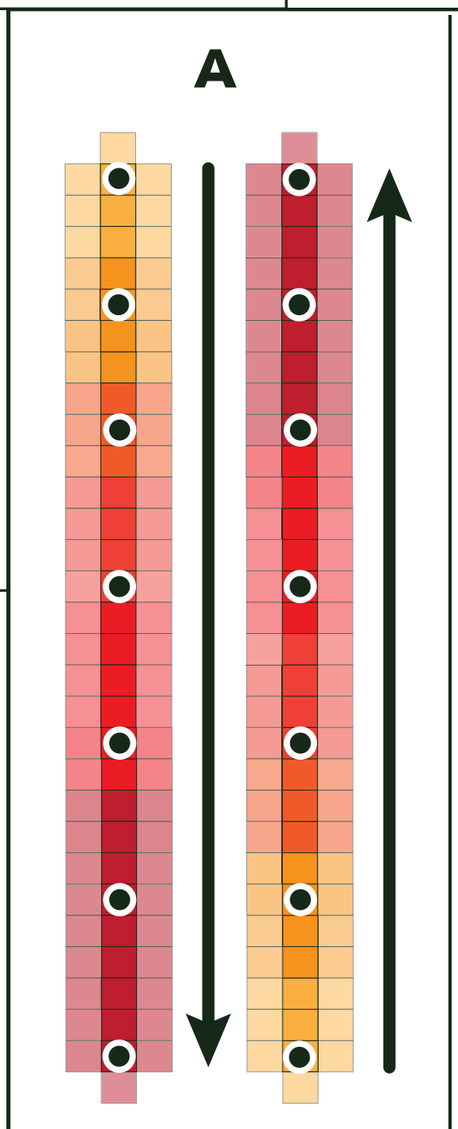
HAPTIC DESIGN GUIDELINES OVERVIEW

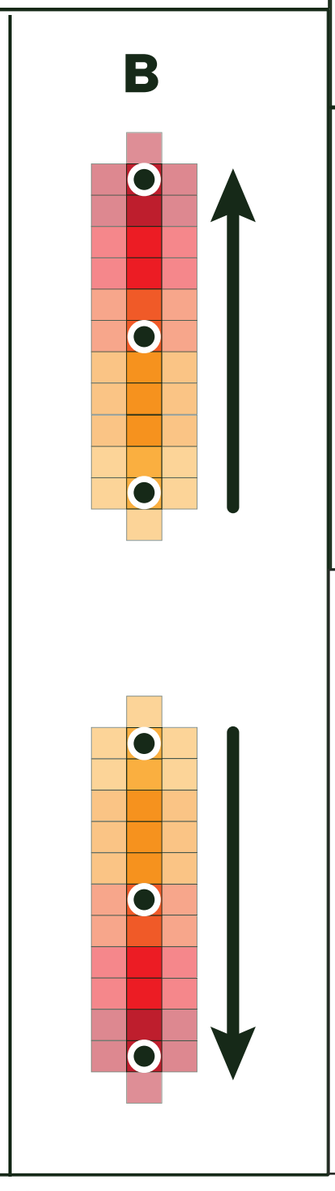


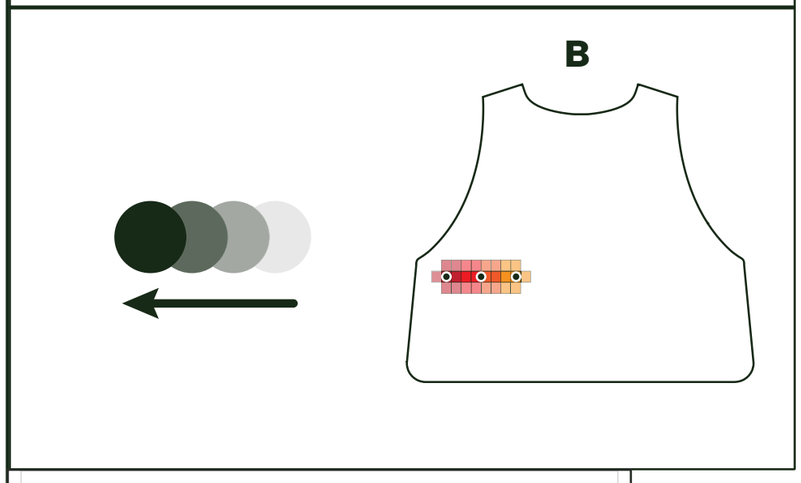


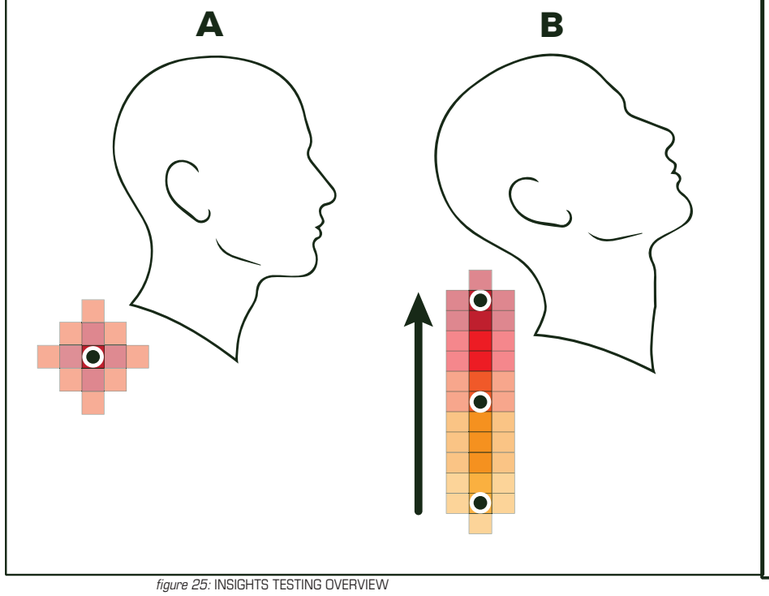












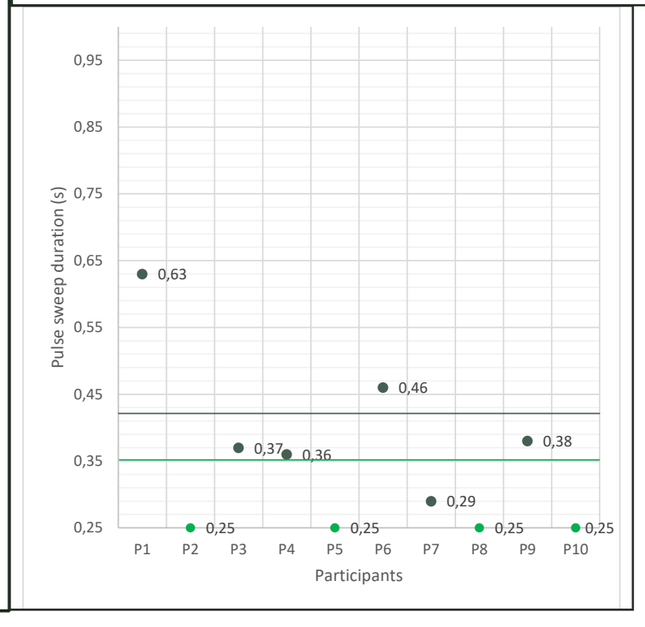


figure 25: INSIGHTS TESTING OVERVIEW

4.2.4 - KEY INSIGHTS USER TESTS RQ3 AND RQ4

Participants consistently preferred clear, focused cues over patterns that spread across multiple regions of the back. While cues simulating movement were often effective for communicating direction, increased complexity rarely improved clarity and frequently resulted in ambiguous interpretations. Therefore, simplicity should be prioritized, with complexity introduced only when it provides a clear communicative benefit.

A key finding was that different types of cue parameters appear to be suited for different sets of information. Participants related the location of an actuator on the body to the direction of a presence around them in 3D space. This happened very literally, almost if as the torso acted as a spatial map of the environment. For instance, P1 mentioning that a sweep going from the midback to the right side of the torso felt like something moving from behind and around them. In contrast, The temporal characteristics of a cue give information about the presence at that given location. This information is often perceived as urgency, distance or importance.

Finally, Although subtle changes in timing, vibration intensity or spacing were mostly interpretable, they required conscious effort from participants to distinguish the differences. Attention should also be drawn to the opposite effect: Increasing cue complexity can increase cognitive effort and reduce perceptual clarity. These insights were directly used as guidelines for the final design in loop 3.

LOOP 3: VALIDATING AN INTEGRATED HAPTIC DISPLAY

4.3.1 - FINAL DESIGN

The final design was based on all the relevant findings from the studies done throughout the project. The following sections will discuss the final actuator layout, the final vibration pattern and how the prototype was developed.

4.3.1.1 - Final Actuator Layout

As mentioned previously, participants often interpreted actuator locations very directly as corresponding positions in their surrounding environment, essentially using their torso as a spatial map. Due to the curved nature of the torso, vibrations presented on the side of the torso corresponded well to the intended spatial directions. The same principle applies to a cue on the midback indicating that something is located behind the body.
As a result, the final layout utilized a single actuator for each the left, right and back cues. More complex patterns were sometimes interpreted as containing additional information, but these interpretations varied considerably between participants.
The communication of upward and downward directions proved to be more complicated. Unlike lateral directions, participants did not consistently perceive a cue on the upper or lower back as a presence being above or below them. Instead, these cues were often interpreted as something being behind the body at a higher or lower location. To communicate vertical direction more efficiently, three actuators were placed on the both the upper and lower back to simulate apparent motion. By sequentially activating the vibrations, the cue created a sense of movement either upwards or downwards, resulting in a more intuitive interpretation of vertical direction compared to static vibrations.
The final layout was intentionally kept simple to maximize intuitiveness and limit ambiguous interpretations and tactile clutter. Since results showed that overlapping cue locations often resulted in confusion about directionality, cue locations were kept separated and the number of actuators was minimized wherever possible.

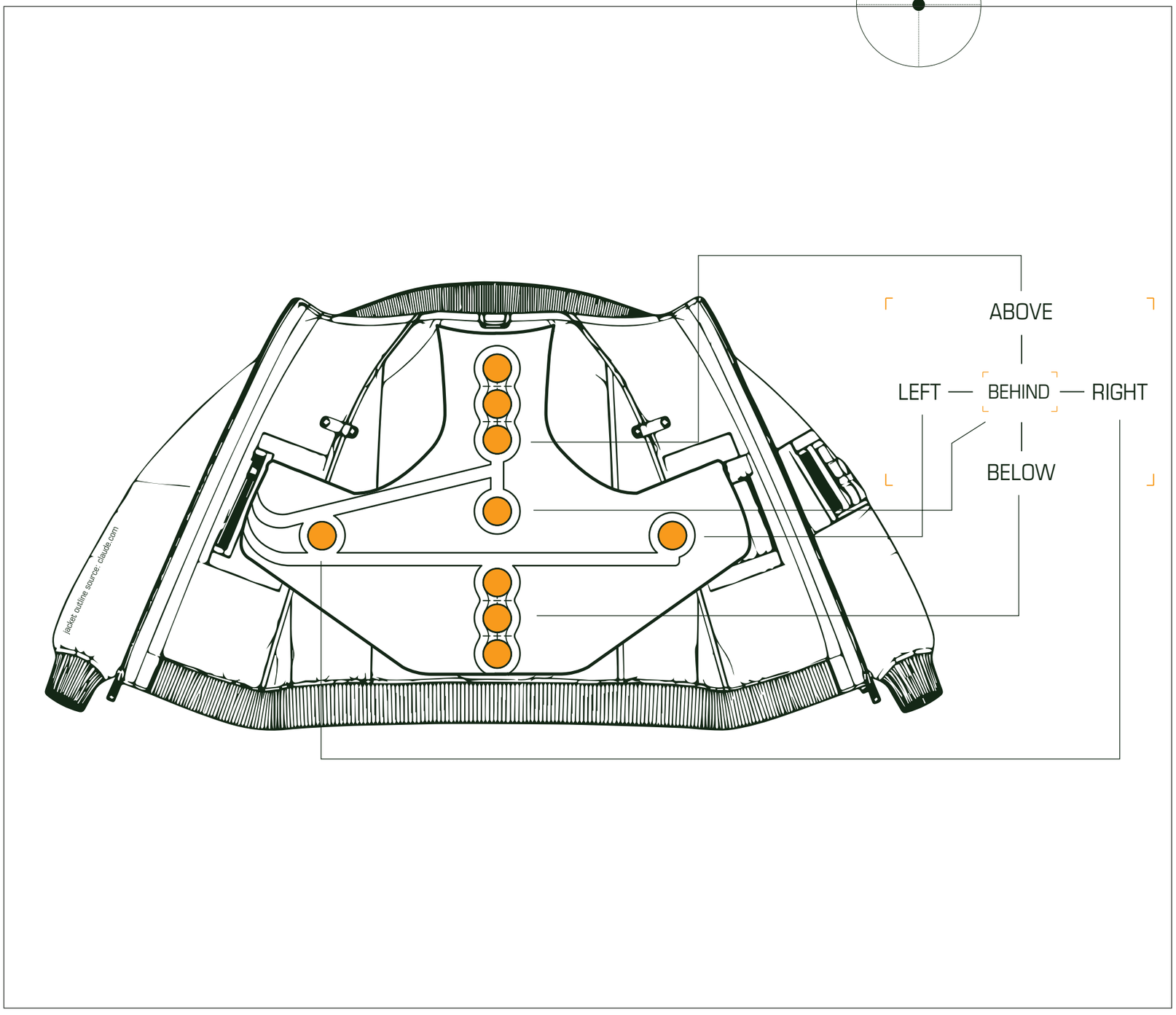


figure 26: FINAL ACTUATOR POSITIONS

4.3.1.2 - Final Vibration Patterns

The final vibration patterns were again determined based on their ability to communicate information intuitively while minimizing conscious effort. Since the cues are intended to support situational awareness in time-critical environments, specific focus was placed on the perceived urgency and clarity of a pattern. Pulse speed and vibration intensity were rated highest for communicating urgency. However, pulse speed was preferred because variations remained clearly perceivable across the full range, whereas low-intensity vibrations were more difficult to detect. As a result, the final design uses constant vibration patterns (meaning not ramped) in the form of a varying pulse speed between 0.25 and 1.00 second per pulse, depending on the urgency of the surrounding presence/threat. This means that over time the pulse duration will shorten, resulting in a faster pulse and an increased sense of urgency.

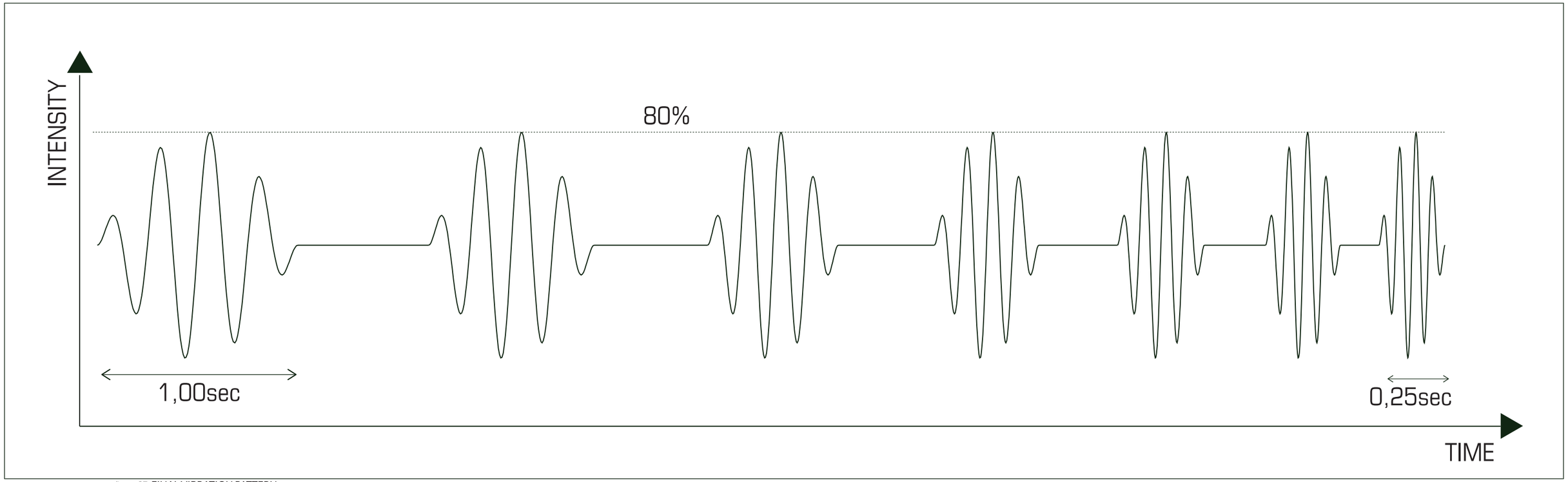


figure 27: FINAL VIBRATION PATTERN

4.3.1.3 - Integration

Hardware

The final prototype was integrated into an existing flight jacket to create a wearable system that more closely represents the intended application. Unlike previous iterations, which focused on rapid experimentation and repositioning of actuators and comparing vibration patterns, the final garment incorporated fixed actuator positions and vibration characteristics derived from user evaluations. The final design includes nine ERM vibration motors without the larger LilyPad PCBs that were used in earlier iterations [58]. Not using the PCBs reduced the overall size of the motors, enabling a more compact and integrated design. To improve comfort and prevent pressure points caused by the actuators, each motor was embedded within a 3D printed housing. These housings were printed in flexible TPU and surrounded the motor while allowing it to protrude beyond the housing surface to still allow close actuator to skin contact. The housing was designed with a small clearance between the motor and the TPU, enabling it to move freely without being restricted by surrounding material and thus reducing the risk of vibration dampening. To ensure efficient cable management, channels were incorporated into the bottom of the TPU housing, allowing wires to be guided cleanly between actuators. These wires were then secured by melting parts of the TPU on top, to create modules that were easy to handle during assembly (see figure 31 top left).
After soldering and positioning all the components, the complete assembly of electronics was laminated between two layers of textile using a heat-activated TPU adhesive film, with only a connector exposed for connection to the control case.



figure 28: 3D PRINTED MOTOR HOUSING



figure 29: FINAL PROTOTYPE FULL VIEW

The control case was developed by an employee at Touchwaves, and consisted of an Arduino Beetle attached to a custom PCB enclosed with a 3D printed casing [59]. The case could be connected to a laptop or PC and receive serial data regarding when to trigger certain haptic cues, enabling integration with applications such as a flight simulation used during the final evaluation. The communication architecture was also altered. Whereas earlier iterations used BLE to trigger certain vibration cues through a smartphone or tablet, the final prototype received all data through serial communication from a laptop. This was determined since participants were already interacting with laptop based simulations requiring continuous and fast data exchange, making a wired serial connection a more reliable solution than BLE communication.
To maintain modularity to show parts of the design on Demo Day and to simplify maintenance, the complete actuator panel was attached to the inside of the flight jacket using Velcro patches. This allowed all the electronics to be easily removed or replaced without changes to the garment. When the product would be manufactured for production, the panel would either be stitched or laminated into the flight jacket.

Software

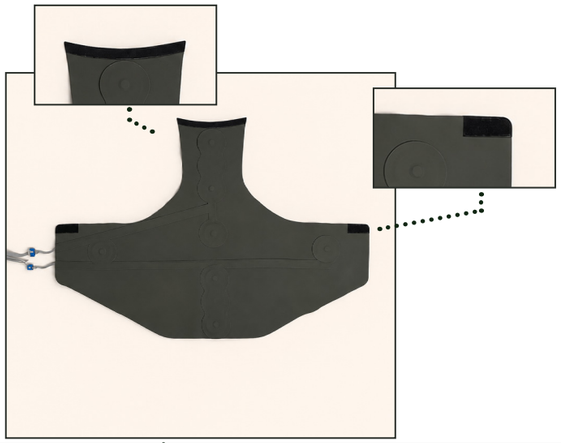
Processing
For the final prototype, a large part of the software architecture remained consistent compared to previous iterations. The Processing sketches continued to function the same, only sending data that communicated when certain cues should be triggered. The Processing sketches required only minor modifications, as they continued to send directional commands while actuator control remained handled by the microcontroller.

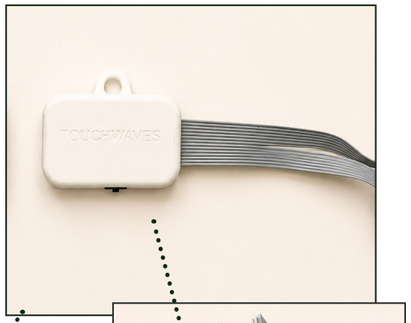
Arduino IDE
More significant changes were necessary in the Arduino IDE that uploaded firmware to the microcontroller that controls the actuators. Earlier prototypes used an Adafruit Feather 32u4 with Bluetooth Low Energy (BLE) and seven PWM pins to individually control vibration motors. The final prototype however used an Arduino Beetle and a total of nine vibration motors that needed individual control. Due to the limited number of PWM pins on the Beetle (four), it was not possible to control all motors through conventional hardware PWM. Thus, a library was used to control the motors using Software PWM so the actuators could still be controlled on digital I/O pins.

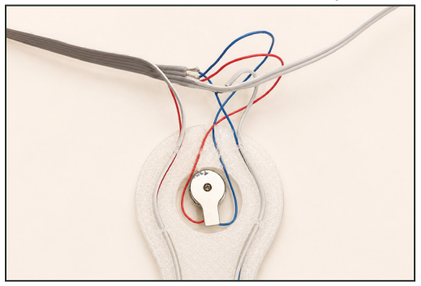


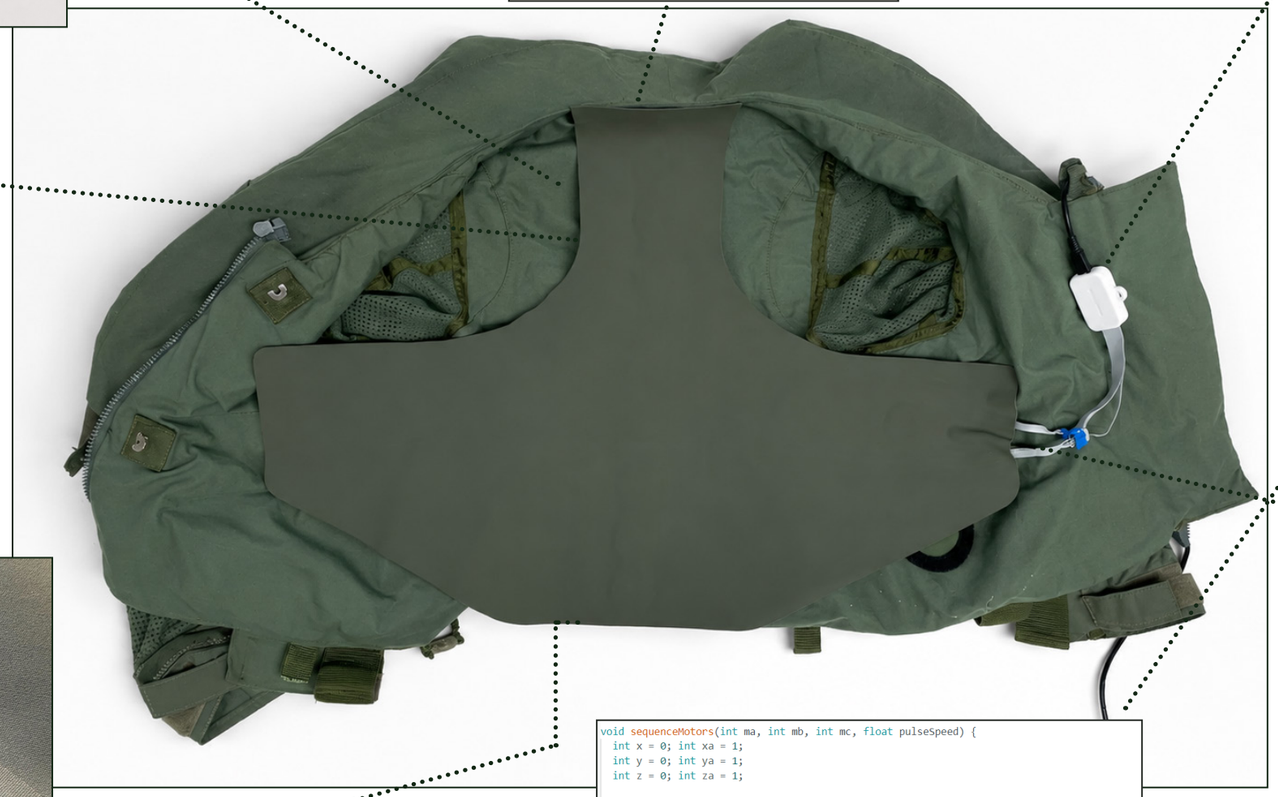
figure 30: CONTROL CASE 1 AND 2

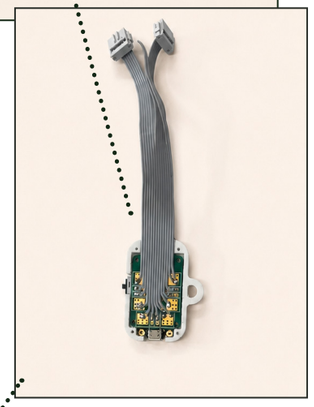


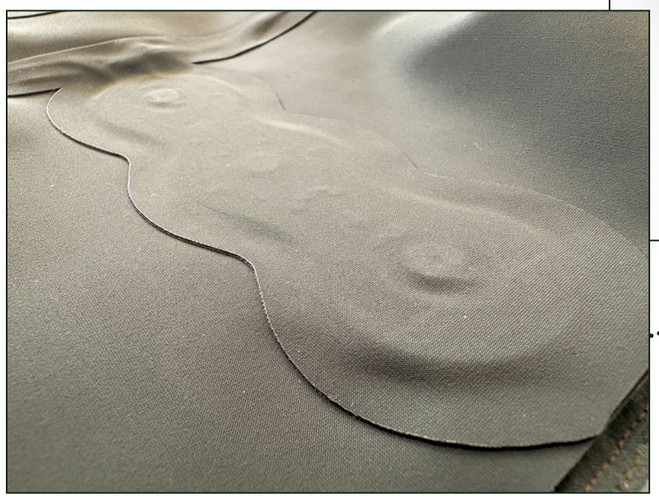












```
void sequenceMotors(int ma, int mb, int mc, float pulseSpeed) {
  int x = 0; int xa = 1;
  int y = 0; int ya = 1;
  int z = 0; int za = 1;

  for (int teller = 0; teller < 265; teller++) {

    if (teller >= 0 && teller <= 162) {
      SoftPWMSetPercent(ma, toPercent(150 + (x * 2.5 * Intensity / 100.)));
      x += xa;
      if (x == 81) xa = -1;
    }
    if (x < 2) SoftPWMSet(ma, 0);

    if (teller >= 51 && teller <= 213) {
      SoftPWMSetPercent(mb, toPercent(150 + (y * 2.5 * Intensity / 100.)));
      y += ya;
      if (y == 81) ya = -1;
    }
    if (y < 2) SoftPWMSet(mb, 0);

    if (teller >= 102 && teller <= 264) {
      SoftPWMSetPercent(mc, toPercent(150 + (z * 2.5 * Intensity / 100.)));
      z += za;
      if (z == 81) za = -1;
    }
    if (z < 2) SoftPWMSet(mc, 0);

    if (teller < 264) delayMicroseconds(int(pulseSpeed * 3730 / 100.0));
  }
```

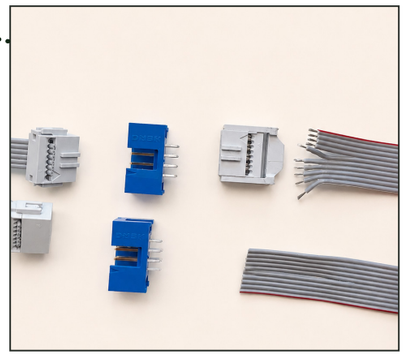


figure 31: FINAL PROTOTYPE FEATURES

4.3.2 - TEST SETUP ITERATION 3 PART 1

Unlike iteration one and two, where the goal was too develop a prototype that can be used to explore design variables, the final iteration focused on evaluating the usability and intuitiveness of a complete embedded system.
The final evaluation consisted of two complementary parts. First, a task-based A/B test on a laptop was conducted to compare the integrated haptic cues to more conventional audiovisual cues such as a screen display and an alarm. Participants performed a flight simulation created in Processing with each feedback type in random order: visual only, audio only, visual+haptic, audio+haptic and haptic. During the simulation, participants used a LOGITECH extreme 3D pro joystick to fly through rings [60], while directional cues were presented for five directions in random order: LEFT, RIGHT, ABOVE, BELOW and BEHIND. Participants were instructed to respond by tapping the corresponding location on the screen regarding where they perceived the cue to be coming from. Quantitative data including given directional cue, interpreted user direction, response time and task succes rate were automatically logged in an excel file after task completion. Additionally, a NASA TLX questionnaire was conducted after each flight simulation to assess physical and mental demand of identifying the cues [61].

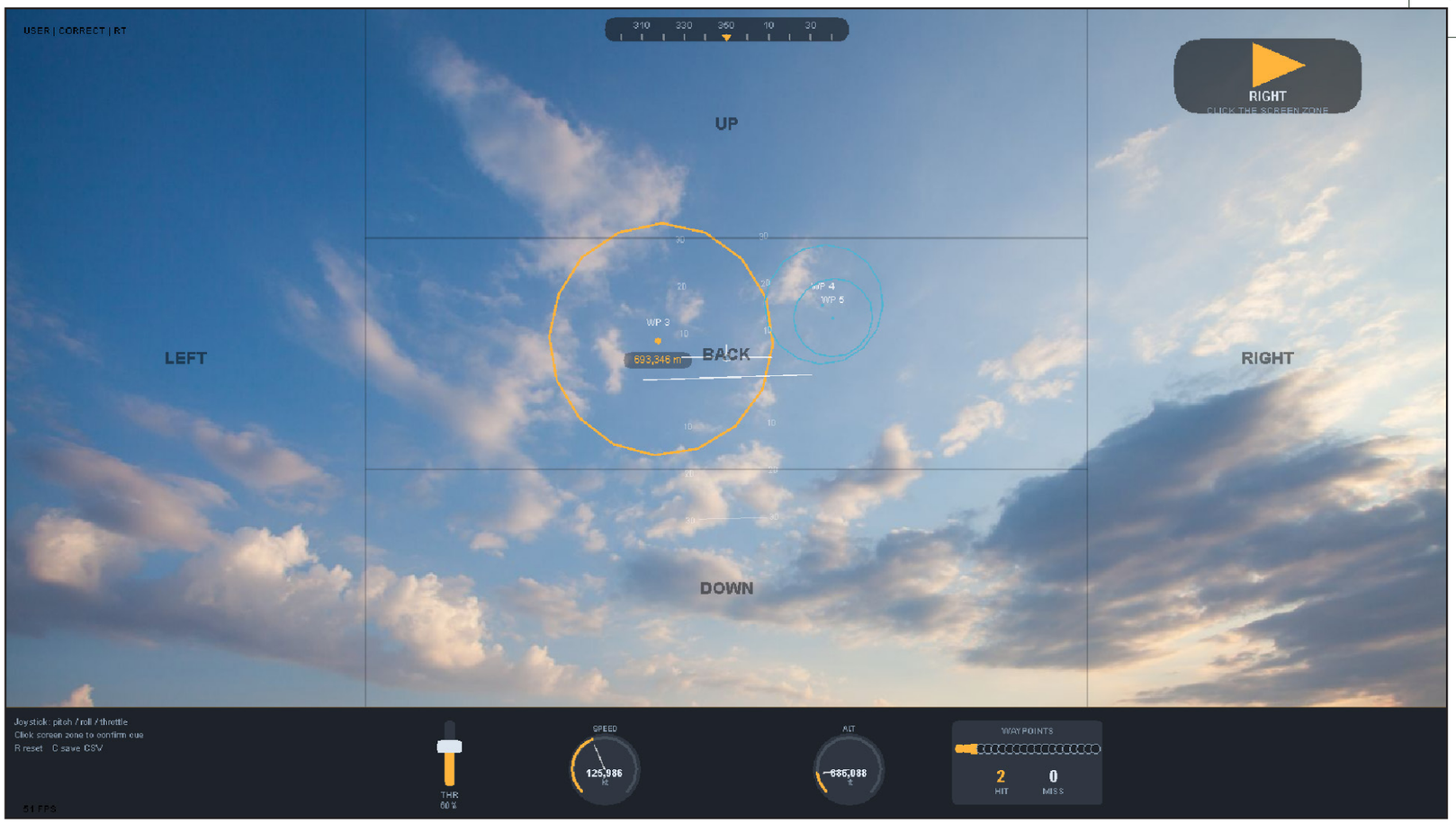


figure 32: FINAL FLIGHT SIM

4.3.3 RESULTS ITERATION 3 PART 1

All types of feedback resulted in high recognition accuracies, with average accuracies ranging from 91.7% to 100%. The audio condition achieved the highest average accuracy (100%), while the haptic-only condition achieved 91.7%. Interestingly, the visual-haptic condition resulted in the fastest average respons time (1057ms), followed by the haptic-only condition (1112 ms). This suggests that haptic cues could be interpreted rapidly even during flight-related tasks.

The NASA-TLX results showed that workload differed across feedback types. On average, the visual condition resulted in the highest workload ratings (61,53), while the visual-haptic resulted in the lowest (40,67) . This may be because the visual condition required switching the participants' view between parts of the screen, while the haptic only condition allowed for full attention to the center part of the screen at all times. Across participants, both visual-haptic and audio-haptic conditions generally reduced perceived workload compared to their visual and audio counterparts (see Appendix G for full results).

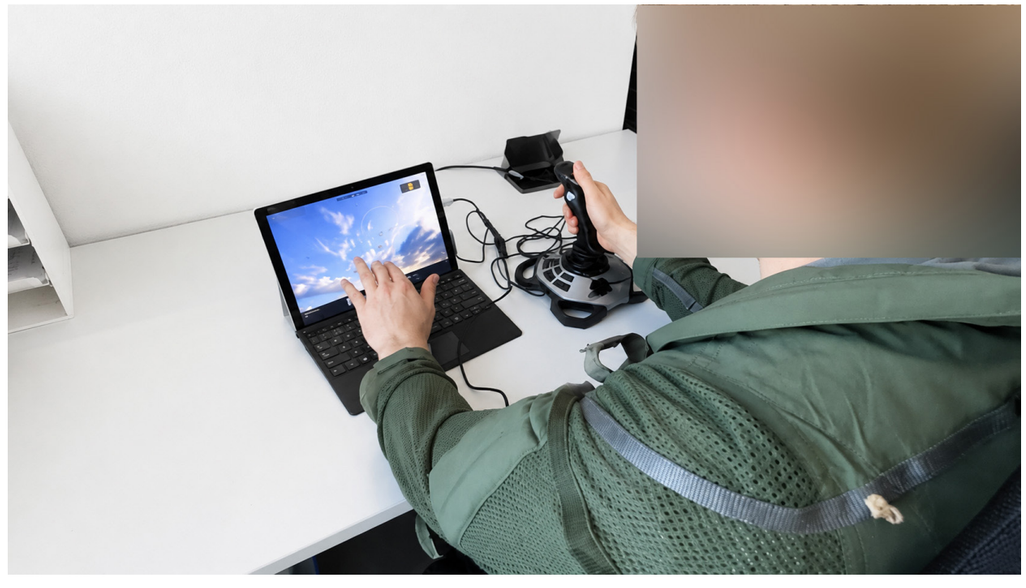


figure 33: FINAL TEST SETUP

FULL SYSTEM ARCHITECTURE

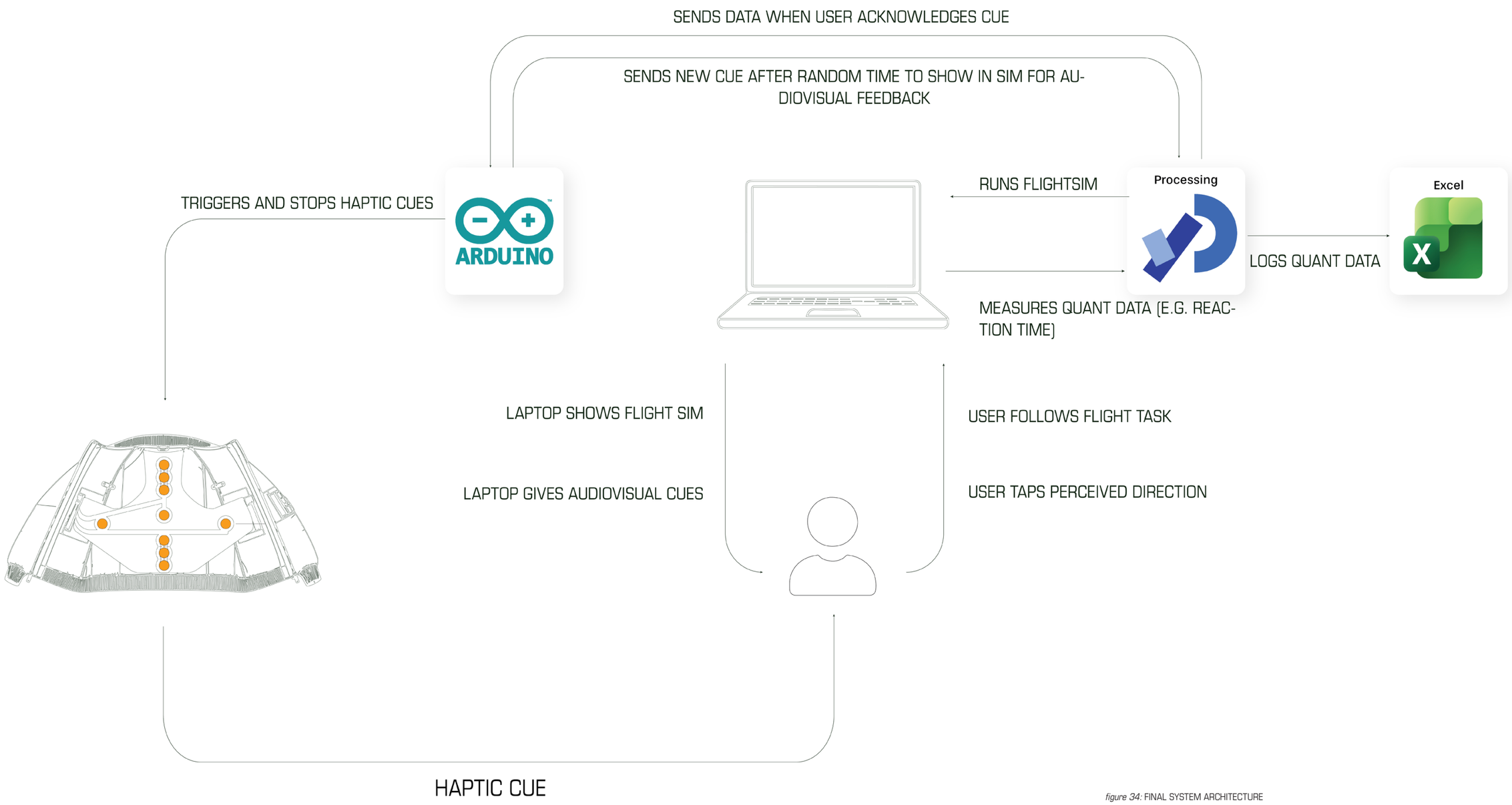


figure 34: FINAL SYSTEM ARCHITECTURE



figure 35: FINAL TEST AT MILITARY TRAINING CENTER

4.3.4 - TEST SETUP ITERATION 3 PART 2

The second part of the final evaluation was conducted in a simulator at a military training institute. In this setting, the final prototype was tested in a more immersive and realistic environment. Three military staff persons including one pilot performed a flight simulation while receiving directional vibrotactile cues through the flight jacket. Participants completed a 10-minute flight session consisting of routine tasks, including basic and combat maneuvring. During each session, 20 directional haptic cues were presented at random times. Since the prototype was not connected to the simulator itself, feedback came from the participants verbally indicating the perceived direction during the task. Following the flight, a NASA TLX questionnaire was completed.

4.3.5 - RESULTS ITERATION 3 PART 2

Both P1 and P2 correctly identified 17 out of 20 cues (85% accuracy). P1 confused the DOWN cue with the BEHIND cue three out of four times, while P2 confused UP with BACK once, DOWN with BACK once, and DOWN with LEFT once. P3 correctly identified all 20 cues (100% accuracy). These results suggest that the directional cues were generally interpretable, although some ambiguity remained between the down and up directions, likely due to less close contact to the skin. The NASA-TLX results indicate moderate workload levels for the fighter pilots, with scores of 46.33 and 54.00. P3 reported a higher workload with a score of 71.67. this difference may be explained by P1's and P2's greater familiarity with the flying tasks and a therefore higher ability to focus on the interpretation of haptic cues (see Appendix H for full results).

Overall, the results suggest that the proposed system can communicate directional information with a relatively high degree of accuracy and response time, while maintaining acceptable workload levels during flight-related tasks.

ITERATIVE DESIGN PROCESS AND EVALUATION OVERVIEW

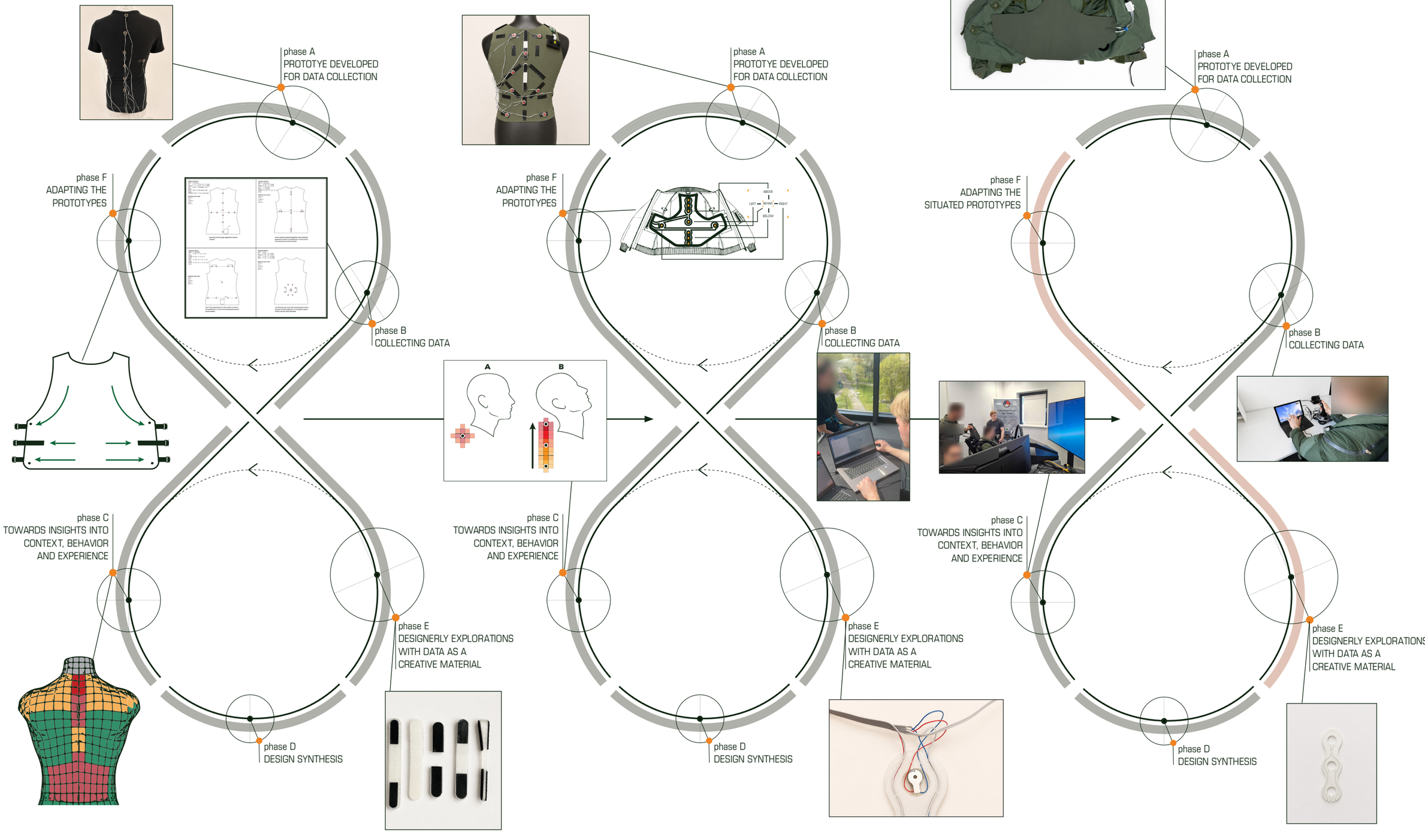


figure 36: FULL DESIGN PROCESS AND EVALUATION OVERVEIW

CHAPTER 5 - DISCUSSION

5.1 – DESIGNING AROUND HUMAN PERCEPTION

An important overall insight that emerged from the evaluations is that effective haptic communication depends less on trying to maximize technical capabilities and more on aligning cues with how users naturally interpret vibrotactile information. While previous work has often focused on increasing spatial resolution through dense actuator matrices [8, 19] the findings suggest increased cue complexity does not necessarily provide extra information, or at least not reliably. Since literature suggests that spatial discrimination on the back is mostly around 2–4 centimetres and even 1–2 centimetres on the spine [37] a haptic display with complex patterns such as arrows and waves should be perceivable in theory, where each vibration functions similarly to a pixel in a visual display. In reality, interpreting vibrations appear to require more conscious effort than interpreting comparable visual information [4]. A common analogy is the difference between seeing a letter and feeling someone tracing a letter on your back. During the evaluations of the spatial positionings in loop two, most participants preferred simpler cues and reported that more complexity did not increase clarity or intuitiveness, and often resulted in confusion or ambiguous interpretations. The same findings occurred during the evaluation of vibration patterns, where a variation in multiple parameters of temporal characteristics of an actuator were less clearly perceived than varying one parameter (e.g. intensity or pulse duration). This aligns with the concept of tactile clutter described by Jan B. F. van Erp , where excessive haptic information can interfere with effective interpretation [8] Similarly, Kim et al. (2022) found a decrease in participants' ability to accurately recognise vibration patterns when the number of actuators increased [22].

From a design perspective, this suggests that haptic systems intended to support rapid decision making should focus on human perception first, rather than starting from maximizing the amount of information that can be communicated based on theoretical and technical possibilities alone. For other applications that require less simultaneous information processing and allow for more time to interpret haptic cues, more complex haptic languages may be more feasible.

5.2 - THE TORSO AS A SPATIAL MAP

Another major overarching finding was how directly participants appeared to use their body as a spatial reference frame. Vibrations on specific locations of the torso were always interpreted as the corresponding location in their surrounding environment. Participants appeared to project the cue outward from the body, mapping the location of a cue in the direction perpendicular to the point of vibration (see figure 38). This insight highlights a fundamental challenge of designing wearable haptics to display spatial information: The range of directions that can be directly communicated is constrained by the geometry of the surface on which the actuators are placed. Since this concept may appear rather abstract at first, we can use a sphere as a thought experiment. If a surface would be used as a haptic map of the surrounding environment, a sphere would theoretically be the ideal shape since it is the only shape with a surface that has a point that perpendicularly translates outwards to every single direction in 3D space (see figure 37). This means that any single direction could be communicated with a single actuator, as every direction can always be mapped directly to a point on the spherical surface. The human torso however, especially when only the back and sides of the torso are used, has a largely different geometry. While the back and sides wrap around the horizontal plane and can therefore directly communicate left, right and back directions, there is no equivalent surface directly above and below the user. Consequently, single actuator cues on the upper and lower back were interpreted as cues still behind the user but at different heights, rather than above or below them (see figure). This challenge was the reason for the use of sequentially activated actuators to create a sense of apparent motion, allowing vertical directions to be communicated through vibration movement rather than location alone.

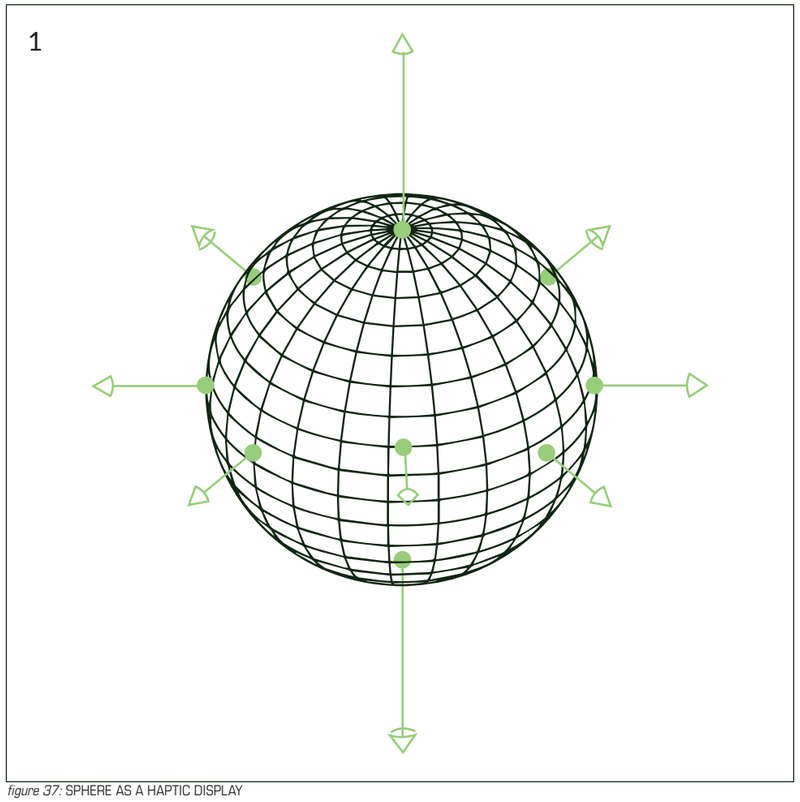


figure 37: SPHERE AS A HAPTIC DISPLAY

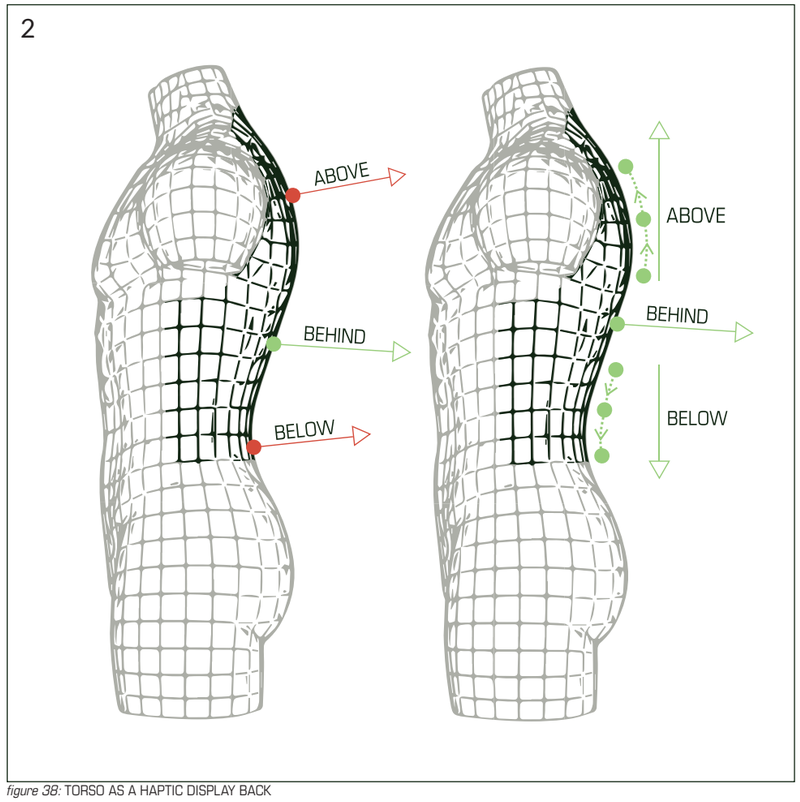


figure 38: TORSO AS A HAPTIC DISPLAY BACK

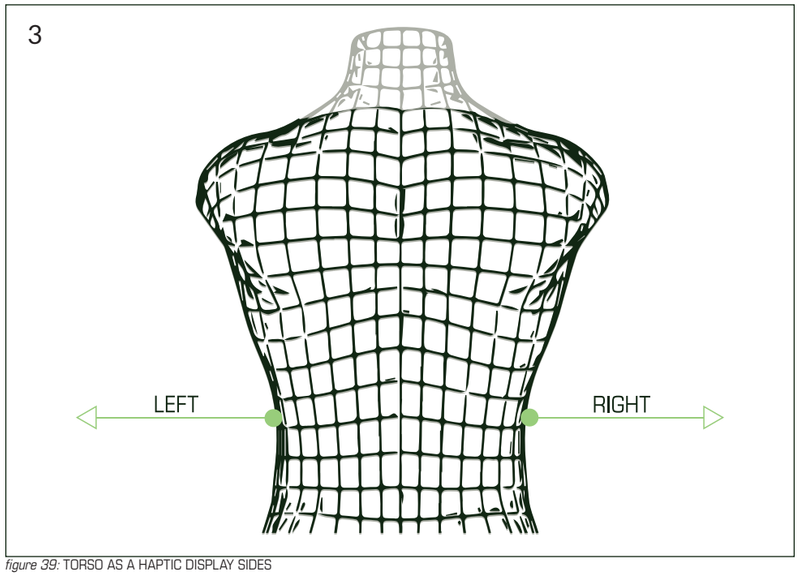


figure 39: TORSO AS A HAPTIC DISPLAY SIDES

5.3 - IMPLICATIONS, LIMITATIONS AND FUTURE WORK

The overall findings during the project suggest that wearable haptic systems may provide a valuable supplementary communication channel in environments where audiovisual attention is already heavily occupied. Rather than completely replacing existing information systems, haptics can serve as an additional channel through which spatial information can be communicated. This is particularly relevant in aviation contexts, where situational awareness often depends on processing multiple types of information simultaneously.

This project includes several limitations that should be acknowledged. First, during most of the evaluations, specifically the explorations of spatial location and vibration patterns, participants were not fighter pilots and were situated in a calm controlled environment, meaning findings should be interpreted as insights into fundamental haptic perception rather than validated aviation-specific design principles. Second, the project deliberately focused on intuitive interpretation and provided no prior training regarding cue meaning. It is therefore entirely possible that when users are trained over time, a more complex haptic language can be learned and more information can be communicated efficiently, which would require a redesign of the actuator layout and vibration patterns. Furthermore, the vibrotactile actuators that were used during the project (ERM motors) were not the most efficient in transmitting vibrations. For example, using ramped vibration patterns could have reduced perceptual clarity, since ERM motors need time to accelerate to reach maximum vibration intensity. A ramped pattern can result in a motor having too little time to reach that intensity, resulting in a weaker vibration. The same principle applies to very short vibration durations. A different kind of vibrotactile actuator, such as an LRA (linear resonant actuator), does not need that time and may make patterns that require very quick changes in intensity more suitable for haptic feedback. Finally, the scope was limited to five directional cues and apart from urgency, did not investigate more complex spatial information such as threat type or multiple surrounding presences.

Future research should investigate how trained users interpret haptic cues over longer periods of time, explore more haptic vocabularies and evaluate such systems more in realistic operational environments. Additionally, different types of vibrotactile actuators and surrounding materials should be further explored to find possibly more efficient ways of transmitting a cue to the user.

CHAPTER 6 - CONCLUSION

This project explored how a wearable haptic system could be designed to support intuitive situational awareness in combat aviation. Motivated by the increasing risk of cognitive overload for fighter pilots, the project investigated how the underutilized tactile channel can communicate spatial information while information is simultaneously being processed audiovisually.

Using a Data-Enabled Design approach consisting of three iterative design loops, multiple subsequent wearable prototypes were developed and evaluated. Through cycles of design, testing and reflection, insights were gathered regarding actuator positioning, vibration patters and garment construction. The main focal point was to create a haptic language that stemmed directly from human perception rather than focusing solely on theoretical technical possibilities and background literature, meaning that design decisions were directly based on user preferences, interpretations and experiences.

Results showed that directional information can be intuitively communicated with minimal training and a relatively small number of actuators. Key insights from the evaluations included that users frequently interpreted haptic cues in relation to the geometry of their body, essentially using their torso as a spatial reference frame. Furthermore, simpler cues consistently outperformed more complex cues on clarity and intuitiveness, regarding both actuator positioning and vibration patterns. These insights formed a final design consisting of a flight jacket with integrated vibrotactile actuators that communicate the directions left, right, behind, above and below with varying levels of urgency. The actuator layout and vibration patterns were based directly on user evaluations to minimize the amount of training and conscious effort required to confidently interpret the cues.

Overall, this project demonstrates the potential of wearable haptic systems to communicate spatial information in high workload environments. Beyond the resulting prototype, the project contributes design knowledge and guidelines regarding how users naturally perceive and interpret haptic cues on the torso, and highlights the importance of designing haptic systems around human perception, intuition and context.

AI ACKNOWLEDGEMENT

WRITING
Claude was used to rewrite certain sentences [62] . Prompts such as 'rewrite this sentence to make it more readable' were used throughout the report writing.

CODING
Claude was used for debugging codes, or writing code for aesthetic parts to processing sketches. Prompts such as 'I'm receveing error ...' or 'add terrain on the bottom of this processing sketch' were used.

PICTURES
AI features of photoshop were used to change the background of report pictures. Promps such as 'change this picture so it has an off white background' were used.

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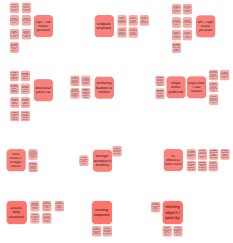
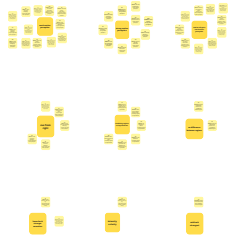
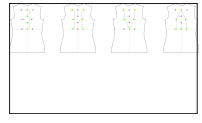
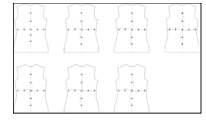
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Layout	Layout 1	Layout 2	Layout 3	Layout 4	Layout 5	across Layouts
raw data quotes						
assigned codes						
						

emerging themes

Theme 1: Simplicity vs Complexity

- Simpler cues are easier and faster to interpret
- Adding more motors does often not improve clarity
- Complex patterns increase cognitive load
- Multi-directional cues lead to confusion
- Users prefer single, localized signals
- More information often reduces understanding

Theme 2: Motion vs Static Signals

- Motion cues communicate direction
- Static cues communicate location or presence
- motion can collapse into a static sensation when distance between motors is too large
- Continuous motion is needed for clear directional perception
- Fragmented or short motion can reduce interpretability
- Different signal types should be used for different purposes

Theme 3: Spatial Interpretation & Embodiment

- Users interpret haptic cues as external objects in space
- Motion is perceived as something moving around the body
- Cues can trigger physical responses like looking or turning
- Directional cues naturally map to intuitive actions

Theme 4: Perceptual Limits & Ambiguity

- Overlapping or competing cues create ambiguity
- Users struggle when multiple interpretations are possible
- Multi-directional signals are hard to resolve
- There is a limit to how much information can be processed at once

Theme 5: Body Location Matters

- The mid-back region provides the clearest motion perception
- Sensation strength does not equal perceptual clarity
- Different regions support different types of signals
- Regional sensitivity varies across the body and across participants

Theme 6: Motion Requires Continuity

- Apparent motion depends on spacing and timing between actuators
- Too few or too distant motors break the sense of motion
- Motion becomes separate points if continuity is lost
- There is a threshold where motion stops being perceived. varies per participants

Appendix

Appendix A – user test iteration 1 questions

User test setup

1. **explain tasks to participant**
2. **assist participant in putting on wearable prototype**
3. **Check if all electronics are connected and working**
4. **position actuators according to layout one**
5. **START TEST**
6. **present one direction at a time (random order)**
7. **Collect responses from questions 1 - 5 (see below)**
8. **After going through all directions, collect responses from questions 6 - 9 (see below)**
9. **Move on to layout two**
10. **repeat steps 6 - 8 until all layouts are tested**
11. **END TEST**

Layout 1

Q1 — What direction was the feedback trying to simulate?

- **Left:**

- **Up:**

- **Down:**

- **Right:**

- **Back:**

Q2 — How intuitive did this placement feel for conveying directional or situational information? (1–5)

Q3 — Did any vibrations feel confusing or difficult to distinguish? Which and why?

Q4 — Did the vibration require conscious effort or feel immediate/instinctive?

Q5 — Compared to other layouts/patterns, how effective did this feel overall? (1–5)

Layout 2

Q1 — What direction was the feedback trying to simulate?

- **Left:**

- **Up:**

- **Down:**

- **Right:**

- **Back:**

Q2 — How intuitive did this placement feel for conveying directional or situational information? (1–5)

Q3 — Did any vibrations feel confusing or difficult to distinguish? Which and why?

Q4 — Did the vibration require conscious effort or feel immediate/instinctive?

Q5 — Compared to other layouts/patterns, how effective did this feel overall? (1–5)

Layout 3

Q1 — What direction was the feedback trying to simulate?

- **Left:**

- **Up:**

- **Down:**

- **Right:**

- **Back:**

Q2 — How intuitive did this placement feel for conveying directional or situational information? (1–5)

Q3 — Did any vibrations feel confusing or difficult to distinguish? Which and why?

Q4 — Did the vibration require conscious effort or feel immediate/instinctive?

Q5 — Compared to other layouts/patterns, how effective did this feel overall? (1–5)

Layout 4

Q1 — What direction was the feedback trying to simulate?

- **Left:**
- **Up:**
- **Down:**
- **Right:**
- **Back:**

Q2 — How intuitive did this placement feel for conveying directional or situational information? (1–5)

Q3 — Did any vibrations feel confusing or difficult to distinguish? Which and why?

Q4 — Did the vibration require conscious effort or feel immediate/instinctive?

Q5 — Compared to other layouts/patterns, how effective did this feel overall? (1–5)

Appendix B – user test iteration 2 RQ1 and RQ2 setup

User Test RQ1 questions

Part 1 – Initial Comfort (Before Vibration)

1. How comfortable does the vest feel when worn?

1 – Very uncomfortable
2 – Uncomfortable
3 – Neutral
4 – Comfortable
5 – Very comfortable

2. Does the vest feel too tight or restrictive anywhere?

- no

- Yes

If yes, where?

Subquestion. Does the TPU layer feel uncomfortable?

3. Does the vest feel stable on your body (not shifting or sliding)?

1 – Not stable at all
2 – Slightly unstable
3 – Neutral
4 – Stable
5 – Very stable

4. Do you feel pressure from the motors even when they are not vibrating?

- Yes
- no

If yes, where?

5. Do you think you could wear this vest comfortably for 10–15 minutes?

Part 2 – Vibration Perception Per Region

(Repeat these questions for each region)

Regions:

- Upper spine
- Mid spine
- Lower spine
- Shoulder blades
- Mid sides
- Lower sides

Upper spine

6. How strong did the vibration feel?

7. How clearly could you feel the vibration in this location?

1 – Very unclear
2 – Unclear
3 – Neutral
4 – Clear
5 – Very clear

8. How localized did the vibration feel?

9. Did the vibration feel like it came from the intended area?

- Yes
- Mostly
- No

10. Did the vibration spread to other areas of your back?

- No
- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Mid spine

7. How strong did the vibration feel?

8. How clearly could you feel the vibration in this location?

9. How localized did the vibration feel?

1 – Very spread out
2 – Slightly spread out
3 – Neutral
4 – Mostly localized
5 – Very localized

10. Did the vibration feel like it came from the intended area?

- Yes
- Mostly
- No

11. Did the vibration spread to other areas of your back?

- no

- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Low spine

8. How strong did the vibration feel?

9. How clearly could you feel the vibration in this location?

1 – Very unclear
2 – Unclear
3 – Neutral
4 – Clear
5 – Very clear

10. How localized did the vibration feel?

11. Did the vibration feel like it came from the intended area?

- Yes

- Mostly

- No

12. Did the vibration spread to other areas of your back?

- No

- Slightly

- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Shoulder blades

9. How strong did the vibration feel?

1 – Very weak
2 – Weak

3- neutral

4- strong

5- very strong

10. How clearly could you feel the vibration in this location?

1 – Very unclear
2 – Unclear
3 – Neutral
4 – Clear
5 – Very clear

11. How localized did the vibration feel?

1- localized

2- slightly spread out

3- neutral

4- spread out

5- very spread out

12. Did the vibration feel like it came from the intended area?

- Yes
- Mostly
- No

13. Did the vibration spread to other areas of your back?

- No

- Slightly

- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Mid sides

10. How strong did the vibration feel?

1- weak

2- slightly weak

3 - neutral

4 – Strong

5- very strong

11. How clearly could you feel the vibration in this location?

1 – Very unclear

2 – Unclear

3 – Neutral

4 – Clear

5 – Very clear

12. How localized did the vibration feel?

1- localized

2- slightly spread out

3- neutral

4- spread out

5- very spread out

13. Did the vibration feel like it came from the intended area?

- Yes
- Mostly
- No

14. Did the vibration spread to other areas of your back?

- No
- Slightly
- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Low sides

11. How strong did the vibration feel?

1- weak

2- slightly weak

3 - neutral

4 – Strong

5- very strong

12. How clearly could you feel the vibration in this location?

1 – Very unclear

2 – Unclear

3 – Neutral

4 – Clear

5 – Very clear

13. How localized did the vibration feel?

1- localized

2- slightly spread out

3- neutral

4- spread out

5- very spread out

14. Did the vibration feel like it came from the intended area?

- Yes
- Mostly
- No

15. Did the vibration spread to other areas of your back?

- No
- Slightly
- Yes

If yes, where?

10. What feeling does the vibration give you? E.g. is it uncomfortable, soothing, urgent?

Part 3 – Comparing Regions

11. Which region had the strongest vibration?

12. Which region had the weakest vibration?

13. Which region felt the most clearly defined?

14. Which region felt the least clear or most diffuse?

Part 4 – Overall Interpretation

15. Overall, how easy was it to perceive the vibration signals on the vest?

1 – Very difficult
2 – Difficult
3 – Neutral
4 – Easy
5 – Very easy

16. Were some areas of the vest noticeably better for vibration feedback?

(Open answer)

17. Do you have any suggestions for improving the placement of the vibration motors?

(Open answer)

Appendix C – Iteration 2 user test RQ3 setup

User Test Questions RQ3 - Spatial positioning and patterns

Layout 1 – Apparent Motion & Vertical Direction

After each sequence

1. What did this vibration feel like?

- something moving downward
- something moving upward
- something coming from above
- something coming from below
- separate vibrations
- one static vibration

- something else

2. How clear was that sensation?

3. Did this feel more like continuous movement or separate vibration points?

4. How confident are you in your answer?

- not confident
- somewhat confident
- very confident

5. Can you briefly describe what this sequence felt like?

After all sequences in layout 1

6. Which sequence felt most like one continuous movement?

7. Which sequence felt least like movement and most like separate vibrations?

8. Did the sequences with more motors feel more like motion than the sequences with fewer motors?

9. In which sequence was the upward or downward direction easiest to recognize?

10. Did top-to-bottom or bottom-to-top feel clearer?

11. Did any sequence clearly feel like something was coming from above?

12. If yes, which one?

13. Which felt clearer to you:

- a full sweep across the whole back

- a sweep from the top to the midpoint

- a sweep from the midpoint to the bottom

- no clear difference

14. Did the midpoint make the cue easier or harder to understand?

15. Did it feel more natural for the movement to:

- go across the whole back

- stop at the midpoint

- start from the midpoint

- no preference

16. Did the reduced-motor versions still feel like motion?

17. What was the minimum version that still felt like a clear movement?

18. Compared to the moving sequences, how did the single top motor feel?

19. Did the single motor already communicate enough on its own?

20. If you wanted to communicate “something is above you,” which would work better?

- a moving sequence
- a single motor at the top
- both would work equally well

21. If this layout were used to communicate a cue from above or below, which version would you trust most?

- full sweep

- midpoint version

- reduced-motor version

- single motor

- other

22. Why?

Layout 2 – Apparent Motion & Lateral Direction

After each sequence

1. What did this vibration feel like?

- something moving from right to left

- something moving from left to right

- something coming from the right

- something coming from the left

- separate vibrations

- one static vibration

- something else

2. How clear was that sensation?

3. Did this feel more like continuous movement or separate vibration points?

4. How confident are you in your answer?

- not confident

- somewhat confident

- very confident

5. Can you briefly describe what this sequence felt like?

After all sequences in layout 2

6. Which sequence felt most like one continuous movement?

7. Which sequence felt least like movement and most like separate vibrations?

8. Did the sequences with more motors feel more like motion than the sequences with fewer motors?

9. In which sequence was the lateral direction easiest to recognize?

10. Did right-to-left or left-to-right feel clearer?

11. Did any sequence clearly feel like something was coming from the right?

12. If yes, which one?

13. Which felt clearer to you:

- a full sweep across the whole back
- a sweep from the right to the midpoint
- a sweep from the midpoint to the left
- no clear difference

14. Did the midpoint make the cue easier or harder to understand?

15. Did it feel more natural for the movement to:

- go across the whole back
- stop at the midpoint

- start from the midpoint

- no preference

16. Did the reduced-motor versions still feel like motion?

17. What was the minimum version that still felt like a clear movement?

18. Compared to the moving sequences, how did the single motor on the right feel?

19. Did the single motor already communicate enough on its own?

20. If you wanted to communicate “something is coming from the right,” which would work better?

- a moving sequence

- a single motor on the right

- both would work equally well

21. If this layout were used to communicate a cue from the right or left, which version would you trust most?

- full sweep
- midpoint version
- reduced-motor version
- single motor
- other

22. Why?

Layout 3 – Lateral Sweeps Across Back Regions

After each sequence

1. How clear was that sensation?

-

2. Can you briefly describe what this sequence felt like?

After all sequences in layout 3

3. Did combining regions (e.g. upper + mid or mid + lower) improve the sense of motion compared to single regions?

4. In which region was the lateral direction easiest to recognize?

5. In which region did the movement feel strongest?

6. Did any region clearly feel more natural for this type of movement?

7. If yes, which one?

8. Which felt clearer to you:

- upper back only

- mid back only

- lower back only

- combined regions

- all regions together

9. Did combining regions make the cue easier or harder to understand?

10. Did it feel more natural for the movement to:

- stay within one region

- move across two regions

- move across the entire back

- no preference

11. Did the sequences that covered more of the back feel more like continuous motion?

12. Compared to single-region sweeps, how did the combined-region sweeps feel?

13. Which region felt the least clear or most difficult to interpret?

Layout 4 – Questionnaire (Spine vs Shoulder Blade Placement)

After each sequence

1. What direction did that cue feel like?
2. How clear was that sensation?

•

2. Can you briefly describe what this sequence felt like?

After all sequences in layout 4

3. Did the vibrations along the spine or along the shoulder blades feel clearer?

4. Which location felt strongest?

9. Compared to straight vertical lines, how did the split or converging patterns feel?

10. Which type of pattern felt more intuitive to you:

- movement along a single line (spine or side)
- movement spreading outward from the center
- movement converging toward the center
- no preference

15. Which version felt the least clear or most confusing?

Layout 5 – Cues Toward and Away from the Midback

After each sequence

1. What direction did that cue feel like (back?)
2. How clear was that sensation?

-

2. Can you briefly describe what this sequence felt like?

After all sequences in layout 5

3. Did the single point on the midback already feel like a meaningful cue?

4. Did the inward motions toward the midback feel clearer or less clear than the outward motions from the midback?

5. Did cues coming inward from up, down, left, and right feel like one coherent signal or like multiple separate signals?

6. Which felt clearer to you:

- only the single midback point
- inward motion using the closer motors
- inward motion using the farther motors
- outward motion using the closer motors
- outward motion using the farther motors
- no clear difference

10. Did using motors that were closer to the midback make the cue easier or harder to understand?

11. Did using motors that were farther from the midback make the cue feel stronger or more directional?

12. Which version would you trust most to communicate a cue related to the back?

13. Did inward motion toward the midback feel more natural, or did outward motion from the midback feel more natural?

14. Compared to the moving sequences, how did the single midback motor feel?

15. Did the single midback motor already communicate enough on its own?

16. Which version felt the least clear or most confusing?

17. If you wanted to communicate “something is happening behind you” or “pay attention to the back,” which version would work best?

18. Why?

Appendix D – Iteration 2 user test setup RQ4

RQ4 User Test – Vibration Pattern Evaluation

Pattern Evaluation

Pattern ID: __intensity of the pulse____

What did this pattern seem to represent?

(e.g. something approaching, something static, something moving, unclear)

How clear was this pattern?

very unclear

unclear

neutral

clear

very clear

How urgent did this pattern feel?

not urgent

slightly urgent

neutral

urgent

very urgent

Did the pattern clearly communicate that something was getting closer?

Pattern ID: __pulsespeed____

What did this pattern seem to represent?

(e.g. something approaching, something static, something moving, unclear)

How clear was this pattern?

very unclear

unclear

neutral

clear

very clear

How urgent did this pattern feel?

not urgent

slightly urgent

neutral

urgent

very urgent

Did the pattern clearly communicate that something was getting closer?

Pattern ID: __pulsespeed and intensity____

What did this pattern seem to represent?

(e.g. something approaching, something static, something moving, unclear)

How clear was this pattern?

very unclear

unclear

neutral

clear

very clear

How urgent did this pattern feel?

not urgent

slightly urgent

neutral

urgent

very urgent

Did the pattern clearly communicate that something was getting closer?

Pattern ID: __pause between pulse____

What did this pattern seem to represent?

(e.g. something approaching, something static, something moving, unclear)

How clear was this pattern?

very unclear

unclear

neutral

clear

very clear

How urgent did this pattern feel?

not urgent

slightly urgent

neutral

urgent

very urgent

Did the pattern clearly communicate that something was getting closer?

Pattern ID: __intensity, no pulse____

What did this pattern seem to represent?

(e.g. something approaching, something static, something moving, unclear)

How clear was this pattern?

very unclear

unclear

neutral

clear

very clear

How urgent did this pattern feel?

not urgent

slightly urgent

neutral

urgent

very urgent

Did the pattern clearly communicate that something was getting closer?

Block 1 – Distance pulse variables

Which aspect helped you understand distance the most?

intensity

pulse speed

pause between pulses

combination

not clear

Did any pattern feel confusing or hard to interpret? Which one and why?

Block 2 – Pulse Count

Did you notice a clear difference between single, double, and triple pulses?

Was there any difference in the perceived meaning of the feedback

Did more pulses make the signal clearer or more confusing?

Block 3 – Pulse Shape

How did the ramp (fade in/out) feel compared to a regular pulse?

Which felt clearer?

constant pulse

ramp up/down

no difference

Which felt more natural or intuitive?

Block 4 – Motion vs Single Motor

Did the sweep feel like actual movement across the body?

Did the single motor with changing speed feel like movement?

Which one better communicated movement?

sweep across motors

single motor variation

both equally

neither

Which one was clearer to simulate a change in distance?

Block 5 – Apparent Motion Speed

At higher speeds, did the motion still feel like continuous movement?

Was there a point where the sequence stopped feeling like movement and started feeling like separate pulses or just one pulse?

Did faster motion make the cue:

clearer

less clear

no difference

Appendix E – Iteration 2 user test RQ3 thematic analysis

(for assessors, the following Github link includes code that is intended for assessment only, you have received access through e-mail, please do NOT share this data with third parties)

Appendix F – Iteration 2 user test RQ4 quantitative results

https://github.com/gijsvogels02/AXON---FMP.git

Appendix G – Iteration 3 user test A quantitative results

https://github.com/gijsvogels02/AXON---FMP.git

Appendix H – Iteration 3 user test B quantitative results

https://github.com/gijsvogels02/AXON---FMP.git

Appendix I – Codes Arduino

https://github.com/gijsvogels02/AXON---FMP.git

Appendix J – Codes processing

https://github.com/gijsvogels02/AXON---FMP.git

Ethical Review Board
Submitted by Gijs Vogels on March 20, 2026, 10:48:54 AM UTC

Ethics Review Template

Via this template you can create (or upload) your Ethics Review and request a review by the Ethical Review Board (ERB). This Ethical Review template should be completed for every research study that involves human participants or personal data.

Questions: If you have questions for the ethics committee, add them at the end of the form as a comment under "Activity".

Submit: Once you've completed the form, click "Submit". Your form will be automatically sent to the Ethics Review Board for revision.

1. Project Title *

Designing wearable vibrotactile feedback on the torso to enable intuitive and effective situational awareness for combat pilots

2. Are you a? *

- ⊙ Master student

3. Name of the researcher (Student or Researcher) *

Gijs Vogels

4. Email of the researcher (Student or Researcher) *

g.j.vogels@student.tue.nl

When applicable, at least one supervisor should be mentioned.

5. Supervisor(s) Name(s)

Steven Houben

5a. Supervisor(s) email address(es)

s.houben@tue.nl

Sharing: Add the person on the right side panel under the "Shared with" label (on low-resolution computers, this option appears at the end of the form).

6. Department *

Industrial Design (ID)

7. What is the purpose of this study? (select all that apply) *

- ☑ Educational purposes (as part of a course)
- ☑ Scientific purposes (possibly leading to a publication)

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8. What are your main research questions? *

Main RQ:

How does the design of wearable vibrotactile feedback on the torso influence intuitive and effective situational awareness for combat pilots?

Sub RQs:

How can a wearable haptic system be designed to balance interpretability, comfort, and wearability?

Which areas of the torso are most suitable for perceiving vibrotactile feedback?

How do different spatial positionings of vibration actuators influence the interpretation of haptic cues?

How do vibration patterns (e.g. rhythm, intensity, sequencing) influence perception and interpretability?

9. Has your proposal already been approved by an external Ethical Review Board? *

☑ No

This means that your project has already been approved by an other Ethical Review Board (e.g. when you are collaborating with another university and the project has been approved by their Ethical Review Board, Medical Ethical Approval Board (METC) approvals, etc).

Device Information

10. Does your research include a device? *

☑ Yes

A device is a complete piece of **physical** hardware that is used to compute or support computer functions within a larger system.

11. Please describe your device or link to an online description of the device *

The prototype developed for this study is a wearable haptic vest designed to deliver vibrotactile feedback across different areas of the torso. The system consists of a textile-

based vest structure integrated with multiple small vibration motors (ERM actuators), distributed across the back and sides of the torso.

The vest is constructed from a combination of flexible and supportive materials to balance comfort, fit, and stability. Adjustable fastening mechanisms (e.g., straps and buckles) are incorporated to ensure close contact between the actuators and the body, which is essential for consistent haptic perception.

Each actuator is connected to a central electronic system comprising a microcontroller, a custom or off-the-shelf printed circuit board (PCB), and a rechargeable battery. The system allows controlled activation of individual actuators or groups of actuators to generate specific spatial patterns or localized vibration cues.

An internal layer is included to house and protect the electronics, while maintaining user comfort and preventing direct contact with wiring or components. The placement of actuators is modular, allowing for different configurations to be tested across studies.

The prototype is designed for use in a seated position and aims to provide clear, localized vibrotactile feedback to support perception, interpretation, and potential situational awareness applications.

12. Will you use a device that is 'CE' certified for unintended use (meaning you will use existing CE certified devices for other things than they were originally intended for) or use a device that is not 'CE' certified? *

☑ No

13. Please explain to what extent the device was assembled according to relevant standards and provide a risk assessment *

The system operates in a low voltage range on a rechargable battery.

Electonic components are either covered with a layer of fabric or enclosed in a 3d printed casing.

There is no direct contact with the skin.

Risk assessment:

The risks associated with the wearable haptic vest are low due to its use of low-voltage electronics and controlled testing conditions. Potential issues such as minor discomfort, heat generation, or loose components are mitigated through insulation, secure assembly, short test durations, and the ability for participants to stop at any time.

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Population & Measurement Information

15. Please check the box that indicates the relevant study population *

- ☑ Students
- ☑ General healthy population

16. Age category of participants *

- ☑ 18 years or older

17. Description of the research method and/or measurement (select all that applies) *

- ☑ (Semi-structured) interviews
- ☑ Behavioral observations
- ☑ Wearable device (e.g. Fitbit watch, on-skin sensors)
- ☑ User testing

Please attach any other relevant documentation (e.g. survey questionnaire, text used for ads to recruit participants, text used for debriefings, etc.) to this ERB in question 18.

18. Please use this box to attach any other relevant documentation (e.g. survey questionnaire, text used for ads to recruit participants, text used for debriefings, etc.)

50dd2482-1c27-45cf-91db-f78605da4ceb, 99d39b87-b9d4-4078-a638-4ed10049800d

19. Describe the procedures, measurements, and stimuli/treatments used in your study. *

Participants will wear a wearable haptic vest equipped with multiple vibrotactile actuators distributed across the torso. During the study, vibration stimuli will be presented at controlled locations and/or in predefined temporal patterns, depending on the specific research question. Stimuli are delivered using low-intensity ERM motors, activated individually or in sequence, while participants remain seated.

The procedure consists of short trials in which participants are exposed to one stimulus at a time in randomized order. Depending on the study phase, participants

Please describe:

What participants will do or experience.

What data will be collected (e.g., surveys, observations, physiological measures).

What tools or materials will be used (e.g., validated scales, prototypes, databases).

If your study involves multiple stages or methods, please describe each step chronologically.

are asked to indicate where they perceive the vibration (localization tasks), interpret the meaning or direction of the cue, or evaluate characteristics such as clarity, intensity, and comfort. Responses are collected through verbal feedback, Likert-scale ratings, and observational notes.

Measurements include localization accuracy, response time (where applicable), perceptual clarity ratings, and qualitative feedback on comfort and interpretability.

for a chronological procedure see the attached file called 'FMP testing plan".

20. Describe and justify the number of participants and observations for each stage of your study. *

Please specify:

How many participants are needed per method and why?

Whether participants will be involved once or multiple times.

If different and/or multiple participant groups are involved in each study stages, please describe them all accordingly.

The study is structured in multiple stages, each aligned with a specific research question. For the first two research questions, approximately five participants will be involved. These stages focus on early evaluation and iterative refinement of the wearable prototype, including aspects such as comfort, wearability, and global actuator placement. A smaller sample size is appropriate here, as the goal is to identify major usability issues and inform design iterations rather than to collect a large dataset.

Once a stable and functional prototype has been established, the third and fourth research questions will involve a larger group of approximately 8–12 participants. These stages focus on testing of the interpretability and intuitiveness of different actuator placements and vibration patterns, where more consistent and comparable data is required. The increased number of participants allows for more reliable observations and supports the identification of placements/patterns across users.

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21. Explain why your research is societally important. What benefits and harm to society may result from the study? *

This research explores how wearable haptic systems can support intuitive, non-audiovisual communication for fighter pilots, where visual and auditory channels are often overloaded. It may improve situational awareness and decision-making in aviation contexts. Results from the research may be relevant for applications in other high-performance environments.

22. Describe the way participants will be recruited *

☑ Personal network

How do you plan to recruit participants for your study? Consider methods such as distributing flyers, leveraging personal networks, or using panels.

23. Will the participants give their consent – on a voluntary basis – either digitally or on paper? Or have they given consent in the past for the purpose of education or for re-use in line with the current research question? *

⊙ Yes

23a. Are you using the TU/e consent templates?

⊙ Yes

You can find the TU/e consent templates by clicking here.

23b. Please upload here your consent template

e9da6b16-a130-46f7-a60d-6ed9dd61e0bf, 01a39657-4538-499e-83d6-6c3fd719bf35, 6af9720a-54b8-4172-8973-752e305c7f93, 23c3d00e-cc11-4153-a9de-2691f6d6dd24

23. Provide a statement of the risks regarding the safety or well-being (think about stress, extreme emotions, visual or auditory discomfort) that you expect for the participants or others involved in the study and how you plan to mitigate them. *

Explain these possible risks and describe the way these risks are mitigated. Also take into consideration any personal data you may gather and associated privacy issues.

The risks associated with participation are minimal. Participants may experience mild physical pressure from the vest and low-intensity vibrotactile stimuli on the torso, which could feel unusual or slightly uncomfortable. There is no exposure to extreme stimuli. To mitigate any potential discomfort, vibration intensities are kept within safe, commonly used levels, sessions are short, and participants are seated throughout the test. Participants are informed that they can stop the study at any time without consequences.

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24. Please provide a brief statement of the risks associated with the privacy and breach of data collected from the participants and how you plan to mitigate them. *

The risks to participant privacy are minimal, as mostly non-identifiable data will be collected (except from age and gender). All responses will be anonymized using participant codes. Data will be stored securely on password-protected devices and will only be accessible to the researcher. Any link between participant identity and data will be removed after data collection, minimizing the risk of a data breach.

Self-assessment checklist

Questions: If you have questions for the ethics committee, add them at the end of the form as a comment under "Activity".

If you answer "Yes" in questions 26 to 35, your request will not be eligible for fast-track approval.

26. Does the study involve human material? (e.g., surgery waste material derived from non- commercial organizations such as hospitals) *

☑ No

27. Will blood or other (bio)samples be obtained from participants? (e.g., hair, sweat, urine or other bodily fluids or secretions, also external imaging of the body) *

☑ No

28. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator? *

☑ No

Consider conducting research involving your own students or employees. If there is a dependency or power imbalance between you and the research participants, your answer to the next question should be 'yes'.

29. Does the study involve participants who are particularly vulnerable or unable to give informed consent? *

☑ No

Vulnerable people: children (<16 years of age), people with learning difficulties, patients, people receiving counseling, people living in care or nursing homes,

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people recruited through self- help groups, etc.

30. Will participating in the research be burdensome? *

☑ No

For example: requiring participants to wear a device 24/7 for several weeks, filling in questionnaires for hours, traveling long distances to a research location, to be interviewed multiple times, etc.

31. May the research procedure cause harm or discomfort to the participant in any way? *

☑ No

Harm or discomfort examples; causing pain or more than mild discomfort, stress, anxiety, administering drinks, foods, drugs, showing explicit visual material, etc.

32. Will financial inducement (other than reasonable expenses and compensation for time) be offered to participants? *

☑ No

For an explanation of what is considered a reasonable compensation, see the topic participant fees from the HTI group.

33. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people) *

☑ No

34. Will the study involve actively deceiving the participants? *

☑ No

Will participants be deliberately falsely informed, will information be withheld from them, or will they be misled in such a way that they are likely to object or show unease when debriefed about the study

35. Will participants be asked to discuss or report sexual experiences, religion, alcohol or drug use, suicidal thoughts, or other topics that are highly personal or intimate? *

☑ No

Think about your research population. For some participants, particular topics can be considered sensitive or intimate, whereas the same topics will not be perceived as such by other participants.

Click the "submit" button in order to send it for review, this will send a message to your **indicated supervisor** based on provided e-mail for approval.

Once your supervisor has approved, it will automatically proceed for review to the Ethical Review Board (ERB).

Ethical Review Board

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Please wait a minute or so and **refresh** the page manually to see the next steps.

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Date
2026-03-20

Our reference
ERB-821

Ethical review board TU/e

T +31 (0)40 247 6259
ethics@tue.nl

intranet.tue.nl/ethics

Ethical review research proposal with reference ERB-821

Dear ,

It is a pleasure to inform you that the Ethical Review Board (ERB) has discussed and preliminarily approved your application with reference ERB-821.
Furthermore, the Board wants to draw your attention to the terms and conditions in the appendix.
Success with your research!

Sincerely,



Dr. D. Lakens
Chair Ethical Review Board TU/e

The ERB retains the right to revise its decision regarding the implementation and the WMO1/WMH2 status of any research study in response to changing regulations, research activities, or other unforeseen circumstances that are relevant to reviewing any such study. The ERB shall notify the principal researcher of its revised decision and of the reasons for having revised its decision.
1WMO: Law on Medical Scientific Research involving Human Beings (in Dutch: Wet medisch-wetenschappelijk onderzoek met mensen)
2WMH: Medical Device Directive (in Dutch: Wet op de medische hulpmiddelen)

APPENDIX 1

Terms and conditions

Amendments

When considerable amendments are made to the design of the study or educational activity, or when the time period between ERB approval and start of the study is longer than one year, please consult the ERB.

Privacy and research data management

The ERB would like to point out that collecting, handling and storing personal information is subject to the General Data Protection Regulation. Please visit TU/e intranet for the latest information and regulations on www.tue.nl/rdm