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Shape-changing pneumatic interfaces for emotion and trust in Human-computer interaction

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**SHAPE-CHANGING PNEUMATIC INTERFACES FOR EMOTION AND
TRUST IN
HUMAN-COMPUTER INTERACTION**

Yang Liu

**TÉLÉCOM PARIS
Institut Polytechnique de Paris**

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Yang LIU

ABSTRACT

INTERFACES PNEUMATIQUES A CHANGEMENT DE FORME POUR L'ÉMOTION ET LA CONFIANCE DANS L'INTERACTION HOMME-MACHINE

Yang LIU

Cette thèse explore le potentiel transformateur des interfaces haptiques pneumatiques à base de silicone pour enrichir l'engagement émotionnel, la confiance et la communication non verbale dans trois domaines interconnectés : les expériences cinématographiques, les systèmes de conduite automatisée et l'interaction homme-robot (IHR). À l'intersection de l'informatique affective et de l'interaction homme-machine (IHM), cette recherche étudie comment un retour haptique bio-inspiré — transmis par des textures de surface et des changements de forme dynamiques — peut approfondir les expériences utilisateur en alignant les stimuli tactiles sur les émotions contextuelles, la conscience situationnelle et les signaux physiologiques.

Le premier volet de ce travail aborde l'amélioration des émotions au cinéma, où les récits audiovisuels traditionnels sont augmentés par un retour haptique pneumatique pour créer une narration cinématographique immersive et multisensorielle. S'inspirant de structures biologiques telles que les épines d'oursin et les coussinets de chat, l'interface conçue utilise des textures texturées (pointes) et lisses pour moduler la valence émotionnelle, tandis que les rythmes de gonflage régulent l'éveil. Des expériences contrôlées révèlent que des stimuli haptiques congruents améliorent considérablement les réponses émotionnelles, les retours à haute fréquence et à texture de « chair de poule » intensifiant l'excitation, et les textures lisses à basse fréquence renforçant le calme. À l'inverse, un retour haptique non congruent a des effets négatifs sur l'alignement émotionnel, soulignant l'importance d'une conception contextuelle. Ces résultats valident le rôle de l'haptique pneumatique en tant que support de communication émotionnelle, dépassant les alertes fonctionnelles pour évoquer des expériences affectives incarnées.

La deuxième partie se concentre sur les systèmes de conduite automatisée, en se consacrant à la conception d'interfaces pneumatiques bio-inspirées pour les demandes de reprise en main dans

les véhicules autonomes de niveau 3. Le volant « Pneumatic Haptic Silicon Sac », inspiré des mécanismes de gonflage animal comme les sacs vocaux des grenouilles, utilise un retour rythmique doux pour réduire la charge cognitive et favoriser la confiance lors des transitions de contrôle. Des études comparatives avec des systèmes vibrotactiles démontrent que les signaux pneumatiques suscitent des réactions de conduite plus calmes et plus douces, tandis que les alertes vibrotactiles permettent des temps de réaction plus rapides au prix d'un stress accru. Cependant, l'ambiguïté directionnelle du retour pneumatique, en particulier pour les changements de voie à gauche, souligne la nécessité de modalités hybrides qui équilibrent l'urgence et le confort. Ces résultats font progresser le développement de systèmes haptiques adaptatifs basés sur les exigences situationnelles.

La troisième partie explore l'interaction non verbale homme-robot, en introduisant une interface haptique pneumatique qui simule des rythmes d'inspiration physiologique, tels que la respiration et les battements de cœur. Intégré dans la poitrine d'un robot humanoïde, ce système silencieux à base de silicone combine des gestes volontaires à des signaux physiologiques subliminaux pour améliorer la reconnaissance des émotions. Les résultats expérimentaux montrent une amélioration de 16% de la précision lorsque l'haptique d'inspiration physiologique est associée à des gestes, en particulier pour les états émotionnels « down-tuning » comme la tristesse. Les participants ont décrit le retour d'information comme « intime » et « réaliste », soulignant son potentiel à favoriser la confiance et les liens affectifs en robotique sociale.

En conclusion, cette thèse établit des principes de conception clés : la congruence émotionnelle et la modulation bio-inspirée de la confiance. Les limites, telles que la variabilité culturelle de la perception tactile et les biais directionnels dans les interfaces de conduite, soulignent les opportunités pour les travaux futurs. Les systèmes adaptatifs exploitant les états utilisateur en temps réel, les études interculturelles sur l'haptique émotionnelle et les innovations en matière de matériaux durables sont des prochaines étapes cruciales. En unifiant les principes du biomimétisme, de la conception émotionnelle et des facteurs humains, cette recherche jette les bases de technologies haptiques qui transcendent la fonctionnalité pour favoriser des relations homme-machine plus profondes et plus intuitives.

Malgré les contributions significatives de cette thèse, plusieurs limites doivent être reconnues et ouvrent la voie à des recherches futures. Tout d’abord, dans le contexte cinématographique, si les textures haptiques bio-inspirées ont permis de moduler efficacement la valence et l’éveil émotionnels, la perception de ces stimuli reste culturellement contingente. Les interprétations émotionnelles des textures varient selon les individus et leur bagage culturel, ce qui limite la généralisation des correspondances établies entre caractéristiques tactiles et ressentis affectifs. De plus, la synchronisation des séquences haptiques avec les récits filmiques reposait sur des scénarios préprogrammés, et l’adaptation en temps réel en fonction de l’état physiologique ou émotionnel du spectateur n’a pas été explorée.

Dans le domaine de la conduite automatisée, bien que les interfaces pneumatiques aient démontré leur capacité à réduire la charge cognitive et à renforcer la confiance, leur précision directionnelle s’est avérée inégale, en particulier pour les changements de voie à gauche. Ce biais, probablement lié aux habitudes de conduite en circulation à droite, mériterait une validation dans des contextes interculturels plus larges. Par ailleurs, les études en simulateur, bien que contrôlées, ne reproduisent pas entièrement la complexité et l’imprévisibilité des situations de conduite réelles, notamment en ce qui concerne les distractions multiples ou les transitions d’urgence.

Enfin, dans le cadre de l’interaction homme-robot, l’intégration de signaux physiologiques comme la respiration et les battements cardiaques a montré un potentiel prometteur pour améliorer la reconnaissance émotionnelle. Cependant, ces effets n’ont été observés que lors d’interactions brèves en laboratoire. La durabilité de ces impressions de « présence affective » dans le temps, la sensibilité aux artefacts liés aux mouvements du robot, ainsi que l’impact de variables environnementales comme le bruit ambiant, restent à étudier. Des recherches longitudinales seraient également nécessaires pour évaluer l’évolution de la confiance et l’éventuelle fatigue émotionnelle liée à une exposition prolongée à ces stimuli.

Cette thèse apporte plusieurs contributions majeures à la conception et à l’évaluation d’interfaces haptiques pneumatiques bio-inspirées dans le champ de l’interaction homme-machine. Sur le plan théorique, elle introduit et valide le concept de congruence émotionnelle dans la conception haptique,

en montrant que l’alignement des stimuli tactiles avec le contenu narratif ou contextuel améliore significativement l’expérience utilisateur, que ce soit dans un cadre immersif ou sécuritaire. Elle propose également le principe de calibration bio-inspirée de la confiance, selon lequel des signaux organiques doux et rythmiques, inspirés de mécanismes naturels, peuvent réduire la charge cognitive et favoriser une relation de confiance plus intuitive avec les systèmes automatisés.

D’un point de vue pratique, cette thèse a donné lieu à plusieurs réalisations concrètes. Un prototype d’interface cinématographique pneumatique a été développé, intégrant des textures dynamiques capables d’enrichir l’expérience émotionnelle des spectateurs, avec une augmentation mesurable de l’immersion et de la satisfaction. Dans le domaine automobile, le volant « Pneumatic Haptic Silicon Sac » a démontré son efficacité pour améliorer les performances de reprise en main tout en réduisant le stress perçu, ouvrant la voie à des systèmes d’alerte plus humains et acceptables. En robotique sociale, une interface thoracique en silicone reproduisant les mouvements respiratoires et cardiaques a permis d’améliorer de manière significative la reconnaissance des émotions, en particulier les états subtils comme la tristesse, et a été perçue par les utilisateurs comme plus vivante et engageante.

Enfin, cette thèse propose des lignes directrices concrètes pour la conception d’interfaces haptiques contextuelles, en fonction des exigences propres à chaque domaine d’application. Elle met en évidence la complémentarité des modalités pneumatique et vibrotactile, et suggère des pistes pour l’intégration de systèmes hybrides adaptatifs. En unissant les principes du biomimétisme, de l’informatique affective et de l’ingénierie des facteurs humains, ce travail pose les bases d’une nouvelle génération d’interfaces haptiques, capables de dépasser la simple fonction utilitaire pour instaurer une communication plus naturelle, plus riche et plus humaine avec les machines.

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CHAPTER 1

Introduction

Imagine sitting in a cinema, sinking in darkness except for the glowing screen. You're drawn into the narrative—a character trembling with fear, a heartfelt hug in love, a triumphant victory—but something is different: as the story unfolds, you feel it, literally feel it with your hands: the sharp jolt of spikes when the sorrow explores, the gentle goosebumps bump during a heartwarming reunion. This is not just a movie; it's an experience where emotion travels beyond the screen to meet your sense of touch.

Now, bring yourself in an automated car, the steering wheel subtly pulsing beneath your palms. A gentle inflation on the right side nudges you to shift lanes, accompanied by soft auditory cues. Unlike the jolting vibrations of older alerts, this tactile signal feels calm, vivid and reassuring.

These futuristic scenarios form the foundation of my research journey into haptic interfaces. These projects explore how touch, mediated through silicone-based haptic technology, can transform the way we experience emotions, build trust, and connect with machines and each other.

At the heart of these projects lies a profound question: **How can haptic interfaces be designed to enhance emotional communication, trust, and understanding in diverse interaction scenarios?** This question drives my research, bridging the domains of emotional rendering for mass audiences, critical driver-vehicle communication in automated systems, and human-robot interaction. By exploring how silicone-based haptic interfaces can evoke emotional responses, improve situational awareness, and facilitate intimate, naturalistic interactions, I aim to push the boundaries of what soft haptic technology can achieve.

By focusing on haptic systems that deliver complex tactile feedback through advanced materials and actuation techniques, my research contributes to the goal of designing technologies that seamlessly integrate into human experiences those who create opportunities for soft interface applications.

Prior to the widespread adoption of soft robotics, tactile systems in HCI were predominantly explored in mechanical or vibrotactile forms, providing basic feedback such as buzzes or vibrations [16]. While these solutions were effective in alerting users to specific actions, they lacked the sophistication to convey vivid emotional information. What’s more, emotional communication through haptics was primarily explored in person-to-person touch, often using simple vibrotactile signals to replicate a squeeze, or a mechanical buzzing.[17]. On the other hand, in a communal emotion-sharing, in cinema for example, there was lack mechanism to deliver a shared, tangible emotional experience to multiple individuals simultaneously.

In automotive settings, early haptic alerts were limited to vibration-based notifications [18] [19], which were often jarring and induced stress in drivers, particularly in high-pressure situations like take-over requests (TORs) in automated vehicles [20] [21]. These systems left potential consideration of the interplay between trust to the new technique and reaction time performance, which are critical for safe and effective driver-vehicle interaction. On the other hand, alternative haptic approaches that employ gradual, organic feedback—such as soft directional pressure—have shown comparable reaction times to conventional vibration alerts. However, while pneumatic alerts tend to elicit slower lateral movement responses compared to vibrotactile cues, this delay has been linked to reduced driver stress and more measured lane-change behaviors. These findings suggest that designing haptic feedback in automated driving requires a careful balance—ensuring timely reactions without inducing unnecessary stress.

Similarly, early human-robot interaction studies primarily relied on visual and auditory cues for conveying emotion and intention [22] [23]. However, these channels often failed to evoke naturalistic, embodied engagement, resulting in mechanical interactions that lacked emotional depth. Building upon this gap, this work explores how bio-inspired haptic interfaces—particularly those simulating physiologically-inspired rhythms like breathing and heartbeat—can serve as subtle, low-cognitive-load communicative channels in non-verbal human-robot interaction [24]. By combining these physiologically-inspired cues with voluntary gestures, the system enhances emotional recognition accuracy and fosters more intuitive, trust-rich exchanges. This integration highlights the

potential of soft pneumatic feedback not only as a functional signaling tool but as an affective medium that aligns with the embodied nature of human social interaction.

These limitations highlight the need for innovative solutions that move beyond mechanical or vibrotactile systems, embracing new materials and technologies to create haptic interfaces capable of conveying complex, multimodal information.

Recent achievements in material science and actuation technologies inspired new approaches to haptic research. The advent of silicone-based interfaces, pneumatic actuation, and multimodal systems has opened new possibilities for designing haptic feedback that is more dynamic, expressive, and sophisticated [25, 26]. Among those, silicone, as a versatile material for haptic interfaces due to its flexibility, durability, and ability to simulate organic textures, makes itself an ideal medium for creating life-like and emotional interactions. Pneumatic actuation, which enables inflation and deflation to produce tactile sensations such as pressure or texture changes, further enhances the realism and versatility of haptic feedback [27, 9].

The integration of multimodal cues—combining haptic, visual, and auditory signals—has also gained prominence. Researches indicate that multimodal feedback can improve user performance [28], enhance emotional engagement [29], and build trust [30] in technology. These technological trends meet the calling with the growing demand for haptic systems that emphasize user experience and emotional interaction, leading the way for innovative applications in diverse fields, from entertainment to transportation to robotics.

However, significant gaps remain in the design and application of haptic interfaces for emotion and communication. Existing studies mainly focus on isolated use cases, yet there are promising domains which might highlight the potential of haptics to transform interactions remain unexplored [31] [32] [33]. This gap underscores the need for a comprehensive approach to haptic design, one that considers scalability, user experience, and emotional impact.

My research addresses this call by investigating silicone-based haptic interfaces in three distinct yet interconnected contexts:

- **Cinema and Emotion Rendering:** Traditional cinema relies heavily on visual and auditory elements to convey emotional contexts. My work explores how haptic stimuli, delivered through a silicone interface with textures like spikes and goosebumps, can enhance audience emotional understanding and satisfaction during movie watching. This project extends the concept of social touch to a cinematic context, providing insights into the effects of congruent and incongruent haptic stimuli on shared emotional experiences.
- **Automated Driving and Take-Over Requests:** As the trend of wide spreading automated driving systems in our daily life, effective driver-vehicle communication is critical. My research investigates the role of silicone-pneumatic haptic interfaces on steering wheels in multimodal Take-Over Request (TOR) notifications. Additionally, I compared pneumatic notification with vibrotactile notification under TOR, my findings suggest that pneumatic notifications reduce mental load, offering a calmer and slower post TOR speed.
- **Human-Robot Interaction:** Early social robots often relied heavily on visual and auditory cues, which, while functional, lacked the embodied richness necessary for natural emotional engagement. To address this limitation, I designed a bio-inspired haptic system integrating a silicone chest and pneumatic actuators that simulate physiologically-inspired rhythms such as breathing and heartbeat. This interface enables robots to convey affective states through subtle, low-cognitive-load tactile cues. When combined with voluntary user gestures, this approach significantly improves emotion recognition accuracy and fosters intuitive, trust-rich interaction. The study demonstrates that soft pneumatic feedback is not merely a signaling mechanism but a powerful medium for non-verbal communication—aligning robot expressivity with human expectations of lifelike, emotional social interaction.

Through my work on silicone-based interfaces in cinema and automated driving, my research aims to advance the field of HCI by demonstrating the transformative potential of haptic technology. Ultimately, my research seeks to develop haptic systems that not only improve functional performance but also foster emotional engagement, trust, and understanding in diverse applications.

1.1. Definition

In this section, frequently mentioned items will be introduced and defined, in aiming to providing a solid and unique understanding of my dissertation.

- **Emotion:** Emotion refers to short-term affective states that involve physiological arousal, subjective feelings, and expressive behaviors, often triggered by specific internal or external events [34]. These states are typically associated with psychological and physical changes such as increased heart rate, facial expressions, and behavioral tendencies [35]. In this dissertation, I adopt an operational definition of emotion aligned with the experimental psychology perspective. Specifically, emotional states are measured using the Self-Assessment Manikin (SAM) method [36], which captures user-reported levels of valence (pleasantness) and arousal (intensity). This methodological framework suits the goal of quantifying affective responses in controlled HCI experiments.
- **Trust:** Trust is defined as a reliance on and confidence in the truth, worth, and reliability of a person or thing [37]. It has two major mechanisms: on cognitive aspects, it confirms the objective to trust that partners will behave as desired; On behavioral mechanisms, trust is described as the process of facilitating risk acceptance, promoting transparency, enabling smooth knowledge-sharing, encouraging joint problem-solving and reducing negotiation and monitoring costs. [38] In this dissertation, trust is specified as the trust from a user to an operating mechanism, i.e. an automated driving vehicle. Although NASA-TLX is used to evaluate drivers' perceived mental workload during interaction with automated driving systems, it does not directly measure trust [39]. However lower reported cognitive load is often associated with greater ease of use and can indirectly inform our understanding of system acceptance and user confidence. Hence, we follow the methodological approach of Khastgir *et al.* [40] and Chien *et al.* [41], who demonstrate that perceived cognitive workload—measured via NASA-TLX—can serve as an indirect indicator of system trust and user acceptance in automated systems.

- **Multimodal interaction:** The term “multimodal” is the adjective form of multiple-modality, that refers to the presence or use of multiple modes or methods. In the field of Human-Computer-Interaction, multimodal interaction represents a transformative approach, aiming to create comprehensive and natural communication between humans and digital systems, by integrating multiple sensory channels like verbal, vision, and touch. The field has evolved significantly in the recent decades in the revolution of mobile devices and advanced sensors, enabling computers to perceive and interpret diverse input and output modes. This approach provides more adaptive, responsive, and human-centered technological experiences. [42] In this dissertation that focuses on the designing of a pneumatic haptic interactive system, any forms those who combines haptic and other channels are referred as “multimodal”.
- **Haptics:** Haptic, encompasses both tactile and kinesthetic, which are interrelated concepts within the realm of touch perception. Haptic sensing refers to the overall sense of touch and involves the perception and manipulation of objects using touch and proprioception. Meanwhile, tactile sensing specifically relates to the detection of force on the skin surface. It involves direct contact with objects to identify features like edges, holes, humps and surface friction. Kinesthetic sensing, often used interchangeably with proprioception, deals with the awareness of body movement, muscle strength, and position. It involves sensing mass, torque, and the body’s position in space. In brief, tactile sensing focuses on skin-level sensations, while kinesthetic involves deeper sensations from muscles and joints [43]. In addition, haptic also covers the concepts of thermal, electrotactile, pressure forms (Figure 1.1) [44, 45, 46]. In this dissertation, we use haptic as a range of touch-based interactions and perceptions that involves various sensations experiences such as pain, pressure, surface components, vibration, etc.
- **Affective Computing:** Affective computing refers to the development of systems and devices that can recognize, explain, process and simulate human emotions [47, 48, 49]. It involves both the sensing of affective states—such as joy, sad or stress—and the ability of computational systems and devices to respond adaptively to such affective states. Affective computing integrates

cross-field disciplines from computer science, psychology, and neuroscience to enable systems and devices to understand and interact with users on different emotional levels. Approaches to emotion recognition in this domain often deal with physiological signals (e.g., heart rate, skin conductance), behavioral cues (e.g., facial expressions, voice tone), and self-report measures. Meanwhile, affective response generation may involve visual, speech or sound effects, or haptic feedback tailored to emotional context. In this dissertation, affective computing is discussed in relation to how haptic interfaces can serve as non-verbal emotional communication channels, supporting rich and intuitive human-computer interaction through haptic-based affect modulation.

- **Human-Robot Interaction:** Human Robot Interaction (HRI) is a field that lies at the intersection of Human-Computer Interaction (HCI) and robotics [50, 51], focusing on the design, implementation, and study of interactions between humans and robotic systems. Unlike conventional interfaces, HRI involves communication with robots—complex, adaptive, and often autonomous agents capable of sensing, reasoning, and acting within physical environments. HRI deal with how users perceive, trust, and emotionally engage with these intelligent machines through various modalities such as speech, gesture, gaze, and haptic interaction [52, 53]. The topic emphasizes both the functional aspects of collaboration—task efficiency, control sharing, and safety—and the affective aspects of interaction, such as empathy, social bonding, and emotional expression. In particular, social HRI explores robots as social partners rather than tools, investigating how embodiment, behavior, and non-verbal cues influence user experience [54, 55, 56]. In this dissertation, non-verbal communication is applied and examined in HRI, where soft pneumatic haptic interfaces simulate physiological rhythms to foster intuitive, emotional interactions between human and robot.
- **Takeover Request:** A Takeover Request (TOR) refers to the system-generated signal in Level 3 automated vehicles that prompts the driver to resume manual control of the vehicle [57, 58]. Following the Society of Automotive Engineers (SAE) automation classification, Level 3 automation allows the driver to disengage from active driving tasks under certain conditions

but requires them to be available to intervene when the system encounters certain conditions or unexpected scenarios [59, 60]. TOR is a critical interaction factor between the automated system and the human operator, the effectiveness of a TOR depends on how well the system communicates urgency and/or direction information, achieved through visual or auditory cues, traditionally. However, these modalities may induce stress or cognitive overload [61, 62, 63]. In this dissertation, TOR is examined through the application of bio-inspired pneumatic haptic interface on steering wheels, investigating how haptic cues—delivered via shape-changing silicone interfaces—can support smoother transitions of control, reduce cognitive workload, and improve trust in automation.

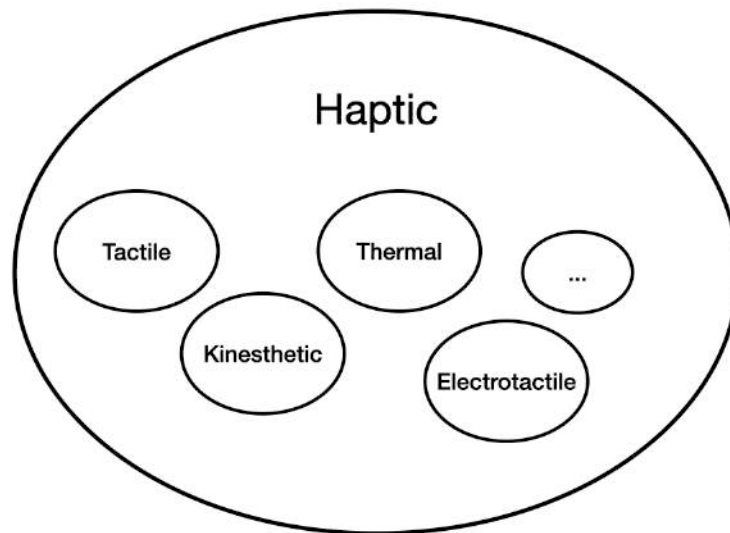


Figure 1.1: Haptic

1.2. Research questions

This dissertation explores the transformative potential of silicone-based pneumatic haptic interfaces across three interconnected domains: enhancing cinematic emotional experiences, optimizing driver-vehicle interaction in automated driving systems, and enriching non-verbal human-robot communication. By integrating bio-inspired design principles with HCI methodologies, this research explores

the role of haptic feedback—not merely as a functional alert system but as a medium for emotional communication, trust-building, and immersive interaction. The overall problematic driving this dissertation is: **How can bio-inspired pneumatic haptic interfaces be designed and applied to enhance multimodal interaction experiences?** This global question is addressed through four specific and interconnected research questions, each targeting a different application scenario:

- **Research Question 1: How can pneumatic haptic interfaces enhance emotional engagement in cinematic experiences?** Traditional cinema relies heavily on visual and auditory stimuli, limiting the extent of audience immersion. This research explores a novel affective haptic rendering approach, introducing bio-inspired pneumatic interfaces with dynamic shape changes to emotional cinematic experiences. This project investigates: *Can pneumatic haptic feedback enhance audience emotional perception during film viewing? How can surface textures—like spikes (negative valence) and goosebumps (positive valence)—influence the interpretation of emotional content? What parameters should be considered in designing haptic stimuli for an optimal emotional experience?*
- **Research Question 2: Does biomimetic pneumatic feedback on steering wheels improve driver’s takeover performance in Level 3¹ automated vehicles?** Effective driver-vehicle communication demands interfaces that balance urgency and calmness. Pneumatic Haptic Silicon Sac (PHSS) steering wheel, inspired by animal inflation patterns, investigates: *Whether gentle inflation rhythms reduce cognitive load compared to mechanical vibrations? In multimodal notification systems (visual-auditory-haptic), does the integration of pneumatic haptic cues improve overall driving safety?*
- **Research Question 3: How do pneumatic and vibrotactile modalities differ in balancing urgency, comfort, and directional accuracy during takeover requests?** While pneumatic haptic feedback may be more comfortable and trust-inducing in low-stress situations, it may lack the urgency needed for high-priority alerts. Conversely, vibrotactile

¹Limited Self Driving Automation: Drivers of Level 3 vehicles can involve in non-driving related tasks, but must be prepared to take over control within sufficient transition time when necessary

feedback can quickly capture attention but may induce stress or misinterpretation. This research compares these two haptic modalities to answer: *Reaction times and post-TOR speeds: Does pneumatic feedback reduce TOR effectiveness in high-urgency scenarios? Directional clarity: Can asymmetrical inflation patterns match localized vibrations' precision? Long-term user acceptance: Which modality better sustains trust across varied driving contexts?*

- **Research Question 4: Can physiologically-inspired haptic cues, such as breathing and heartbeat rhythms, enhance emotion recognition in non-verbal human-robot interaction?** Traditional human-robot interaction relies heavily on visual and auditory signals, which often fail to evoke embodied emotional resonance. This research investigates whether bio-inspired haptic feedback—delivered through soft pneumatic actuators simulating physiologically-inspired rhythms—can serve as a subtle, low-cognitive-load emotional channel. *Does the integration of physiologically-inspired haptic cues improve users' ability to interpret robot affective states? When combined with voluntary gestures, can this approach enhance emotion recognition accuracy and foster more natural, trust-rich human-robot communication?*

These questions collectively advance the thesis' goal: to demonstrate how silicone-based pneumatic interfaces, rooted in biomimicry and emotional congruence, can improve human-computer interaction across entertainment and safety-critical systems.

1.3. Research approach

Research approaches in this dissertation includes:

- **Ideation:** The process includes literature reviews, sketching and brainstorming. Laboratory members, collaboration partners and social connections contributed to this approach.
- **Prototyping:** For each project, I designed the functions of the prototypes based on the users needs and storylines. I used program-able clips, 3D modeling software, 3D printers and silicone molds to achieve the high quality prototype fabrication.
- **Controlled experiments:** In each project, controlled experiments were conducted for the

usability of the prototypes. These methods include quantitative measurements, and open-ended interviews.

- **Data analysis:** Data collected from each of the experiments were analyzed under statistical methods, such as ANOVA, Friedman test and post-hoc test.

1.4. Collaboration works

This thesis is part of the ANR² SecondSkin project (SecondSkin: Shape-Changing Materials for HCI³). This project is at the crossroad of Human-Computer Interaction (HCI) and the physics of programmable materials, with a connection to the world of interactive arts. Its objective is to enrich user experience with the sense of touch through new tactile shape-changing interfaces, both for enabling new interactions and for supporting emotional interpersonal communication. The goal of this project is to investigate novel ways of producing richer and more human-like touch signals. There are 4 scientific tasks in these projects: the development of more versatile Baromorph⁴ [27](Task 1), the combination of Baromorphs with other input and output modalities (Task 2), adaptive/adaptable interaction techniques (Task 3) and social touch (Task 4). There are 4 research partners that involve in the tasks: PMMH⁵, LIG⁶, I3-SES⁷, and LTCI⁸. As a member from LTCI, my works contribute to the Baromorph applications and adaptive interactive techniques. There are two forms of collaborations: First, my supervisors and I report new tryouts and the difficulties we met on the regular meetings with all partners, as well as they provide precise mentoring, reporting thesis progress on their side through all my projects. Second, I collaborated with Shangguan Zhegong, a member from ENSTA Paris, Institut Polytechnique de Paris, on the pneumatic haptic steering wheel project, and with Mickaël Bouhier, research engineer from DIVA⁹ group, LTCI on the prototyping of cinematic emotion experience project.

²L'Agence nationale de la recherche (ANR) <https://anr.fr>

³<https://anr.fr/Projet-ANR-21-CE33-0018>

⁴Baromorphs are bio-inspired pneumatic shape-morphing elastomers—thin, flexible sheets embedded with a network of air channels that, when inflated, undergo controlled anisotropic expansion to morph into pre-programmed 3D shapes

⁵Laboratoire de Physique et Mécanique des Milieux Hétérogènes

⁶Laboratoire d'Informatique de Grenoble

⁷Institut Interdisciplinaire de l'Innovation

⁸Laboratoire Traitement et Communication de l'Information

⁹Design, Interaction, Visualisation & Applications

1.5. Thesis overview

This dissertation explores the design, implementation, and evaluation of silicone-based pneumatic haptic interfaces across cinematic, automotive and robotics contexts. Each chapter builds upon the previous to address the interconnected research questions, culminating in a holistic understanding of haptic technology’s potential to enhance emotional engagement and safety-critical interactions.

1.5.1. Chapter 2: Background

This chapter provides an interdisciplinary review of the relevant concepts and prior work that inform the research in this dissertation. Firstly, it outlines how emotion is understood and modeled in interaction design, with emphasis on both categorical and dimensional approaches, and highlights the value of Self-Assessment Manikin (SAM) as a simple and cross-culturally accessible tool for measuring affective states in experimental settings.

The chapter then introduces the concept of trust in automated systems, especially in the context of automated vehicles (AVs). It reviews how trust is shaped over time by user experience, system transparency, and workload. Special attention is given to Level 3 automation, where human drivers must respond to Take-Over Requests (TORs). To assess trust and mental effort, the NASA Task Load Index (NASA-TLX) is introduced as a relevant subjective metric.

The third section of the chapter focuses on touch and haptic interaction, summarizing the physiology of tactile perception and how it has been applied in HCI systems. It discusses different haptic modalities, such as vibrotactile and pneumatic feedback, and examines their use in various interactive contexts, including wearable devices and in-car systems. The limitations of earlier vibrotactile approaches are discussed, alongside more recent developments in soft pneumatic materials that allow for richer, more expressive feedback.

The fourth section introduces the field of Affective Human-Robot Interaction (HRI), with a particular emphasis on non-verbal communication. The review highlights prior works on using touch and body signals—such as heartbeat and breathing patterns—as cues for emotional state recognition.

Finally, the chapter presents an overview of Baromorphs, a class of shape-morphing pneumatic materials used in the prototypes developed in this dissertation. The physical principles behind Baromorph actuation are briefly introduced, along with some of the fabrication challenges and design considerations.

1.5.2. Chapter 3: Designing Interactive Pneumatic Interfaces for Enhanced Movie Experience

This chapter presents the cinematic emotion enhancement project, addressing RQ1.

- **Bio-Inspired Pneumatic Interface:** A silicone-based system with surface textures (spikes, goosebumps) and inflation rhythms, inspired by biological structures like sea urchin spines and frog vocal sacs.
- **Two-Stage Experiment**
 - *Stage 1:* Validated haptic stimuli’s standalone emotional impact using SAM scales.
 - *Stage 2:* Investigated congruent vs. non-congruent haptic feedback during movie excerpts.

Mixed-Methods Analysis: Combined quantitative metrics (ANOVA, Wilcoxon tests) with qualitative feedback to map texture-frequency parameters to valence-arousal outcomes.

1.5.3. Chapter 4: Enhancing Takeover Requests Through Multi-Modal Haptic Steering Wheel Interfaces

This chapter details the automotive haptic interface studies, addressing RQ2 and RQ3:

- **Study 1: Pneumatic Tactile Interface on Steering Wheel**
 - *Design:* Silicone sacs integrated into a steering wheel, mimicking animal inflation patterns (e.g., Frog vocal sacs)
 - *Evaluation:* CARLA simulator trials showed a 15% reduction in takeover time and 30% higher trust scores compared to visual-auditory systems.

- **Study 2: Comparative Analysis of Pneumatic vs. Vibrotactile Feedback:**

- *Dual-Modal Prototype Design:* Steering wheel supporting both pneumatic and vibrotactile alerts.
- *Comparison:* Vibrotactile cues had 12% faster reaction times but increased post-TOR speeds (a stress indicator), while pneumatic feedback suggested lower stress (low post-TOR speed).

1.5.4. Chapter 5: Integrating Physiologically-inspired Physiological Cues in Non-Verbal Human-Robot Interaction

This chapter explores the role of physiologically-inspired haptic cues—such as simulated breathing and heartbeat—in enhancing emotion recognition and trust within non-verbal human-robot interaction, addressing RQ5.

- **Bio-Inspired Haptic Interface:** A wearable silicone-based system was developed to simulate physiological rhythms via soft pneumatic actuation, mimicking natural signals like chest movement and cardiac pulse.
- **Multimodal Interaction Design:** The system combines physiologically-inspired tactile cues with voluntary gestures to enable richer emotional expressivity and intuitive interaction.
- **Emotion Recognition Experiment:**
 - *Design:* Participants interacted with the robot under different cue combinations—gesture-only, physiologically-inspired-only, and combined modalities.
 - *Outcome:* The combined condition significantly improved recognition accuracy for low-arousal emotions and was rated more “intuitive” and “emotionally engaging” by users.
- **Mixed-Methods Evaluation:** Quantitative classification accuracy and SAM ratings were complemented with qualitative feedback to assess the perceived naturalness and effectiveness of haptic emotion communication.

1.5.5. Chapter 6: Conclusion

This chapter synthesizes the dissertation’s core contributions across cinematic, automotive, and human-robot interaction contexts. Rather than proposing a single unified framework, the findings suggest a set of interconnected design principles that link emotional congruence—aligning haptic feedback with contextual affective states—and biomimetic trust modulation, where rhythmic tactile patterns inspired by natural processes (e.g., breathing, heartbeat, vocal sac inflation) support calm, interpretable, and emotionally resonant user experiences. These principles inform both affective computing and human factors engineering, showing how soft pneumatic haptics can support immersion in entertainment, reduce stress in safety-critical systems, and foster non-verbal social cues in embodied interaction with robots.

Looking ahead, several future directions emerge. First, adaptive haptic systems that respond dynamically to user states—such as real-time affect recognition or situational urgency—may enhance the personalization and responsiveness of interaction design. Second, further investigation is needed into the cultural variability of emotional interpretations of tactile stimuli, such as the perceived valence of textures or the comfort of physiological rhythms across diverse populations. Third, sustained attention to material sustainability, including the use of biodegradable and skin-compatible silicones, will be critical for wearable and long-term deployments. Finally, continued exploration of physiologically-inspired touch in social robotics opens opportunities for designing intuitive, low-bandwidth emotional communication, offering a promising direction for affective and embodied HCI.

CHAPTER 2

Background

This chapter reviews the prior research literature related to the physiological and psychological perceptions of Human-Computer-Interaction, pneumatic haptic interfaces and the mechanics techniques involved.

2.1. Emotion in Human-Computer-Interaction

By incorporating emotional interaction into systems, HCI aims to enhance user experiences, improve usability, and build deeper connections between humans and computers.

2.1.1. Emotion

Emotion is a complex and multifaceted phenomenon that has been studied across various disciplines in decades, including psychology, physiology, and social science. Each aspect offers particular perspectives on what emotions are, how they arise, and their impact on human behavior and interactions.

In psychology, emotion is defined in the book *Psychology of Emotion* by Paula M. Niedenthal and François Ric as: "Episodic, short-term, biologically based patterns of perception, experience, physiology, action, and communication that occur in response to specific physical and social challenges and opportunities" [64]. Emotions have components such as physiological changing (e.g., increased heart rate [65], sweating [66]) and behavioral expressive actions (e.g., smiling, crying [67, 68]).

Recent advancements, such as fMRI and EEG, are being used to measure brain activity and gain deeper insights into the biophysical mechanisms underlying emotions. These technologies help researchers analyze the brain's electrical and chemical processes, revealing how different neural patterns correspond to emotional experiences (Figure ??)[69, 12, 70]. Besides neuroimaging approaches, scientists argue that emotions are closely tied to cognitive processes, such as perception, memory, and decision-making [71].

On the other hand, social scientists study how emotions are shaped by cultural communication,

social contexts, and interpersonal relationships [72, 73]. They believe emotions play a key role in social communication and conflict resolution. What's more, exploring how emotions can spread through groups, leading to phenomena like mass hysteria, shared joy, and social movements makes emotion a social factor among mass population, for instance, emotion in economic activities [74, 75, 76].

In 1897, David Irons in his paper *The Primary Emotions* firstly identified primary forms of emotion. This theory are lately widely accepted and spread [77, 78, 79]. In this theory, primary emotions are innate, universal, and shared across humans and highly intelligent animals. They are biologically driven and primarily processed in the limbic system of the brain [80]. These emotions are considered "basic" because they are instinctual and serve essential survival and social functions. There are six primary emotions: happy, sadness, fear, anger, surprise and disgust ¹⁰.

On the contrary, secondary emotions, or sub emotion, are more complex and are usually defined as emotions developed through personal experiences, cognitive processes, and cultural influences. They often arise from combinations of primary emotions and involve higher-level cognitive appraisal [83, 84, 85]. Examples of secondary emotions are shame, anxiety, jealous and guilty. However, the definition and grouping of secondary emotions are highly controversial and may be identified differently across-culturally, this issue is not addressed in this dissertation [86, 87].

2.1.2. Affective Engineering

Affective Engineering, also known as Emotion Engineering or Kansei Engineering[88], is a multi-disciplinary field that focuses on designing systems, products, and technologies that incorporate human emotions and subjective experiences [89, 90]. It meld the gap between human emotions and engineering by understanding, measuring, and applying emotional interaction to improve user experiences. The concept originated by a Japanese scholar Mitsuo Nagamachi, University of Hiroshima, in the 1970s as Kansei Engineering, where "Kansei" refers to the psychological feelings and emotions evoked by a product or system. The goal is to design emotionally intelligent systems

¹⁰Whether disgust is considered a primary emotion is controversial, and this dissertation does not address this issue. [81, 82]

that understand, interpret, and respond to human emotions in meaningful ways.

Emotion modeling

Emotion modeling is a computational approach to simulating and understanding human emotions. It aims to create systems that can recognize, interpret, and respond to human emotional states. There are different approaches:

- **Categorical Models:** Categorical Models classify emotions into distinct categories. The up-mentioned primary and secondary emotions are examples for emotion classification studies. These models propose a limited set of fundamental emotions that serves as the building elements for all human emotional experiences. For instance, based on observing facial expressions across different cultures, Paul Ekman identified six basic emotions—anger, disgust, fear, happiness, sadness, and surprise [91]. Similarly, Carroll Izard proposed ten primary emotions in his studies over decades: joy, interest, surprise, distress, anger, disgust, contempt, fear, shame, and guilt. Each primary emotion is considered to have unique motivational properties and physiological responses [92]. Categorical emotion models are utilized in various fields such as psychology and psychiatry for diagnosing and understanding emotional disorders, Emotion-aware AI, and human-computer interaction interfaces and marketing and consumer research in aiming for assessing consumer emotional responses to products or advertisements. These models have significant advantages: By categorizing emotions into identifiable labels, they provide a straightforward framework for identifying and discussing certain emotions. Moreover, basic emotions identified in these models are universally recognizable, facilitating cross-cultural studies and applications. However, there are noticeable limitations. First, categorical models may be oversimplified considering the complexity of emotions. Blended emotions (e.g., "bittersweet") or mixed emotional states are ignored, as well as the dynamic emotional states or context-dependent variations [93]. Plus, the expression and interpretation of emotions may differ across cultures and individuals, challenging the universality of specific categories [94].
- **Dimensional Models:** Dimensional emotion models conceptualize emotions along continuous dimensions rather than discrete categories. This approach posits that emotional ex-

periences can be mapped within a multidimensional space, capturing variations, mostly in continuous values along axes like valence (positive/negative) and arousal (intensity), often with a third dimension like dominance (control/power)[95, 96, 97, 98]. For example, the Circumplex Model of Affect by James Russell, arranges emotions in a circular structure defined by valence and arousal dimensions. In this model, excitement is characterized by high arousal and positive valence, while calm is associated with low arousal and positive valence [99]. These approaches are widely applied in affective computing for predicting emotional states in speech, text, or images for human-computer interaction [100, 101, 102]. Dimensional emotion models offer several advantages. They capture subtle variations in emotional intensity, such as the difference between mild and extreme anger. Their flexibility allows integration with categorical models, making them useful for hybrid approaches [103]. Additionally, these models reduce complexity by avoiding predefined emotion categories, enabling broader applicability across different contexts. However, they also come with limitations [104]. One major drawback is oversimplification, as they may miss categorical distinctions, such as the difference between anger and fear. Communication challenges arise because continuous scales are harder to interpret than discrete emotion labels like "happy" or "sad." Furthermore, scholars argue that these approaches' effectiveness varies based on stimulus ambiguity and cultural factors [105]. Despite their strengths in capturing emotional complexity, the challenges of interpretation and cross-cultural applicability remain significant considerations.

- **Appraisal Models:** Appraisal models hypothesize that emotions arise from cognitive evaluations of events, focusing on how individuals interpret situational factors like goal relevance, responsibility, and control. These models emphasize that emotions are not direct reactions to stimuli but are shaped by subjective appraisals of events[106, 107]. Appraisal models explain emotional responses through sequential evaluations of events based on multiple dimensions. These include motive consistency (whether the event aligns with personal goals), accountability (who or what is responsible), control potential (the perceived ability to influence outcomes), and normative significance (alignment with social or moral standards) [108, 109]. These dimensions interact dynamically, determining emotional intensity and certainty. A

notable example is Scherer's Component Process Model (CPM), which evaluates emotions through relevance, implication, coping potential, and normative significance [110]. In terms of application, appraisal models are widely used in emotion classification within text analysis, where appraisal dimensions help infer emotions from language cues [103]. Additionally, these models contribute to emotional intelligence (EI) assessment by providing structured frameworks for evaluating emotion comprehension and management. Their ability to link cognitive evaluations to emotions makes them valuable across psychology, artificial intelligence, and human behavior research [111]. However, these models face challenges, such as the complexity of identifying and measuring the numerous appraisal dimensions involved in emotional responses. What's more, assessing rapid, unconscious appraisals can be difficult, and there is debate about whether emotions can occur without any cognitive appraisal [112].

- **Machine Learning Models:** Machine learning emotion models use trained algorithms to recognize patterns in emotional states, enabling classification and prediction of emotions from various datasets like text, speech, or visual data. [113, 114]. Machine learning emotion models are reinforced by analyzing diverse data sources like facial expressions, speech voicetracks, textual data from social media or chat, and physiological signals captured through wearable devices. Machine learning models, including convolutional neural networks (CNNs), support vector machines (SVMs), and deep neural networks, are trained to map extracted features from rough data to emotional states. These models have wide-ranging applications: In mental health clinication, they provide support for early intervention strategies [115]. In marketing research, they help build businesses assess to consumer emotional responses to advertisements, products, and services[116]. In robotics, they contribute to the development of emotionally intelligent chatbots and humanoid robots [117]. Machine learning emotion models provide automated, data-driven approaches to emotion intelligent. However, their effectiveness largely depends on the quality of input data, the sophistication of preprocessing techniques, and the accuracy of the trained models. Plus, they also face significant challenges, such as privacy concerns related to emotion detection, and contextual variability that affects the reliability of predictions [118, 119].

Emotion Measurement

Modern techniques like facial expression analysis[120], voice emotion recognition, physiological sensing (e.g., heart rate, skin conductance), and brain-computer interfaces are used to measure emotional states. Meanwhile, Surveys and self-reports are also used to gather subjective emotional feedback.

For instance, researchers explored studies on facial emotion recognition (FER) using deep neural networks (Figure 2.1)[1]. Their neural network training model primarily focused on mouth and nose regions as key features for emotion recognition, meanwhile eyes and ears were found to be less important features. They also reported the effectiveness of FER systems often depends on the quality and diversity of training data. Major databases like AffectNet and RAF-DB provide large collections of facial images with emotion labels, though they may still have limitations in representing global population diversity.

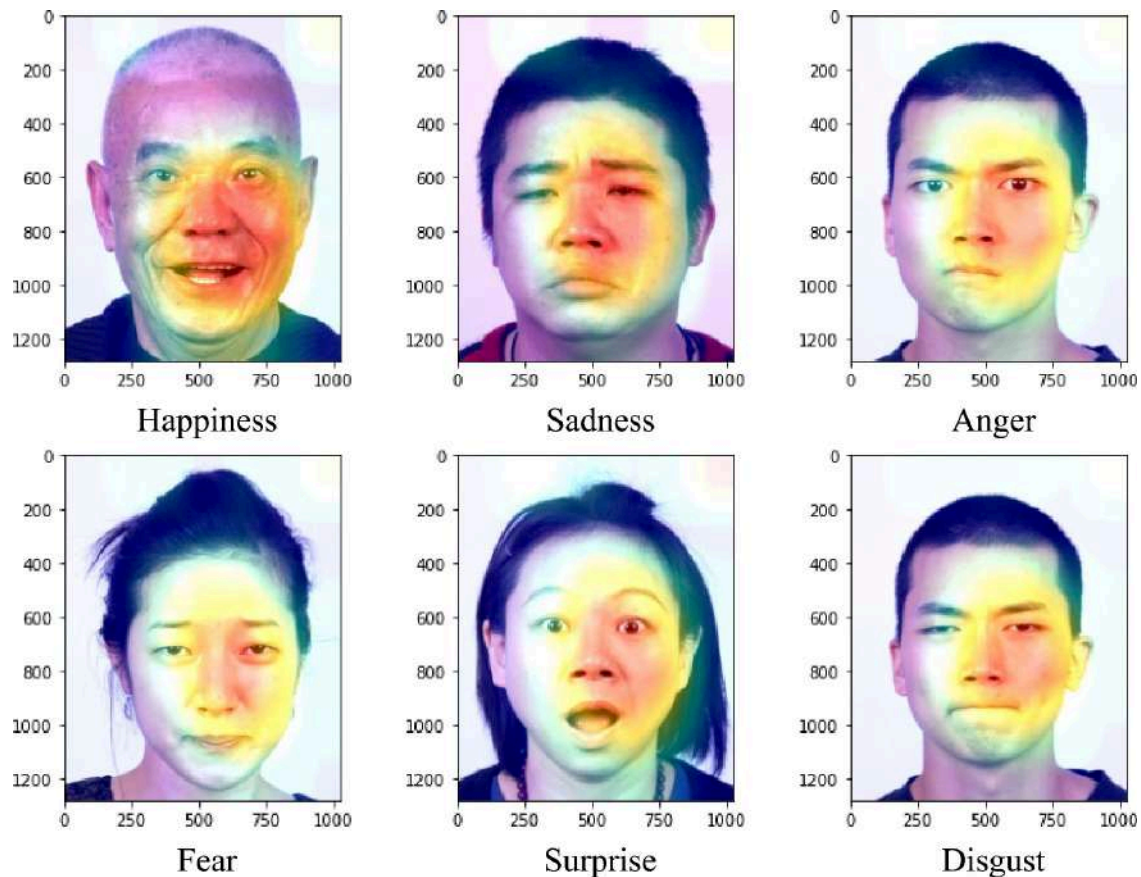


Figure 2.1: Facial emotion recognition database examples (From [1])

The continuous development of portable noninvasive human sensor technologies such as brain-computer interfaces (BCI) brings new possibilities in the area of affective computing. Researchers discuss the progress of research into multi-modal emotion recognition based on BCI and presented a hybrid neurophysiology approach to emotion recognition [121]. They reported an emotion recognition model is based on various hybrid neurophysiology modalities, a method of emotion recognition of multi-modal physiological signals by a convolutional recurrent neural network.

However, self-report methods offer significant benefits in emotion measurement over facial recognition or brain-computer interfaces: First, self-reports provide subjective insight into individuals' personal emotional experiences, which are not accessible through other means; second, self-report can be used in situations where observational data are not typically available, which is relatively simple to access; third but not the least, self-report is often more economical than other methods, especially for large-scale studies. These benefits make self-report methods an indispensable tool in emotion measurement, particularly for assessing the subjective experience of emotions in research and practical applications.

Self-report methods such as Positive and Negative Affect Schedule (PANAS) [122], Experience Sampling Methods (ESM) [123] and Self-Assessment Manikin (SAM) (Figure 2.2) [2] are widely applied. Among them, SAM offers several advantages over PANAS and ESM for measuring emotions: First, SAM uses pictorial representations, making it language-independent and accessible to a wider range of participants, especially for cross-cultural experiment settings and non-native speakers [124]. Second, there are three judgements with 5-scale, that can be accessed quickly and easily. Third, SAM measures pleasure, arousal, and dominance, providing a more completed assessment of emotional states compared to the binary positive/negative approach of PANAS, and the results can be effectively incorporated into both qualitative and quantitative research, offering more flexibility than ESM. Hence, in this dissertation, we applied SAM as the measurement of emotion under experimental settings.

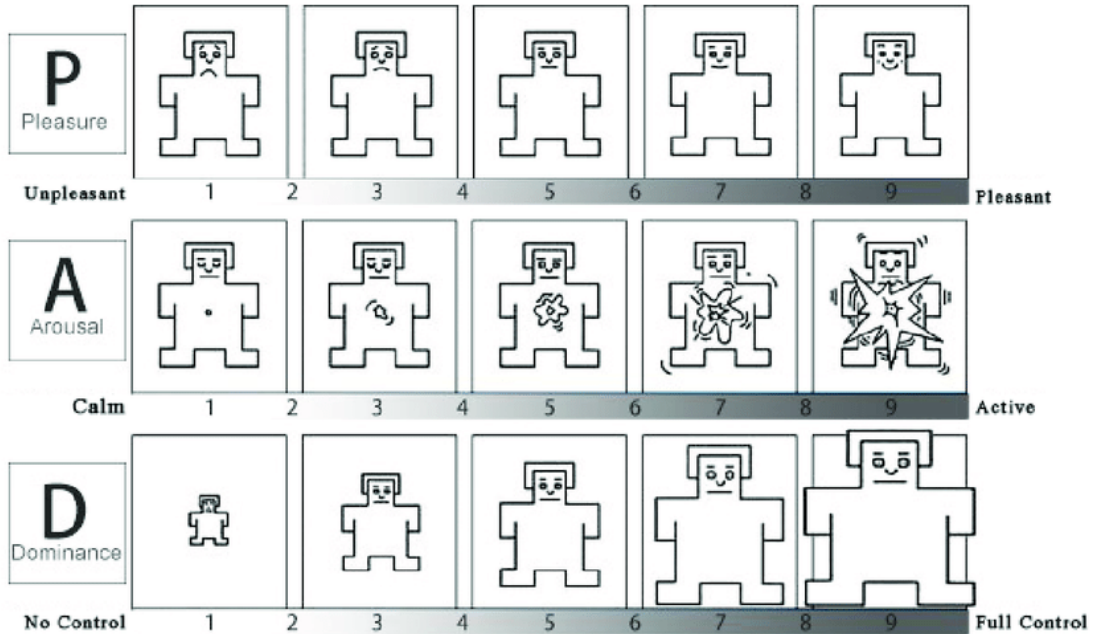


Figure 2.2: Self-Assessment Manikin (SAM) Scale (From [2])

The numbers in the figure represent the scoring range of each dimension, with 1 representing the lowest and 9 representing the highest

2.2. Trust in Automated Vehicles

Trust in automated vehicles (AVs) represents a critical intersection of human-computer interaction (HCI) principles and technological innovation. At many researchers pointed out, trust is not a fixed attribute but a dynamic, evolving construct shaped by continuous interactions between users and systems [125]. To begin with, Muir’s work emphasized that trust forms and adapts through accumulated experiences, where users’ mental status of a system’s reliability are refined over time [126]. Lately, Lee and See introduced the role of context in shaping trust, arguing that situational factors—such as environmental risks or time pressures—significantly influence how individuals rely on automated vehicles (Figure ??) [127]. Hoff and Bashir *et al.* catalogued trust into three layers: dispositional (pre-existing traits like cultural background or age), situational (context-specific factors), and learned trust (evolving through direct interaction) [128]. These models collectively highlight that trust in AVs is not merely a binary state of reliance or skepticism but an interplay of preconditions, real-time experiences, and contextual variables. Crucially, fostering appropriate trust

requires not only that the user perceives the system as trustworthy but also that the system itself is designed to be worthy of that trust. This involves ensuring reliable performance, transparency in its operational limitations, and predictable behavior, which are all essential for the user to calibrate their trust accurately.

Recently, surveys by the American Automobile Association (AAA) reveal that 73% of Americans fear riding in fully self-driving vehicles, with only 20% expressing explicit trust [129]. This skepticism stems from a perceived gap between public understanding of the strength of AV and their actual performance. Bridging this gap, as AAA suggests, requires not only technological advancement but also transparent communication between drivers and Avs, and about how AVs operate [130]. As such, trust has been considered to be critical for the success of automated driving [131, 132]. In current trends, "Limited Self Driving Automation", is one of the most promising autonomous solution on the road [133, 134, 135]. According to National Highway Traffic Safety Administration[136], drivers of L3 vehicles can involve in non-driving related tasks, but must be prepared to take over control within sufficient transition time when necessary, an action referred to as Take-Over Requests (TOR) [137].

A central challenge lies in designing systems that balance trustworthiness with user's caution. This paradox, noted in human factors research, demands interfaces that foster confidence without leading users into false security. As researchers pointed out, the goal is not to maximize trust indiscriminately but to calibrate it—aligning user perceptions with a system's true capabilities [127, 128]. Semi-automated vehicles, for instance, must communicate their operational status clearly enough to keep drivers situationally aware, yet not overwhelm them with excessive alerts. Here, transparency and explainability emerge as critical design principles. External Human-Machine Interfaces—such as visual signals indicating an AV's intent to yield or stop—have shown promise in enhancing trust by making the vehicle's "decisions" interpretable. Similarly, in-car feedback mechanisms that explain AV actions in real-time (e.g., "braking due to obstacle ahead") can demystify automation for passengers. However, poorly executed communication—such as information overload or irrelevant details—risks eroding trust further. For example, pedestrians may distrust an AV displaying

conflicting signals, while drivers bombarded with alerts might disengage entirely [138, 139]. Moreover, there are many factors that can influence trust beyond the AVs: credibility of the system an brand, social influence, performance and reliability and individual differences [140, 141]. Recently, researchers argue against over-reliance on visual modes, advocating multimodal interfaces that integrate auditory or haptic feedback to accommodate diverse user needs, including those with visual impairments [142, 143].

2.2.1. Measurement of trust in Automated Driving Systems

Measuring trust in Automated Driving Systems (ADS) is critical for insights of user acceptance, safety, and effective collaboration between driver and ADS. According to the Society of Automotive Engineers (SAE), ADS process is defined in five levels: from conventional manual driving—no driving automation (SAE Level 0)—through conditional automated driving (SAE Level 3) with the fallback-ready user to the full driving automation (SAE Level 5) (Figure 2.3) [3, 144].

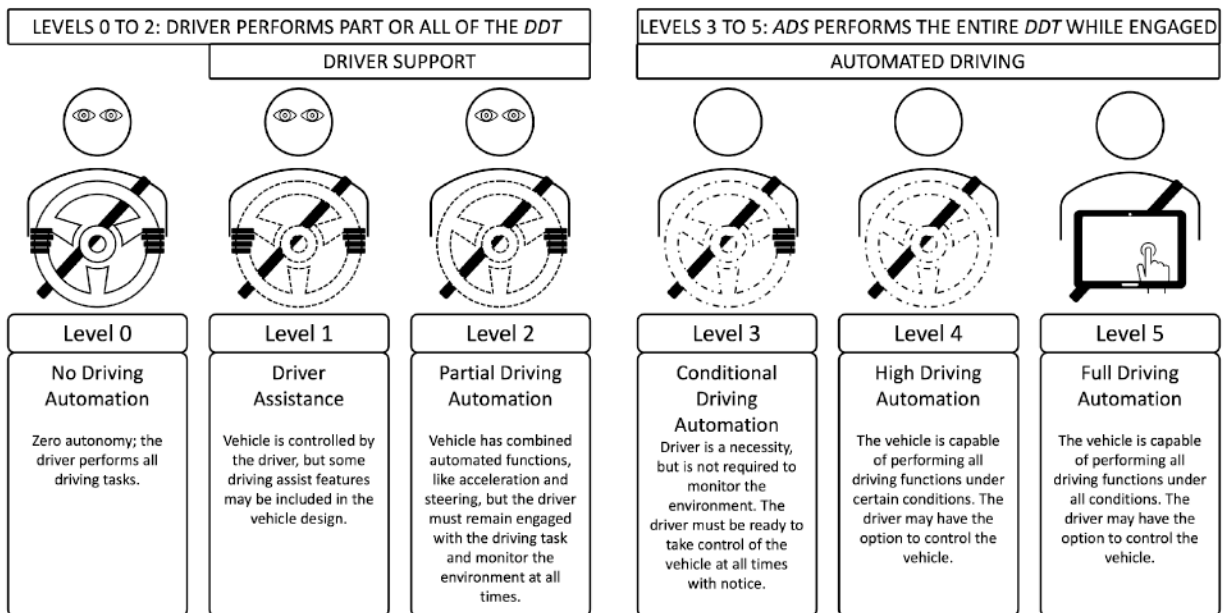


Figure 2.3: Society of Automotive Engineers (SAE) levels for driving automation (From [3])

From a human factors perspective, trust in technical systems and their trustworthiness presents a major challenge. Traditionally, there are several approaches to measure trusts:

- **Self-Report Measures:** Surveys, questionnaires and interviews use scales and open-end questions to asking users directly about their perceptions and feelings toward the system [145].
- **Behavioral Measures:** By observing how users interact with the system, specifically, how users follow system guidance or ignore it[146], how trust impacts task performance’s outcomes (e.g., speed, accuracy, efficiency) [128] and how often users accept or override system recommendations [147], objective observation can be conducted in experimental settings.
- **Physiological Measures:** Physiological responses such as eye tracking, heart rate, skin conductance and facial expression analysis, that can provide insights into implicit trust levels, are widely accepted and applied in automation researches [148, 149, 150, 151].
- **Long-term Trust Measures:** By tracking trust levels across multiple interactions with the system, trust can be measured over time based on system performance and user experience. For example, measure of trust before, during, and after using a new automated driving system, a comprehensive understanding of dynamic trust process can be observed [152].

Trust in ADS is influenced by factors such as reliability, transparency, user experience, and the context of use. By combing multilevel measure approaches, researchers and designers can gain a deeper understanding of trust in ADS and create systems that foster appropriate levels of trust, ensuring both safety and user satisfaction. For instance, scholars measured transparency in automated driving systems. This study underscores the pivotal role of transparency in highly automated driving systems, highlighting the advantages of the Situation Awareness-Based Agent Transparency (SAT) model in enhancing user trust and reliance (Figure 2.4) [4]. The findings demonstrate that interfaces presenting both the system’s actions and future projections (SAT level 1 + 3) significantly increase driver trust and task performance without adding to the cognitive workload, particularly in time-sensitive scenarios. By showing that higher levels of transparency contribute to better trust calibration and collaboration between humans and automation, this research offers actionable insights for designing safer, more intuitive interfaces. These results suggest by fostering transparency

levels to specific driving scenarios, effective communication of automated vehicle behaviors while minimizing user stress and workload can be achieved.

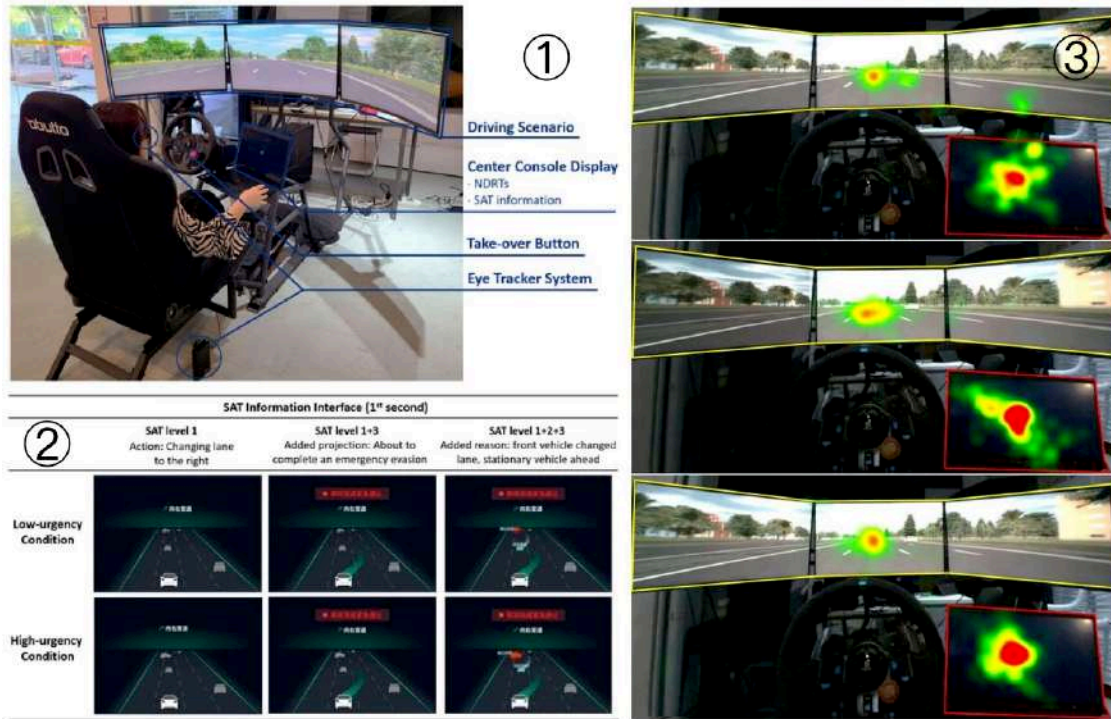


Figure 2.4: The Impact of Transparency on Driver Trust and Reliance in Highly Automated Driving (From [4])

1, Apparatus—driving simulator, center console display, and eye-tracking system.; 2, SAT interface under experimental conditions; 3, Heat maps showing eye gaze duration under SAT conditions. From top to bottom are level 1, level 1 + 3, and level 1 + 2 + 3. Red represents areas of high attention and yellow and green represent areas of low attention.

In this experiment, takeover performance, eye gaze duration and subjective measures of situational trust and work-load were measured as a comprehensive investigation of trust to the automated driving system.

Similarly, the study illustrates that trust in ADS can be enhanced through exposure to a virtual driving simulator, which also incorporated multi-level trust measurement [144]. The use of a driving simulator provided a safe and controlled environment for participants, which positively impacted their trust and acceptance. Specifically, The NASA Task Load Index (NASA-TLX) [153] was used to measure participants' perceived workload during the experiment. In their experiment settings,

participants were only observing the automated system without actively driving, the NASA-TLX provided a way to assess the mental and emotional effort required to monitor the system.

Another research also highlighted the advantages of NASA-TLX approach to measure trust. By combining subjective methods like the NASA Task Load Index (NASA-TLX) and System Trust Scale with physiological measures such as galvanic skin response, the researchers investigated the relationship between trust, automation, and cognitive load in semi-automated unmanned aerial vehicle operation [154]. The results demonstrates the potential of using physiological indicators for real-time trust assessment in automated systems. This approach offers practical insights into enhancing the usability of autonomous systems, especially in critical task environments where trust plays a pivotal role in operational success.

While NASA-TLX is typically used to measure cognitive load, its application in the context of automated driving systems (ADS) is justified. As highlighted by Lee and See, trust in automation is influenced by the user's perception of the system's reliability and their own mental workload [127]. When users experience lower cognitive load, they perceive it as less demanding and more reliable, which likely leads to trust the system. Conversely, users may feel overwhelmed or uncertain about the system's capabilities under high workload, which results in distrust. This relationship is particularly relevant in the context of Level 3 (L3) automated vehicles, where drivers must remain situationally aware and ready to take over control when necessary. A recent study by Morra *et al.* of evaluating trust in AV under multi-modal VR simulations, The core strategy to build trust lies on transparency in HCI design [155]. They suggested transparency influences stress levels , cognitive load, and post-experience trust ratings. In their research approach, integrating NASA Task Load Index (NASA-TLX) aligns with its goals and could strengthen trust assessment. While NASA-TLX does not directly measure trust, a lower perceived workload can be an indicator of a fluent and positive user experience, which is a necessary, though not sufficient, condition for building trust. This approach is adopted here to provide a preliminary, indirect insight into user acceptance, acknowledging that future work should complement these findings with dedicated trust scales.

NASA-TLX provides a quantitative measure of cognitive load, offering insights into how the sys-

tem’s design and interface impact the user’s trust. In addition, the multi-dimensional nature of NASA-TLX—which includes mental demand, physical demand, temporal demand, performance, effort, and frustration—allows for a comprehensive understanding of the user’s experience. This aligns with the dynamic and multi-faceted nature of trust, that is influenced by various factors such as system reliability, transparency, and user experience. By incorporating NASA-TLX into the measurement framework, this dissertation aims to provide a holistic understanding of trust is impacted in automated driving systems.

In this dissertation, trust is not directly measured through a dedicated trust scale but is inferred from perceived cognitive workload using the NASA Task Load Index (NASA-TLX). While NASA-TLX does not explicitly quantify trust, prior studies (e.g., Khastgir *et al.* and [40] Chien *et al.* [41]) have demonstrated that lower perceived mental workload is often associated with system transparency, acceptance, and user confidence—which are closely related to trust in automated systems. Thus, following this methodological approaches, NASA-TLX is applied as an indirect proxy for evaluating user trust and acceptance in takeover request scenarios.

2.3. Touch and haptic interaction

The human sense of touch refers to the spatiotemporal perception of external stimuli through a large number of receptors (e.g., mechanoreceptors—for pressure/vibration, thermoreceptors—for temperature, and nociceptors—for pain/damage [156]) that are distributed all over the body with variable density (Figure 2.5) [157, 158, 159, 160, 161, 162] . The response to mechanical stimulus is mediated by mechanoreceptors that are embedded in the skin at different depths. They distributed estimated to be over 200 in the fingertips and over 50-per square centimeter area-in the palm of adult [163]. From the moment skin is stimulated until the resulting perception, a variety of complex mechanical, perceptual, and cognitive phenomena take place: On contact with an object, the skin conforms to its surface, and projects the deformation to a large number of mechanoreceptors. Each mechanoreceptor thus represents a small portion of the object and encodes the spatiotemporal tactile information as spikes of action potentials-voltage pulses generated when the stimulus is greater than a threshold. The amplitude of the stimulus is then transformed to a train of action potentials—a

step similar to digitizing and coding analog signals by an analog-to-digital (A/D) convertor [164].

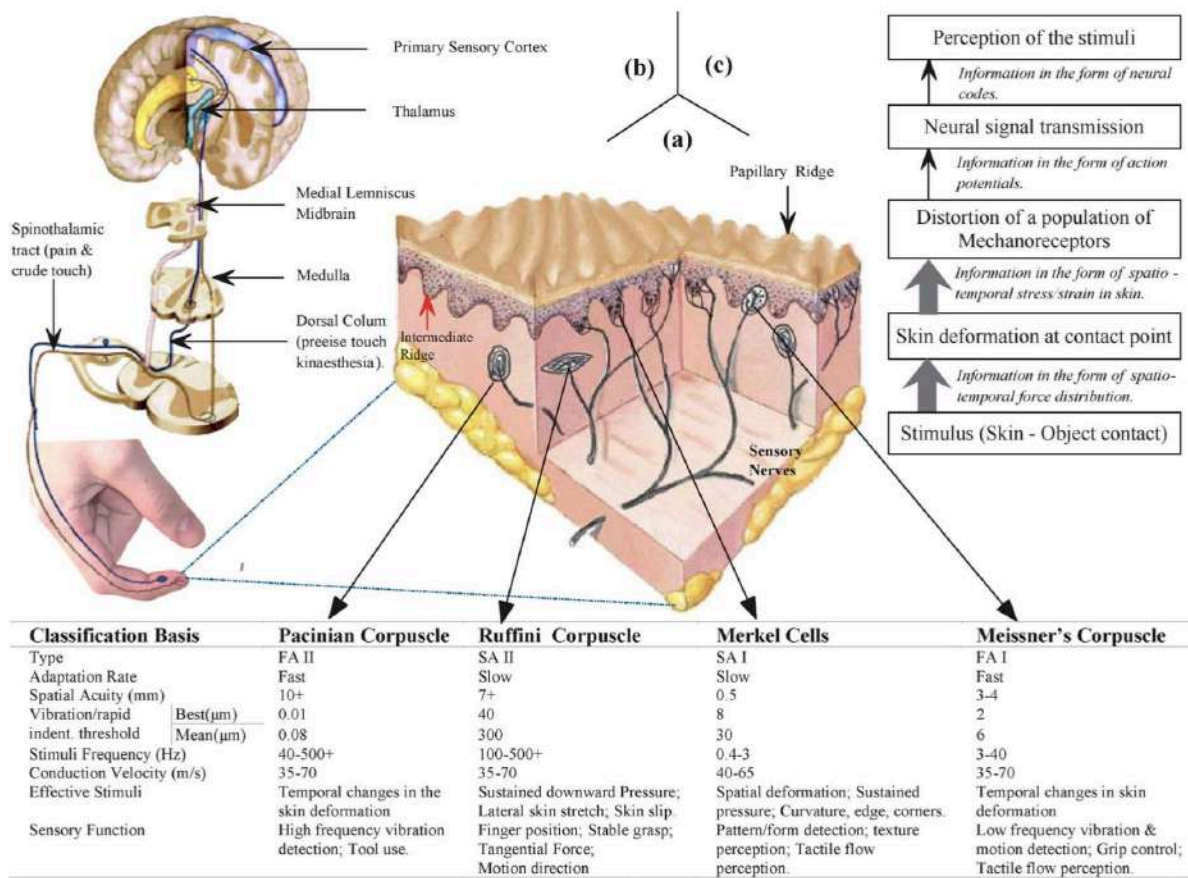


Figure 2.5: Physiological mechanism of touch

(a) Physical location and classification of various mechanoreceptors. (b) Tactile signal transmission from fingertips to somatosensory area of brain. (c) Functional events during tactile signal transmission from contact point to the brain.

The pressure threshold and skin deformation are the most common intensive measures of absolute tactile sensitivity, that gives the concepts of pressure resolution [165]. The higher the pressure threshold, the lower the sensitivity of the body part. Controlled pressure sensitive studies show that pressure thresholds vary with body site. Whereas normal mean threshold values average about 0.158 g on the palm and about 0.055 g on the fingertips of men, the corresponding values for women are 0.032 g and 0.019 g, respectively [166].

On the other hand, temperature sensitivity at the fingertips detects changes of 0.16°C and 0.12°C

for warmth and cold from a baseline temperature of 33°C [167]. These physiological distinctions highlight why the fingertips, as the body's most sensitive tactile interface, dominate our conceptual understanding of touch [168].

In traditional human-computer interaction, vision and audio have dominantly shaped user experiences. However, touch introduces an extra dimension by offering direct, physical feedback, thereby enhancing immersion. Through haptic feedback, users can perceive textures, temperatures, forces etc., leading to a more embodied and engaging interaction. As highlighted by Wang *et al.*, advanced haptic displays enable bidirectional communication between humans and computers, allowing users to experience physical properties such as stiffness, roughness, and texture within a virtual space, thereby greatly enhancing the sense of realism and presence in VR environments[169].

2.3.1. From touch to haptic interaction

The term haptic (originally from the Greek hápto) is the adjective used to describe the ability related to or based on the sense of touch. In the study of human-computer interaction, it refers to the science of all that is relative to tactile sensing and its perception as a means of control and interaction [170]. The information from the haptic sense comes from the active and voluntary manipulation of objects in the environment made from fingers and hands and involves the sense of tact and the perception of the body's movement known as kinesthesia. Typically, in object manipulation, the tactile component involves both static (accumulated) data and the signals detected by the skin's nerve terminals. Kinesthetic, meanwhile, refers to the dynamic aspects of said interaction with the object [171, 172]. Haptic interaction enables human-machine communication through touch (as well as tactile sensory in any part of skin), and mostly commonly, body movement, kinesthesia, position and even weight [173]. Moreover, the thermal sense-the perception of temperature changes through specialized receptors [174] and the piezoelectric-the nature of electrical discharge from various receptors in response to the external stimuli on the skin [158] also contributes to the complexity of touch sensations. While "touch" refers to the basic sensory experience of physical contact, "haptic interaction" encompasses a broader concept: tactile sensation, kinesthetic movements, thermal stimulation, piezoelectric interaction and even spatial resolution. This combination enables users to

feel and project physical properties beyond surface contact, such as weight, resistance, motion, temperature and more. Over-in-all, haptic is leading the human-computer experience to more immersive and natural interactions with new innovative technology.

Early developments of haptic technology primarily focused on vibrotactile feedback, utilizing mechanical vibrators to simulate tactile sensations. Especially, mobile phones employed small motors to provide users with alert modes. In the study by Brewster *et al.* [175], the researchers explored the effectiveness of vibrotactile feedback for touch-screen keyboards on PDAs, particularly in scenarios such as using a mobile device in a moving train. The study pointed out that vibrotactile feedback noticeably improved text entry performance, that users to input more text while making fewer errors. These findings suggest that vibrotactile feedback enhances user awareness and interaction accuracy in complex environments with high visual or auditory distractions. However, the researchers suggested though vibrotactile feedback was beneficial in controlled laboratory conditions, its advantages were less successful in real-world mobile scenarios where physical environmental factors like train vibrations interfered with the effectiveness of the vibrotactile feedback. Similarly, Bial *et al.* investigated vibrotactile feedback in outdoor navigation systems for motorcyclists, to whom traditional visual and auditory cues are limited due to lighting conditions and background noise (Figure 2.6) [5]. They tested different actuator placements on the hand and various vibration patterns to encode directional and distance information. The study suggest that vibrotactile signals could effectively supplement navigation tasks with minimal cognitive load, though accuracy varied based on actuator placement, with fingertips being the most effective location for perception. However, both studies pointed out some limitations of vibrotactile feedback. While it excels in providing discreet, non-visual cues, its bandwidth for conveying complex information is relatively low. Additionally, environmental factors such as train/vehicle vibrations reduce effectiveness. Both studies pointed out that it may require increased cognitive effort in distinguishing signals in real world, making it less reliable in high-demand tasks.

Before the widespread adoption of advanced pneumatic haptic systems, researchers explored pneumatic interfaces as an alternative to vibrotactile feedback to provide more nuanced tactile sensations.

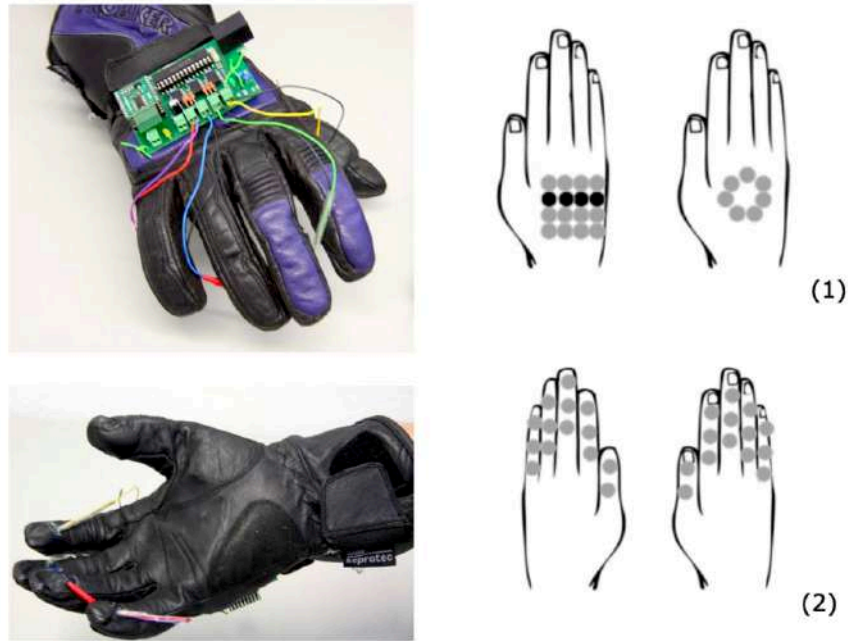


Figure 2.6: Navigation glove for motorcyclists (From [5])

Arrangement of vibration actuators: (1) Back of the hand. Actuators can be arranged in a circle or matrix, allowing vertical / horizontal patterns. (2) Fingers. Actuators can be arranged on the fingers / thumbs or on the back of the hand.

One early example is the work by Moy *et al.* [176], who developed a pneumatic glove for virtual reality applications. This system used small inflatable air bladders embedded in the glove to simulate the sensation of touching virtual objects, offering variable pressure to mimic different textures. The study demonstrated that pneumatic actuation could deliver more complex tactile feedback than vibrotactile motors, though the system required bulky external air pumps, limiting its practicality. Another significant development was by Kim *et al.* [177], who introduced a pneumatic tactile display for medical simulation. Their device used an array of inflatable cells to replicate the sensation of palpating tissue, allowing medical trainees to practice diagnostics without physical models. The system showed promise in delivering localized pressure cues but faced challenges with response time due to the slow inflation and deflation of air cells. Additionally, Gemperle *et al.* [178] explored wearable pneumatic haptic interfaces for navigation aids, embedding air pockets in a vest to provide directional cues through pressure changes. Their findings indicated that pneumatic feedback was effective for coarse directional signals but struggled with precision in dynamic environments due to

latency in air pressure adjustments. These early pneumatic systems laid the groundwork for more advanced interfaces by demonstrating the potential for richer haptic feedback, despite limitations in portability and control precision.

Recent advancements led to the development of pneumatic haptic systems, which use air pressure to create haptic feedback. A research project by Zhang *et al.* [179] introduced In-Flat, a pneumatic haptic interface that enhances smartphone interactions using a transparent, inflatable silicon overlay. The system allows press and pinch-and-pull gestures by dynamically adjusting air pressure, providing bi-directional haptic feedback. From the experiment results, they concluded that users could perform pinch-and-pull as accurately as press gestures, despite their unfamiliarity with the technique. Participants also felt greater control with pinch-and-pull, as the silicone's deformation provided additional resistance cues. Moreover, the integration of visual and tactile feedback significantly enhanced the perception of on-screen interactions, making digital experiences more immersive. They also admitted that higher pressure inputs were challenging to control, leading to reduced accuracy and stability. Additionally, though the transparent overlay maintained visual clarity, inflated airbags could partially obstruct screen content. The need for external air pumps also limited the system's portability, making it less practical for fully mobile applications.

A research project by Talhan *et al.* introduced a soft pneumatic haptic wearable designed to create the illusion of human touch in virtual reality (VR) environments [180]. The system uses soft pneumatic actuators (SPAs) embedded within a wearable jacket to mimic realistic touch gestures such as grabbing, touching, tapping, and tickling. The actuators are made from silicone rubber, this provides a skin-like texture and elasticity, and are controlled via pneumatic mechanisms to deliver both static pressure and vibration. Experiments demonstrated that the system could effectively mimic human touch, with participants finding the artificial stimuli difficult to distinguish from real human touch, making it suitable for applications in VR, telemedicine, and social tele-interaction. However, the authors acknowledged several limitations, including the need for multiple valves to control the SPAs, which increases hardware complexity and weight. The system's reliance on external air supply units also limits its portability. The calibration of SPA positioning and alignment

with the user's body requires further refinement to improve the accuracy and comfort of the haptic feedback.

The latest trend in haptic technology involves multimodal systems that combine vibrotactile, thermal, and visual stimuli to deliver richer sensory experiences, enabling a broader range of emotional feedback within human-computer interactions [181]. For example, soft actuators and sensors are integrated to mimic the tactile sensations of real-world interactions, enhancing user engagement. A research project by Günther *et al.* introduced PneumoVolley, a VR-based haptic system that uses pneumatic actuators to deliver pressure-based feedback on the head [182]. The system employs inflatable air cushions placed around the head to simulate the impact forces experienced during a volleyball game. The study suggested that pneumatic actuation significantly increased user involvement and immersion in VR compared to a no-haptics experience, and the participants rated the pressure-based feedback realistic and highly enjoyable. The study, which underscores the potential of pneumatic haptic interfaces to create immersive and realistic haptic feedback, aligns with the broader trend of integrating multimodal haptic systems where pneumatic actuation is combined with other feedback mechanisms to deliver more immersive and lifelike interactions.

In parallel, the development of bio-degradable biomaterials for soft robotics and haptic interfaces is gaining attention as a sustainable alternative to traditional materials like vinyl and silicone. For example, Helińska explores the use of biopolymers such as gelatin, agar, and alginate for prototyping inflatable actuators [183]. These materials offer unique properties such as organic textures and accessibility, making them suitable for workshops, art installations, and educational projects. Though bio-materials currently face challenges in terms of durability and consistency compared to synthetic counterparts, their potential for reducing environmental impact is significant. The integration of innovative sustainable materials into pneumatic haptic systems could advance the way for more eco-friendly and innovative designs, further inspiring new haptic experience while aligning with the growing emphasis on sustainability in HCI and related fields.

2.3.2. Pneumatic haptic interaction in movie experiences

Haptic interaction in movie experiences is an innovative approach to enhance movie audience engagement by incorporating haptic feedback into on-screen entertainment. This allows viewers to feel physical sensations that correspond to on-screen events, creating a more immersive and multisensory experience.

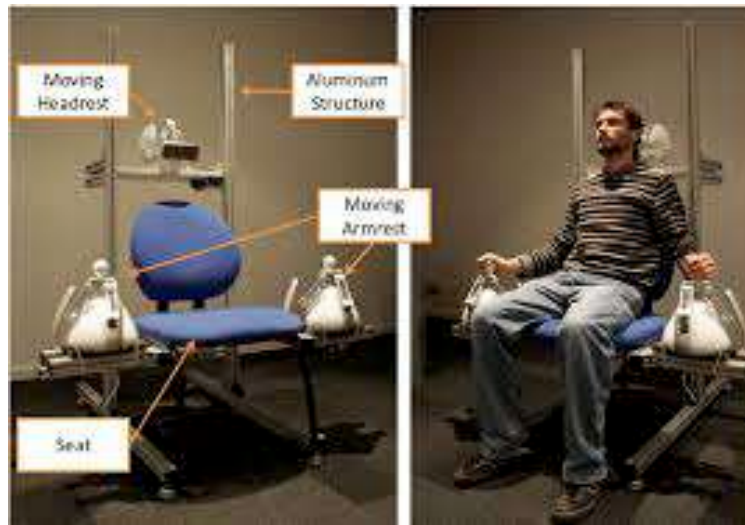


Figure 2.7: Prototype of the HapSeat (From [6])
Left: seat structure with 3 force-feedback devices. Right: the system in use.

Nowadays, 4D movie experiences, which extend traditional 3D cinema by integrating physical effects such as seat motion, vibrations, wind, water sprays, and other haptic stimuli synchronized with audiovisual content, represent the most developed application of haptic interaction in cinematic settings, offering multisensory entertainment that intensifies emotional responses [184, 185]. Recent studies have explored various aspects of this technology. Lee *et al.* [186] investigated the relative contributions of visual and vestibular systems in self-motion perception during simulated roller coaster rides. Jeong *et al.* [187] examined the relationship between viewer empathy, seat motion intensity, and perceived affect in 4D movies. Another notable study aimed to enhance movie experiences by simulating camera-based effects such as Crane Shot and Dutch Angle (Figure 2.7)[188, 6]. However, these studies primarily focus on kinesthetic experiences through the movement of the audience's seats [189], leaving other haptic modalities unexplored.

While haptic studies showed promise, they were limited in conveying complex tactile sensations—such as varied textures, dynamic pressure changes, or subtle surface interactions—using vibrotactile motors, which primarily produce simple vibrations, or kinesthetic mechanisms, which focus on large-scale movements like seat tilting [190, 191]. These constraints, which restrict the ability to replicate tactile experiences, e.g. a textured surface, have motivated research into pneumatic haptic interfaces for movie experiences, as such systems can deliver a wider range of tactile sensations—such as pressure, texture, and rhythmic inflation—thereby supporting more immersive and emotionally engaging audience experiences.

Pneumatic haptic interfaces offer noticeable advantages in movie experiences by enabling dynamic and versatile haptic feedback. In contrast to vibrotactile or kinesthetic systems, pneumatic haptic systems can replicate a diverse array of tactile sensations, making them ideal for delivering immersive and non-intrusive haptic experiences in cinematic environments. Moreover, pneumatic haptics can be seamlessly integrated into existing seats or wearable devices, offering a practical solution for enhancing 4D movie experiences.

A notable study by Ablart *et al.* [7] explored the integration of mid-air haptic feedback ¹¹ into short movie experiences—"one-minute movies"(Figure 2.8) Researchers used ultrasonic transducers to create mid-air haptic sensations, synchronizing with key emotional moments in the movies. The research findings suggest that mid-air haptic feedback significantly enhanced viewers' emotional arousal and immersion, particularly during the first-time viewing. The study demonstrated that mid-air haptics, even when not perfectly synchronized with the movie's emotional peaks, could enhance the viewing experience, opening up new possibilities for designing haptic feedback in cinematic contexts.

Pneumatic haptics have also been applied in virtual reality (VR) to create movie-like entertainment experiences, expanding the scope of 4D cinema. For example, FlowGlove, a liquid-based wearable device developed by Liu *et al.* [8], combines pressure, vibration, and temperature sensations for

¹¹Mid-Air Haptic Feedback refers to the haptic feedback that are created in the air without requiring physical contact between the user and the device's interface. This project applied ultrasonic waves to stimulate the user's skin, creating the sensation of touch without physical contact.

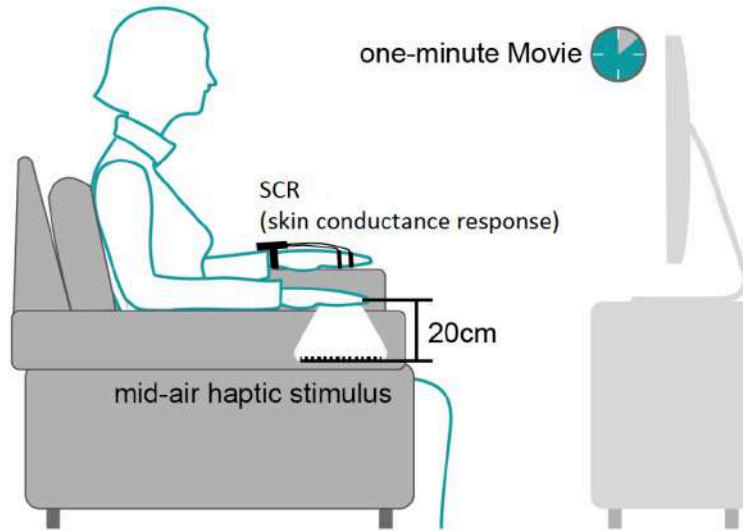


Figure 2.8: Experiment settings of mid-air haptic movie experience (From [7])
 The user with on the left hand the Shimmer2 GSR device (recording the galvanic skin response) and the right hand above the mid-air haptic device.

VR haptic interactions (Figure 2.9). This device uses water flow in a liquid bladder and a water-cycling system to deliver sensations of touch, fondle, and grip through pneumatic actuation and vibration. In a VR game context, FlowGlove provided immersive feedback, simulating movie-like scenarios where users feel physical interactions with the environment. Similarly, Barreiros *et al.* [192] developed a hardware controller with fluidic elastomer actuators at Cornell University. Participants reported lower perceived delays between actions and haptic outputs, as well as enhanced realism in gameplay, suggesting that such controllers could enrich VR-based cinematic narratives. These VR applications take advantages of pneumatic systems for their ability to produce volumetric shape changes, enabling the simulation of complex tactile sensations—such as the soft inflation of a frog’s vocal sac or the raised hedgehog’s spines—that are difficult to replicate using conventional vibrotactile actuators.

Surface texture is a remarkable aspect of haptic feedback that can enhance the realism and emotional rendering of movie experiences. For instance, in a scene where a character is running through a forest, pneumatic haptics could simulate the sensation of leaves brushing against the skin, adding



Figure 2.9: FlowGlove (From [8])

a. Appearance of FlowGlove; b. Internal structure of FlowGlove; c. Application in VR game.

a layer of sensory detail that enhances the viewer’s immersion. By incorporating surface texture into pneumatic haptic systems, filmmakers can create more engaging and emotionally-profound experiences, opening new possibilities in cinematic experiences. This calls the need to explore new bio-inspired haptic modalities that can provide a wider range of haptic interactions in emotional movie contexts.

2.3.3. Pneumatic haptic interaction in non-verbal communication

Haptic interaction, plays a significant role in non-verbal communication, conveying emotions, and social cues that beyond words can express. It is a powerful form of human interaction that can strengthen relationships, establish trust, and provide comfort. Such promising approaches are worthy for receiving more and more attentions for many reasons: first, scientists of social psychology and cognition suggested that approximately 60-65% of social meaning is delivered from non-verbal behaviors [193]. Supporting studies can be found in infants and children education [194, 195]. Liu *et al.* considered the abundant information conveyed by gestures on haptic interface, through innovative devices providing haptic interactions, which showed that haptic interaction in non-verbal communication can deeply impact the way we communication and collaborate. Inflated pads were applied in this research for simulating interpersonal touch in a context of face-to-face communication yet maintaining certain distance for the reason of airborne diseases [196]. LumiTouch, an inflatable photo frame also presented an inflatable user interface for social communication [197]. Hu *et al.* from Cornell University introduced an emotionally expressive robot that communicates using dynamically changing skin textures (Figure 2.10)[9]. This robot demonstrated specific texture-to-emotion

mappings, using texture shape to express emotional valence and texture movement frequency to convey emotional arousal. Similar project as FELT also emphasized the role played by the texture of a computational textile plays in emotion communication [198].

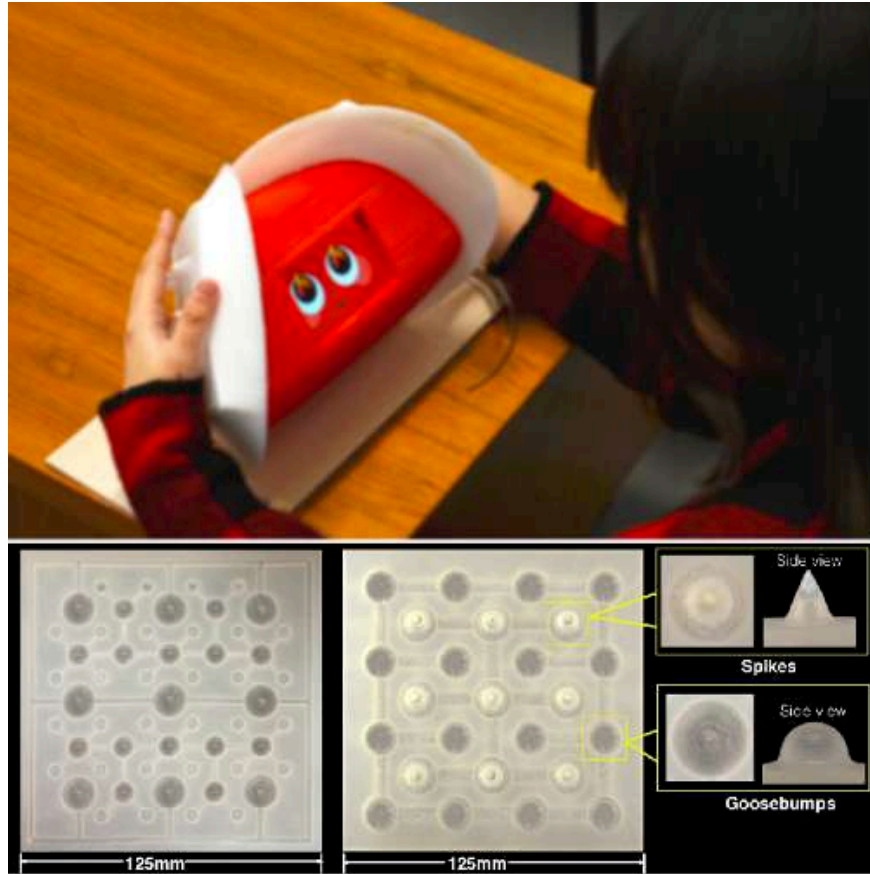


Figure 2.10: Goosebumps robot (From [9])

UPPER: A social robot prototype combining facial expressions and a texture- changing skin. During the interaction, the user makes eye contact with the screen face and puts their palms on the sides of the robot to touch the actuated textures. DOWN: Two socially expressive Texture Modules: multi-scale Goosebump Texture Units (TUs) (left) and a mixture of Goosebump and Spike TUs. Each set of TUs is controlled separately via a fluidic conduit network.

2.3.4. Pneumatic haptic interaction on steering wheel in automated driving system

Haptic interaction on the steering wheel in automated driving systems (ADS) is an emerging area of research that aimed at enhancing user experience, safety, and trust. As technology advances, haptic feedback will become more sophisticated, personalized, and integrated into the broader ecosystem of connected and autonomous vehicles.

Recent research has explored diverse haptic feedback modalities on steering wheels to convey driving-related information. For example, Kern *et al.* [199] investigated how vibrotactile cues could support navigation by delivering directional signals through the steering wheel, finding that combining tactile feedback with auditory and visual cues enhanced driving performance. San Vito *et al.* [10] introduced an innovative "cutaneous push" mechanism, which applies localized pressure or force to the skin's surface through mechanical actuators to simulate tactile sensations like contact or touch, comparing it to thermal cues in a controlled study (Figure 2.11). They found that cutaneous push signals led to fewer errors but had higher workload ratings, suggesting that haptic feedback should be effective yet comfortable. Although vibrotactile feedback is widely studied, pneumatic feedback represents an emerging alternative with unique benefits. For instance, Enriquez *et al.* [200] investigated the use of a pneumatic tactile system in a driving environment to alert drivers to potential issues. The experiment results suggest that pneumatic cues in steering wheels could improve driver alertness and reaction time, especially when visual and auditory channels were heavily occupied, highlighted the potential of pneumatic tactile systems to improve driver alertness and response time in challenging driving conditions.

We believe as automated driving systems continue to evolve, haptic interaction on steering wheels is likely to play an increasingly important role in enhancing driver awareness, safety, trustworthy and overall driving experience.

2.4. Affective Human-Robot Interaction (HRI)

2.4.1. From functional to affective HRI

Human-Robot Interaction (HRI) has evolved significantly from its early focus on functional task execution to a domain that increasingly prioritizes affective communication, aiming to create emotional interactions with users [201] [202] [203]. This shift reflects a growing recognition that robots, as social agents, must convey and interpret emotions to foster intuitive, trust-rich exchanges [204] [205]. Affective HRI seeks to bridge the gap between mechanical functionality and human-like expressivity, aligning robotic behaviors with the emotional and social expectations of users [205]. By integrating emotional cues into robotic systems, affective HRI enhances user engagement, pro-



Figure 2.11: Thermal and Vibrotactile Notifications on the Steering Wheel (From [10])
Upper: Thermally-enhanced steering wheel with small Peltier elements; Down: The set-up of the navigation studies.

notes naturalistic interaction, and supports applications ranging from assistive robotics to social companionship.

2.4.2. Emotion Recognition in HRI

Emotion recognition forms the cornerstone of affective Human-Robot Interaction (HRI), enabling robots to interpret human emotional states through diverse modalities. Traditional approaches have predominantly relied on visual and auditory channels—such as facial expression analysis, vocal prosody, and gesture recognition—to convey and interpret robot intentions and emotions. For example, facial emotion recognition (FER) employs deep neural networks trained on datasets like AffectNet to classify emotions such as happiness, sadness, or anger based on facial features [1]. Similarly, vocal prosody analysis interprets emotional cues through pitch, tone, and rhythm, while gesture-based methods use body movements or hand signals to infer affective states [23, 22]. These

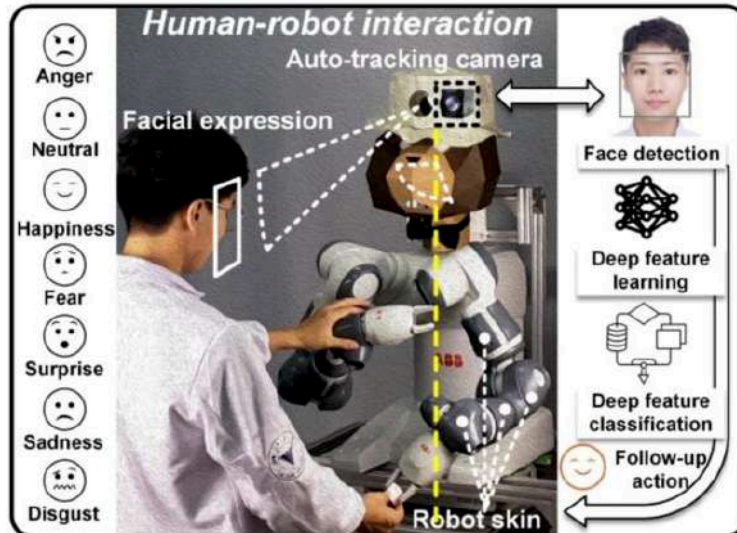


Figure 2.12: Emotional recognition and friendly physical contact based human-robot interaction (HRI) (From [11])

modalities are widely implemented in social robots like NAO and Pepper to support task-oriented and social communication [24].

Although widely used, traditional visual and auditory modalities can increase cognitive load and are often insufficient for conveying the subtle, embodied emotional experience found in natural human interaction [206, 207]. Synthesized speech, for instance, might simulate happiness through tone but lacks the visceral impact of a human voice [23], while visual cues such as LED displays are limited in expressing low-arousal emotions like sadness, which rely on subtler embodied signals such as posture or motion rhythm [171]. However, as Elfenbein *et al.* pointed out, while these modalities provide valuable data, their effectiveness can be limited by cultural variability and contextual ambiguity, necessitating more robust approaches (Figure 2.12) [94].

To address these challenges, physiological sensing has emerged as a promising adjunct to traditional modalities. This approach captures physiologically-inspired biological signals—such as heart rate, skin conductance, and brain activity—through wearable sensors or brain-computer interfaces (BCIs) [208]. By directly accessing the user’s internal affective states, physiological signals bypass the ambiguities of external expression. For example, electroencephalography (EEG) has been employed

to decode neural patterns associated with emotional valence and arousal, enabling high temporal resolution suitable for real-time affective HRI applications (Figure 2.13)[12]. Nonetheless, the integration of physiological sensing in everyday HRI still faces technical hurdles, such as signal noise and the need for user-friendly, non-invasive hardware.



Figure 2.13: A 21-channel OpenBCI electrode cap kit (From [12])

2.4.3. Embodied and Tactile Non-Verbal Interaction

Multimodal HRI systems that integrate physiologically-inspired and voluntary signals represent a frontier in affective computing, drawing inspiration from biological communication. Embodied and tactile non-verbal interactions address key gaps in social presence by leveraging physical expressivity and touch. Bio-inspired designs, such as pneumatic actuators simulating breathing or heartbeat rhythms, externalize internal physiological states to create a sense of lifelike presence [9]. These physiologically-inspired cues, delivered through soft silicone interfaces, mimic natural rhythms like chest expansion or cardiac pulses, providing subtle, low-cognitive-load signals that enhance emotional expressivity without demanding active user attention [209, 210].

Physical movements—such as a robot’s gentle tilt or rhythmic motion—mimic human body language, fostering a sense of aliveness and emotional connection [9]. Tactile interaction, in particular, offers a direct, intuitive channel for communication, as touch is inherently tied to human social bonding [171]. By simulating human-like tactile sensations, robots can evoke emotional responses that feel immediate and authentic, strengthening user trust and engagement. For instance, a soft robotic arm delivering a gentle squeeze can convey reassurance, aligning with human expectations of social touch [211].

When combined with gestures and arm movements, the physiological-inspired cues create a richer communicative framework that mirrors human social interaction patterns, enhancing both emotional and interaction quality. The use of physiological-inspired cues in HRI offers significant advantages for non-verbal emotional communication. Unlike visual or auditory signals, which often require conscious processing, bio-rhythmic inflation operate at a subconscious level, evoking intuitive emotional responses (Figure 2.14) [212]. For example, a soft robotic chest pulsating at a calm breathing rate can signal tranquility, reducing user anxiety during interaction [213]. This low-cognitive-load approach is particularly effective for conveying different emotions, such as sadness or calmness, which are challenging to express through traditional modalities alone. As Meng *et al.* pointed out, low-cognitive-load cues such as physiologically-inspired expressions can significantly enhance non-verbal emotional communication by fostering a more lifelike and emotionally resonant robot presence. Their study introduced a multimodal skin-based system for a communication robot that simulated instinctive fear responses—goosebumps, sweat, and shivers—through actuated thin rods, vibration motors, and a water-based mechanism [214]. These bio-rhythmic expressions, inspired by human physiological reactions, required no conscious interpretation from users and conveyed emotional states in a subtle yet powerful manner. By combining these cues, the robot was able to evoke complex affective impressions, highlighting how physiological-inspired, embodied signals can serve as intuitive, low-effort communication channels that enrich human-robot interaction.



Figure 2.14: A soft robot surface that can breathe [13]

2.5. Baromorphs

This section introduces "baromorphs," a class of bio-inspired pneumatic shape-morphing elastomers developed by Siéfert *et al.* [27], the thin elastomeric plate embedded with a network of airways that enable fast, controllable, and reversible 3D shape morphing through pneumatic actuation (inflation or suction). The shape-changing transformation is achieved by programming the geometry of the airways and controlling the applied pressure, enabling the Baromorph to mimic the differential growth seen in natural structures like petals and leaves. The technique promises aerodynamic expansion or contraction by pressurizing or depressurizing interconnected channels. By spatially varying channel density and orientation, complex 3D shapes—such as cones, saddles, or helicoids—can be programmed into the flat sheet (Figure 2.15). The approach combines principles from soft robotics and bio-inspired morphogenesis, offering rapid actuation (up to 3 Hz) and scalability across sizes, from millimeters to meters, depending on material selection and fabrication precision.

2.5.1. Principle and fabrication

Baromorphs operate on principles inspired by biological morphogenesis, where differential growth—uneven expansion or contraction across a structure—generates complex 3D shapes. In biological systems, such as plant leaves or flower petals, cells grow anisotropically (directionally) due to localized fiber alignment or hydration gradients. Similarly, Baromorph achieve shape morphing by embedding a network of air channels within a soft elastomer. When pressurized, these channels expand or



Figure 2.15: Baromorph made from silicone

contract anisotropically, creating controlled local strains that induce buckling or bending in the plate.

The key physics lies in the anisotropic strain generated by the channel geometry. A channel inflates more in the direction perpendicular to its length (transverse strain, ϵ_{\perp}) than along its axis (longitudinal strain, ϵ_{\parallel}), due to the constraints imposed by the surrounding elastomer walls (Figure 2.16).

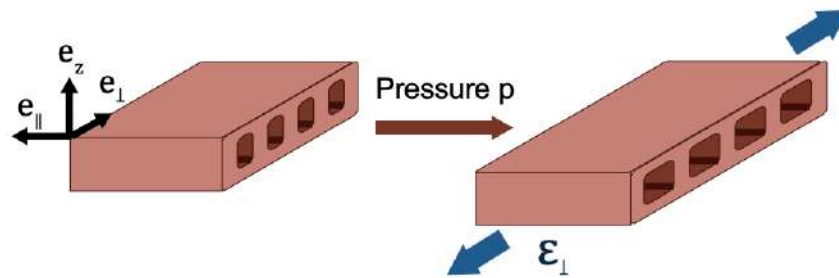


Figure 2.16: Principle of pressure actuated Baromorph plate

This behavior is governed by Hooke's law and stress equilibrium in the elastomer. For incompressible materials (Poisson's ratio $\nu \approx 0.5$), longitudinal strain is negligible ($\epsilon_{\parallel} \approx 0$), while transverse strain depends on the channel's relative height ($\Psi = h/h + 2e$), where h is channel height and e is membrane thickness) and in-plane density ($\Phi = d/d + d_w$), where d is channel width and d_w is wall

width). The resulting strain field mimics differential growth: regions with denser or taller channels expand more under pressure, while sparse or shallow channels remain relatively rigid. The 3D shape emerges from a competition between stretching and bending energies. When pressurized, the elastomer adopts a new "target metric" defined by the channel-induced strains. If the target metric is incompatible with a flat configuration (e.g., requiring Gaussian curvature changes), the plate buckles out-of-plane to minimize elastic energy. For example, radial channels induce circumferential expansion, leading to conical shapes (positive curvature), while azimuthal channels produce saddle shapes (negative curvature). The transition between shapes is governed by the Föppl-von Kármán equations for thin plates, which balance stretching and bending forces.

Baromorphs are fabricated using a 3D-printed mold to cast the elastomer. The process:

1. **Mold Design:** Channels are patterned in software (e.g., Rhinoceros, AutoCAD Fusion 360) to achieve desired strain distributions. Critical parameters include channel width (d), spacing (d_w), and depth (h).
2. **Elastomer Casting:** A two-part silicone is poured into the mold. Vacuum degassing removes trapped air bubbles.
3. **Curing and Sealing:** After curing, a flat elastomer layer is bonded to the molded structure to seal the channels, forming an airtight network.
4. **Actuation:** Pressurizing or depressurizing the channels via an external pump induces shape changes.

The method emphasizes scalability—structures ranging from millimeters to meters can be fabricated by adjusting mold dimensions. However, precision is critical: minor defects in channel alignment or sealing can disrupt airflow and strain uniformity.

2.5.2. Advantages and Drawbacks

In practical applications, Baromorphs demonstrate notable advantages. Their ability to achieve precise shape changes with minimal air volume makes them ideal for agile, palm-sized interfaces.

The technique enabled precise height adjustments through controlled inflation, critical for dynamic haptic feedback, that benefits in our first project in Chapter 3. Additionally, the strong adhesion properties of the elastomer surface facilitated the integration of external components, such as textured elements or sensors, without compromising structural integrity. These features align with the project’s emphasis on reversible actuation and compatibility with functional surface modifications.

What’s more, fabrication complexity challenged our tryouts: creating defect-free molds for intricate airway networks required high-resolution 3D printing and meticulous alignment, leading to frequent failures and inconsistent quality. We encountered unexpected defects during mold production, underscoring the sensitivity of the technique to manufacturing tolerances (Figure 2.17). These issues underscored the disparity between theoretical scalability and practical usability in confined settings .

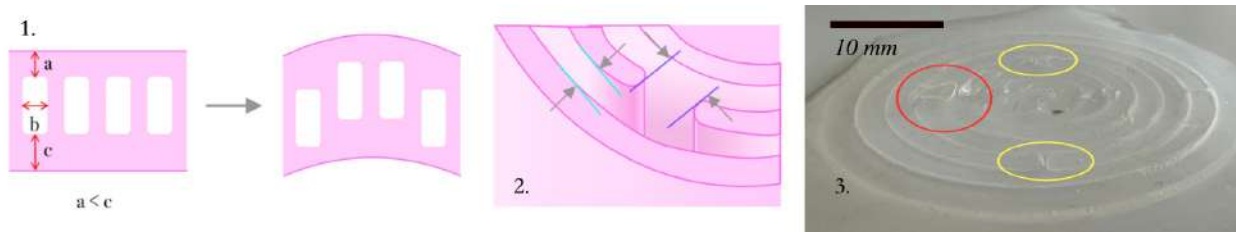


Figure 2.17: Common Baromorph defects

1. For directional shape-changing, the dimensions of Baromorph need meet: $a=b$ while $a < c$, when the size is miniaturized, the silicone fabrication is too fragile. 2 & 3, this structure causes precisely fabrication, while easily over-inflated.

Future applications of Baromorphs could address these challenges through hybrid approaches. Advanced fabrication techniques, such as modular mold designs, might improve reliability and enable smaller-scale production. Integrating porous layers or micro-textures into the elastomer could mitigate suction effects on flat surfaces. Material innovations, like thinner yet stiffer rubbers, might enhance responsiveness while reducing gravitational sagging in larger structures. Combining pneumatic actuation with complementary mechanisms—such as electroactive polymers for finer control—could expand usability in dynamic environments like automotive interfaces. By bridging these technical gaps, Baromorph could unlock broader applications in wearables, adaptive robotics, and interactive systems, capitalizing on their unique blend of speed, programmability, and bio-inspired

design.

CHAPTER 3

Designing Interactive Pneumatic Interfaces for Enhanced Movie Experience

3.1. Introduction

Innovative human-computer interaction (HCI) has evolved beyond visual and auditory modalities in recent decades. Haptic interfaces, which engage the sense of touch through mechanical, vibrotactile, or pneumatic stimuli, hold revolutionary potential to enhance emotional engagement, situational awareness, and trust in technology. While prior researches had explored haptics in various domains, this dissertation investigates silicone-based pneumatic interfaces across isolated yet interconnected contexts: cinematic emotion experience, automated vehicles and robots. Each context presents unique challenges and opportunities for haptic design, while collectively addressing the overarching question: how touch-mediated systems can deepen human-computer relationship across various domains.

Building on these principles, this chapter investigates the application of haptic interfaces in entertainment, specifically within the cinematic experience. Focusing on movies as a primary context illustrates the role of haptic interfaces in evoking engaging emotional responses. Traditional cinema relies on visual and auditory on-screen stimuli to evoke emotions, however, lacks mechanisms to translate these emotions into tangible, shared tactile experiences. Pneumatic haptics offer a scalable solution to bridge this gap, enabling synchronized tactile feedback that mirrors on-screen events. This transformation from the cinematic experience from visual and auditory media to a multi-sensory entertainment approach provides an opportunity to explore how haptics can intensify emotional engagement and social connection in shared viewing environments.

In this chapter, we present a haptic movie rendering prototype that enhances traditional movie-watching by incorporating pneumatic shape-changing and surface texture elements, providing design interactive interface information through visual, audio, and haptic channels. Our research explores the role of haptic stimuli in emotional response during movie viewing in two stages: First, we verified that emotion can be conveyed solely through haptic stimuli, setting the stage for integrating touch-

based feedback into movies. Next, we investigated how congruent and non-congruent haptic stimuli affect the emotional response of movie watching. We hypothesize that congruent haptic stimuli will enhance emotion response in movie watching, while non-congruent stimuli will have a negative effect. By investigating how different haptic stimuli influence audience perception and emotional intensity, we aim to uncover the potential of haptic feedback as a transformative tool in future entertainment forms. Furthermore, this exploration lays the groundwork for broader applications in multimodal human-computer interaction, contributing to the intersection of immersive entertainment, emotional communication, and human-centered design.

3.2. Motivation

Movie is a comprehensive art form that combines motion pictures, dialogue, music, the use of lens and literary narratives. Most improvement of movie techniques focus on visual and sound aspects, such as higher resolution and stereoscopic sound effects [215, 216, 217]. Meanwhile, new technologies have been applied to the movie watching experience, which provides multi-modal forms of entertainment experience [218]. One famous example is Disney’s Soarin’. Soarin’ at the Walt Disney World Park in California combines the motion on screen and kinesthetic acceleration provided by a hanging-riding system, stimulating flight over various sights of the world [219, 220]. Such movie experiences are usually called 4D movies, indicating that one (or even more) sense is provided beyond vision and sound [187, 221]. Recently, innovative haptic interfaces that engaged pneumatic shape-changing techniques in soft robotics have been widely applied in visual reality and social robots, enabling emotion rendering through the haptic channel [222]. However, the application of pneumatic haptic interface in movie watching experience remains challenging.

Traditional modalities often fall short in conveying the physical dimension of emotions—such as tension, warmth, or pressure—that contribute to a deeper embodied sense of presence. We are motivated by the potential of pneumatic haptics to overcome these limitations by introducing tactile feedback that can render emotional states through dynamic shape and surface changes, offering a more immersive and emotionally resonant storytelling experience.

Unlike traditional 4D movie experiences that mainly rely on kinesthetic haptics, pneumatic technol-

ogy adds shape-changing and surface texture elements, providing a touch-friendly haptic experience without requiring complex mechanisms [223]. We are motivated by the potential of pneumatic haptics to overcome the limitations of existing approaches by rendering emotional states through dynamic tactile feedback, offering a more immersive and emotional storytelling experience.

However, the application of pneumatic haptic interfaces in cinema scenarios remains largely unexplored, despite their potential to enrich emotional engagement beyond what is currently achievable with audiovisual and vibrotactile media. Kinesthetic and vibrotactile systems are often bulky, mechanically rigid, and limited to generalized stimuli such as vibrations or gross movements. In contrast, pneumatic haptics can deliver spatially precise, soft, and expressive feedback through localized pressure and shape deformation, making them more suitable for conveying emotion states in a subtle and intimate manner. This advantage positions pneumatic interfaces as a promising direction for advancing emotionally rich, multi-sensory cinematic experiences.

Pneumatic haptic interfaces, capable of dynamic textures and volume changes, offer unique advantages over vibrotactile systems, such as greater sensory variety, operational simplicity. However, existing pneumatic haptic systems are mostly designed for personalized or small-scale applications, such as virtual reality or social communication, and have not been extended to cinematic contexts.

To design an effective haptic interactive system, it is essential to understand how different types of haptic feedback influence user experience. Our approach integrates two key aspects of haptic rendering: pneumatic volume changes and surface texture modulation (Figure 3.1). Pneumatic actuation enables dynamic pressure changes, simulating sensations such as expansion or contraction. Meanwhile, surface texture rendering provides additional tactile information from the microstructures of a surface, enabling the simulation of textures such as roughness, smoothness, or sharpness. This combination allows for a comprehensive tactile interaction, making it particularly well-suited for enhancing emotional responses in cinematic experiences. By engaging both deep-pressure sensations and fine surface cues, the system can convey a broader range of emotional states—such as tension, comfort, or surprise—through touch, aligning physical feedback with the emotional narratives.



Figure 3.1: From left to right: (1) Cat’s pad; (2) Sea urchins’ spines; (3) Frog’s vocal sac

By integrating these haptic modalities, our system aims to achieve expressive, and contextually adaptive haptic feedback. We propose a design that combines the haptic interactive system that combines both pneumatic volume changes and surface texture rendering to convey emotional response in cinematic contexts. The following section details the technical implementation of this system, outlining how pneumatic actuation and texture modulation are realized in practice.

3.3. Implementation

3.3.1. Pneumatic haptic interface

In this section, we propose a pneumatic haptic interface made from soft materials that enables tactile interaction. For this study, we chose silicone over fabric primarily because we believe its skin-like touch and user-friendly experience add an element that enhances audience immersion in a movie.[224, 225].

There are primarily three approaches to pneumatic haptic interface mechanisms explored in prior research. The first approach uses air pumps to drive piston-like vertical pin arrays, forming a matrix of actuated points that can generate localized pressure on the skin [226, 227]. This method allows for high spatial resolution but often comes with highly sophisticated hardware (Figure 3.2).

The second approach employs fabric-based air sacs that rely on the flexibility and anisotropic properties of textiles to achieve deformation [228, 14]. These fabric-based pneumatic actuators, particularly those using knit or woven textiles, offer high compliance, wearability, and ease of fabrication, mak-

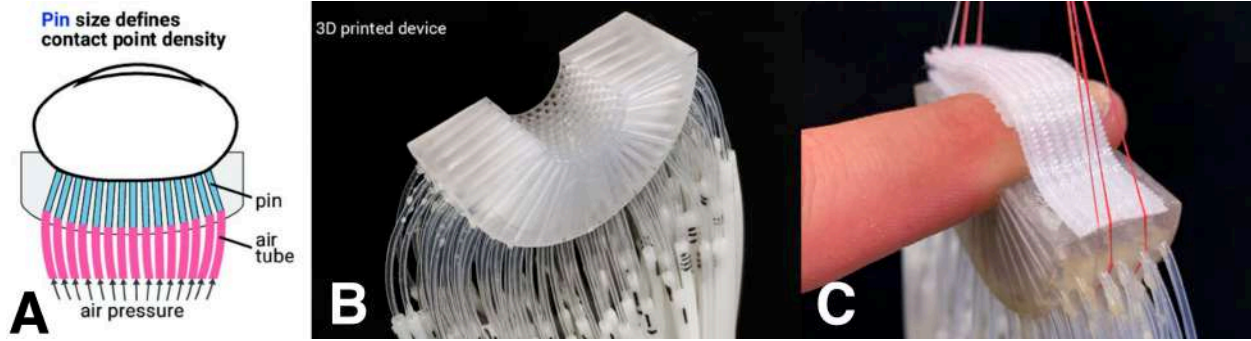


Figure 3.2: Finger-Mounted High-Density Pin-Array Haptic Display
 A. Applying air cylinder as pneumatic actuator; B. 3D printed resin with air tubes; C. Pin-array display fixed to the index finger with Velcro.

ing them suitable for assistive wearables, but less effective in delivering precise or skin-like tactile feedback (Figure 3.3).

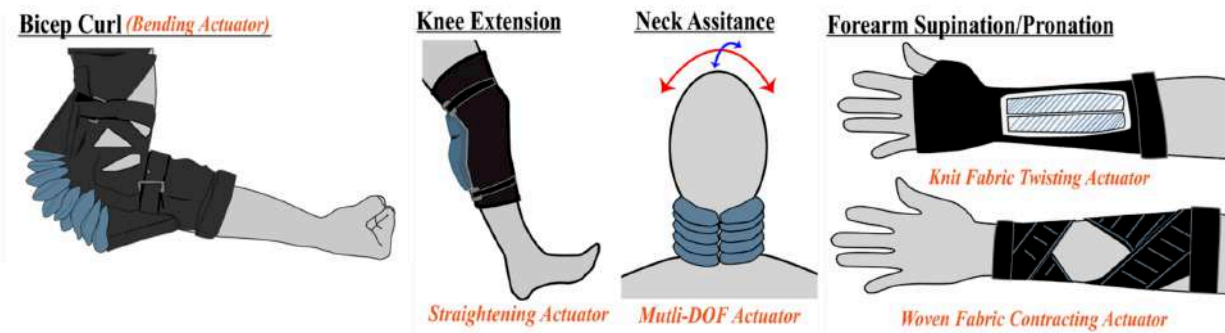


Figure 3.3: Various wearable assistive applications using Fabric Soft Pneumatic Actuators[14]

The third approach utilizes silicone-based pneumatic interfaces, drawing inspiration from biomimetic designs. These use elastic silicone materials to create soft, skin-like surfaces that inflate and deform in response to pneumatic input.

After evaluating all three methods in early-stage prototyping, we found silicone-based interfaces to be the most suitable for our application. In comparison to mechanical pin arrays or fabric-based sacs, the silicone interface offers superior tactile realism, comfort, and emotional resonance—qualities that are crucial for enhancing immersion in cinematic experiences. Its skin-like texture, combined with a smooth, compliant surface, supports both subtle and expressive tactile feedback. This choice is further supported by research emphasizing how material feel affects user comfort, emotional

engagement, and perceived realism [229, 230, 231].

Building on existing findings about the relationship between surface textures and emotional valence [232], as well as frequency and arousal of emotion, we developed two distinct types of silicone haptic interfaces[9]: The first interface, inspired by sea urchin spines, is designed to evoke a sense of mild discomfort without harm, creating an enhanced emotional response. The second interface, inspired by a cat’s paw pad, offers a softer, playful, and adorable tactile sensation, intended to evoke positive valence and enhance emotional engagement in calming or joyful scenes.

As noted by Ouyang *et al.* [233] and De Oliveira *et al.* [234], bio-inspired tactile feedback plays a crucial role in enhancing the realism and functionality of haptic interfaces. Their work supports the idea that mimicking natural tactile sensations, such as those encountered during palpation or multimodal perception, can improve user experience. Furthermore, Ebe and Umemuro [235] as well as Hu and Hoffman [9] emphasized that surface textures and patterns—such as bumps and shape contours—can effectively evoke specific emotional responses, providing a basis for designing emotionally expressive haptic surfaces (Figure 3.4).

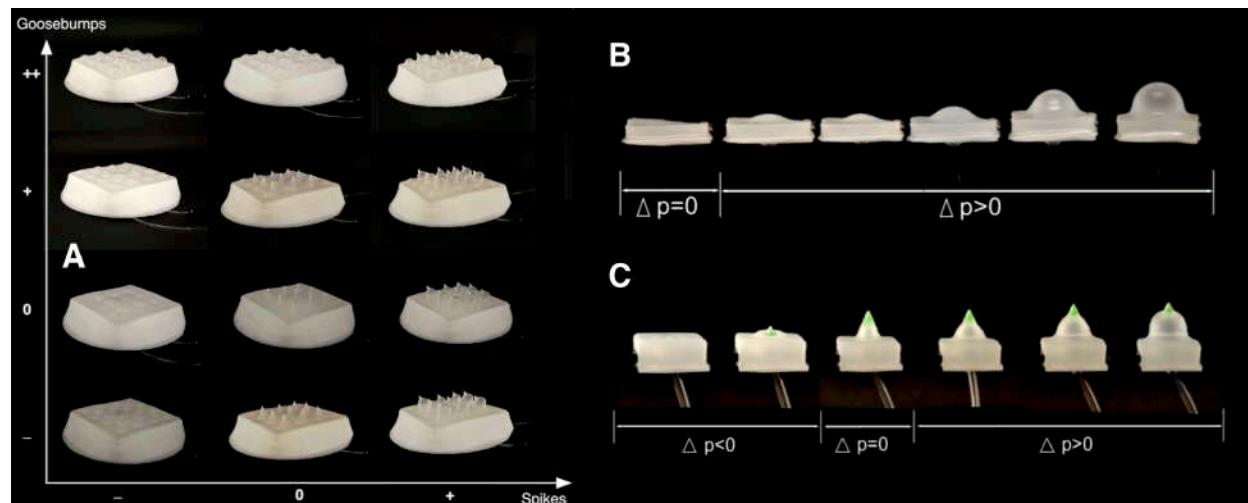


Figure 3.4: Shaped texture units (TU) for haptic expression in soft robotics [9]

A. Deformation of texture module in response to the inner chamber pressure. From left to right, the pressure of the spikes channel changes from negative to positive. From bottom to top, the goosebumps channel inflates from negative pressure to positive pressure; B. A goosebump TU transforms from a flat initial surface to a smooth bump under positive pressure. The volume of the bump increases with the increase of internal pressure; C. Spike TU inflation from negative pressure, with the haptic tip hidden inside the elastomer, to positive pressure, with the sharp thorn protruding.

In our initial prototype, we experimented with inflatable surface bumps, similar to methods seen in related work. However, this approach presented multiple challenges. When each surface bump was inflated independently, the fabrication process became significantly more complex. On the other hand, using a single air channel to inflate all the bumps simultaneously made it difficult to ensure uniform inflation—particularly when the underlying silicone pad was curved due to internal pressurization. The inflation imbalance caused inconsistencies in tactile feedback and diminished overall reliability (Figure 3.5).

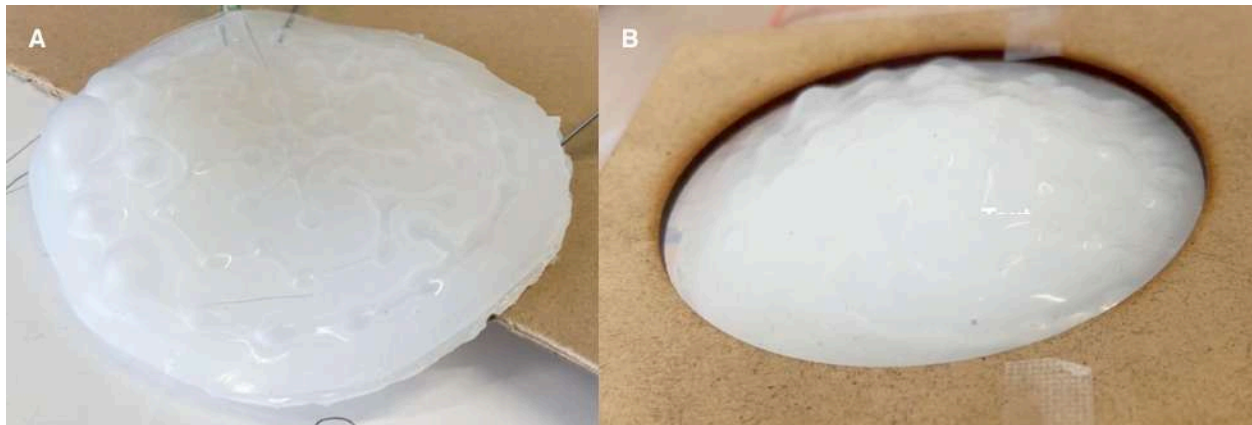


Figure 3.5: Earlier stage prototype shortcomings

A. All surface bumps (bubbles) are inflated in a single air channel; B. The inflated-to-shape-changing underlying silicone pad causes imbalance in surface bumps.

To address these issues, we transitioned to a second version using solid surface bumps instead of inflatable ones. This design change provided two main benefits. First, the solid bumps remained structurally stable and maintained their shape even when the base silicone pad was deformed into a curved geometry. Second, it enabled us to insert small PLA rods into each bump to create a spine-like texture, adding an element of localized stiffness and sharper tactile contrast.

Our implementation of these textures involved embedding a matrix of small silicone hemispheres—resembling goosebumps—on the surface of the pad. For the spine interface, each hemisphere was reinforced with a central PLA stick that extended slightly above the surface, producing a slightly unsettling tactile sensation intended to align with negative emotions. (Figure 3.7). In contrast, the cat-pad-like interface retained smooth, unreinforced hemispheres to generate a soft and soothing tactile experience.

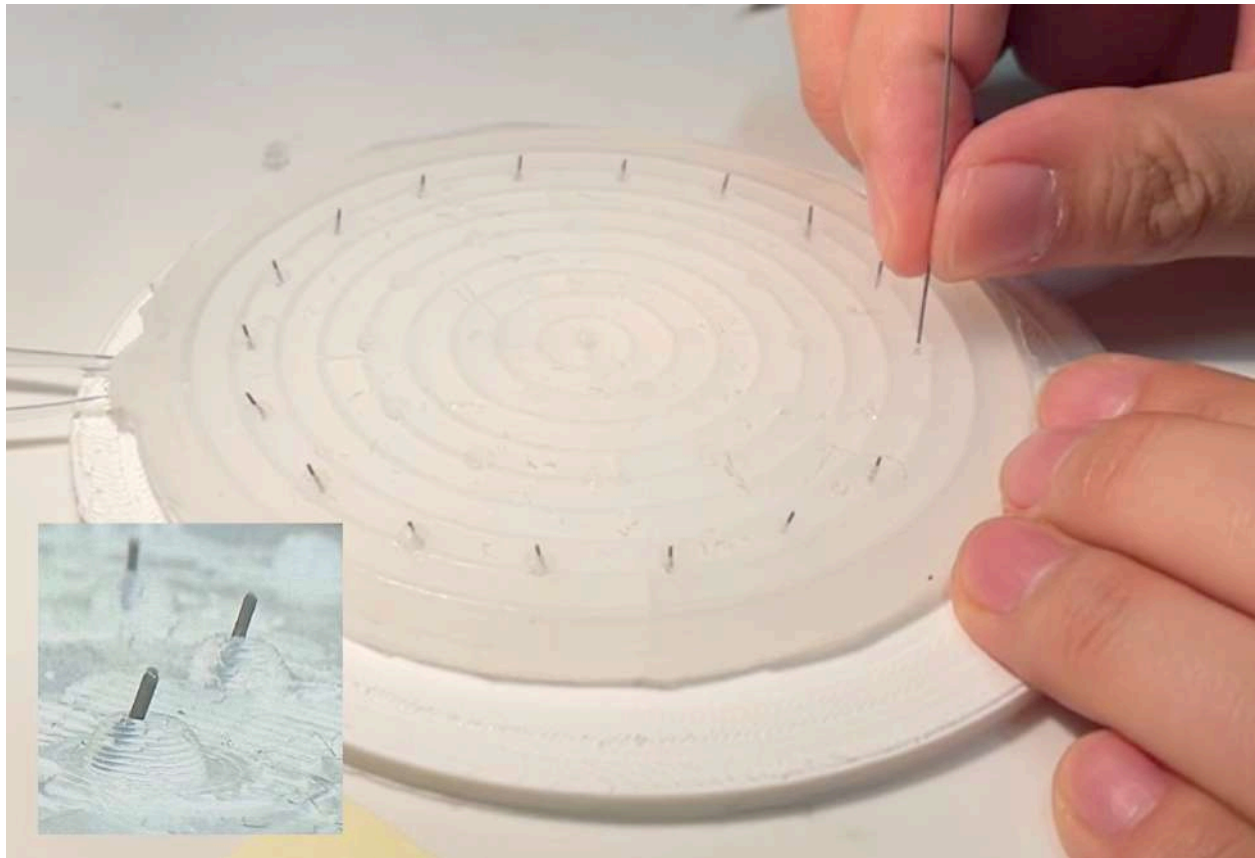


Figure 3.6: Adding PLA sticks into solid surface bumps

To achieve programmable deformation of the silicone base, we integrated Baromorphs, we integrated Baromorphs (Section 2.5) into our design [27]. Compared to traditional inflatable sheets or balloons, Baromorph offers two distinct advantages: (1) it requires significantly less air to achieve the same degree of shape change, enabling faster and more responsive actuation; and (2) it ensures more uniform surface tension, making it particularly well-suited for supporting additional surface features such as solid bumps and embedded spines (Figure 3.7).

However, we encountered unexpected air pressure limitations when deploying Baromorph on flat surfaces. When placed on smooth substrates, the elastomer adhered to the surface due to suction effects, resisting shape changes until a threshold pressure overcame the vacuum. This necessitated workarounds like the "tent" structure in our first project to minimize surface contact and ensure smooth actuation (Figure 3.8). The rationale behind these two texture designs was to create a binary

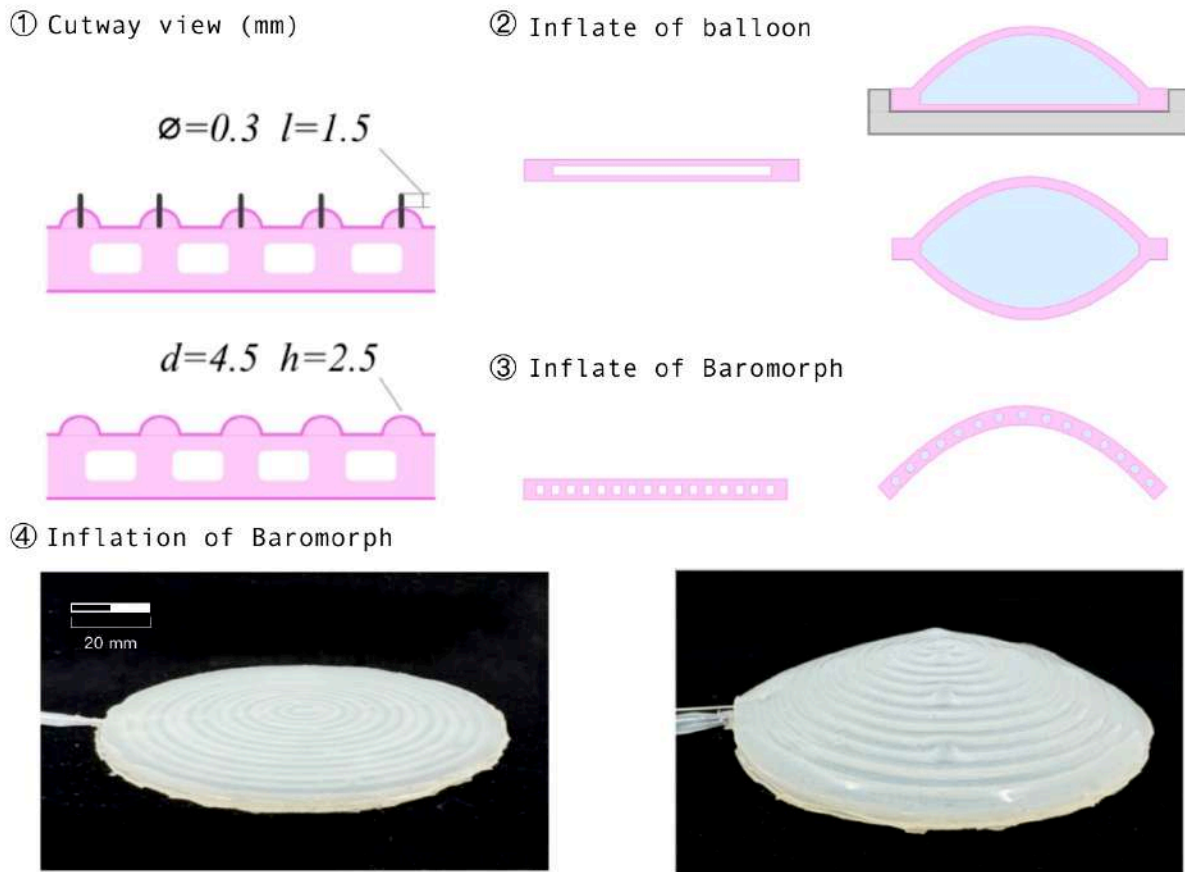


Figure 3.7: Technique breakdowns (1) Dimensions of two types of surface components; (2) Inflation of balloon; (3) Inflation of Baromorph; (4) Dimension of inflated Baromorph

valence cue. The spiked texture, inspired by a naturally aversive stimulus (sea urchin spines), was intended to evoke negative valence or discomfort, aligning with scenes of tension or fear. In contrast, the smooth, paw-pad-like texture was chosen for its association with softness and comfort, aiming to elicit positive valence and enhance feelings of calm or happiness during corresponding scenes. This direct mapping of texture to emotional valence, combined with inflation frequency to modulate arousal, formed the core of our haptic-emotional design language.

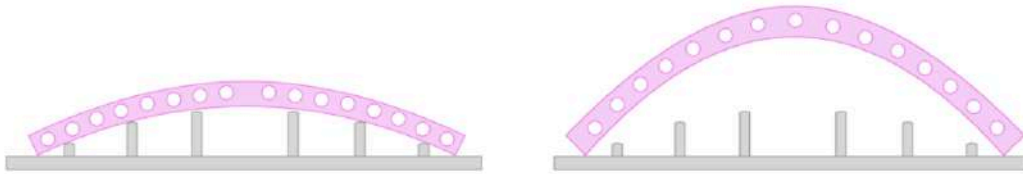


Figure 3.8: Preset Baromorph bending

The Baromorph is not completely flat when un-inflated to prevent air pressure resistance

3.3.2. Hardware

The design criteria for the system are: its abilities to (1) control the frequency of inflation/deflation; (2) control the inflation volume of the device, and (3) support comfortable palm placement by adapting to the natural curvature of the hand. The device features a palm-sized tactile interface, designed to inflate in a way that mimics the biomechanical curvature of the human palm, allowing users to rest their hand naturally on the surface. The system is covered by a 3D printed container, with a curved shell on the top. Its size is 12cm in height.

The electronics design architecture is shown in Figure 3.8. Four transistors of MOSFET (RFP30N06LE) were applied as the switches of signals. Three mini air pumps (ZT370-01) and 2 air valves (JS0520L) are used in combination to inflate the systems for the silicone pad. The circuit was controlled by an Arduino UNO board, with an extra 6V power.

The system is equipped with two air injection ports and two valves. When the valves are closed, air is directed into the silicone pad, causing it to inflate. Conversely, when the valves are opened, the pressurized air is released, and the silicone pad remains deflated and inactive. Port (1) is connected to two air pumps, while port (2) is connected to a single pump. This configuration allows port (1) to deliver approximately twice the airflow rate of port (2). As a result, the system is capable of inflating the silicone pad at either a fast or slow rate, despite each pump operating at a constant flow velocity under a fixed voltage (Figure 3.9).

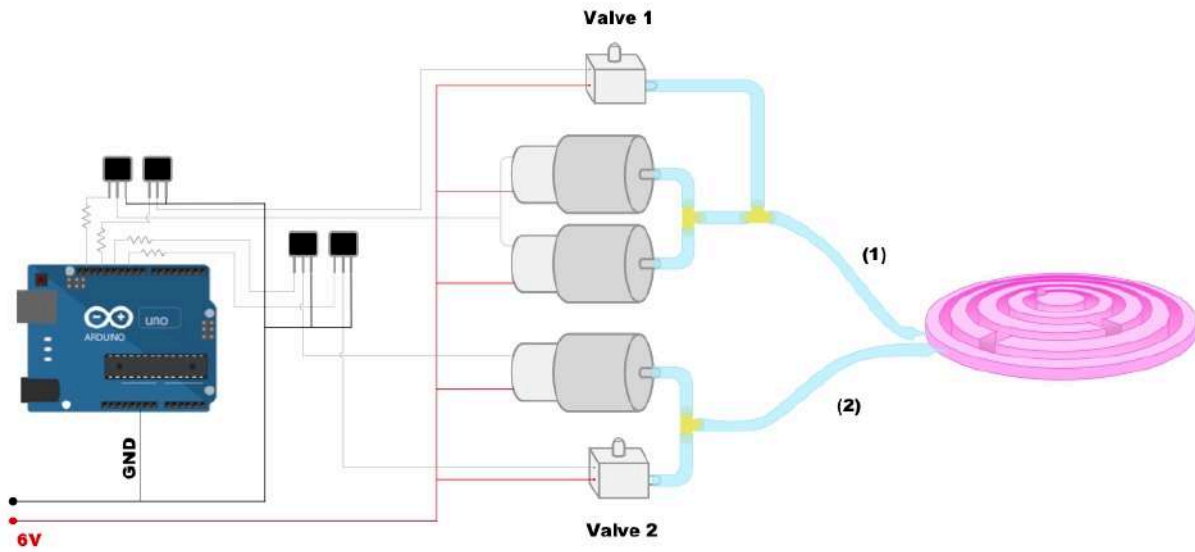


Figure 3.9: Schematic of the electrical system

For frequency, 0.5 second per inflate/deflate was defined as 'high frequency', which is the frequency of 120 bpm of heart rate[236, 237]. In contrast, five second per inflate/deflate was defined as 'low frequency'(i.e. the frequency of a calm breathing. [238]). For inflating volume, 3 centimeters of inflation height was labeled as 'large volume' (the maximum capacity of the silicone pad) and 1 centimeter of inflation height was marked as 'small volume', relatively (Figure 3.10).

3.3.3. Software

The system is controlled via a Python program running on a MacBook using Microsoft Visual Studio Code. This software manages the air pumps and valves to generate real-time changes in frequency and volume of the silicone pad. Inflation occurs when the air pumps are activated and the valve is closed, while deflation happens when the valve is open, regardless if the air pumps are on or off. The system allows for varying inflation rates: rapid inflation uses both pumps connected to port (1), while a slower rate employs a single pump connected to port (2). This setup enables independent control of frequency and volume.

The user interface features on/off switches for the air pumps and each valve, along with stepper sliders for fine-tuning valve cycles from 10 seconds to 0.25 seconds per on/off cycle. To create a

'high frequency, big volume' stimulus, for instance, the user would activate valve 1, set its slider to 2 (0.5 seconds per cycle), and then turn on the air pumps. Importantly, the valve must be activated before the pumps to prevent over-inflation of the silicone pad.

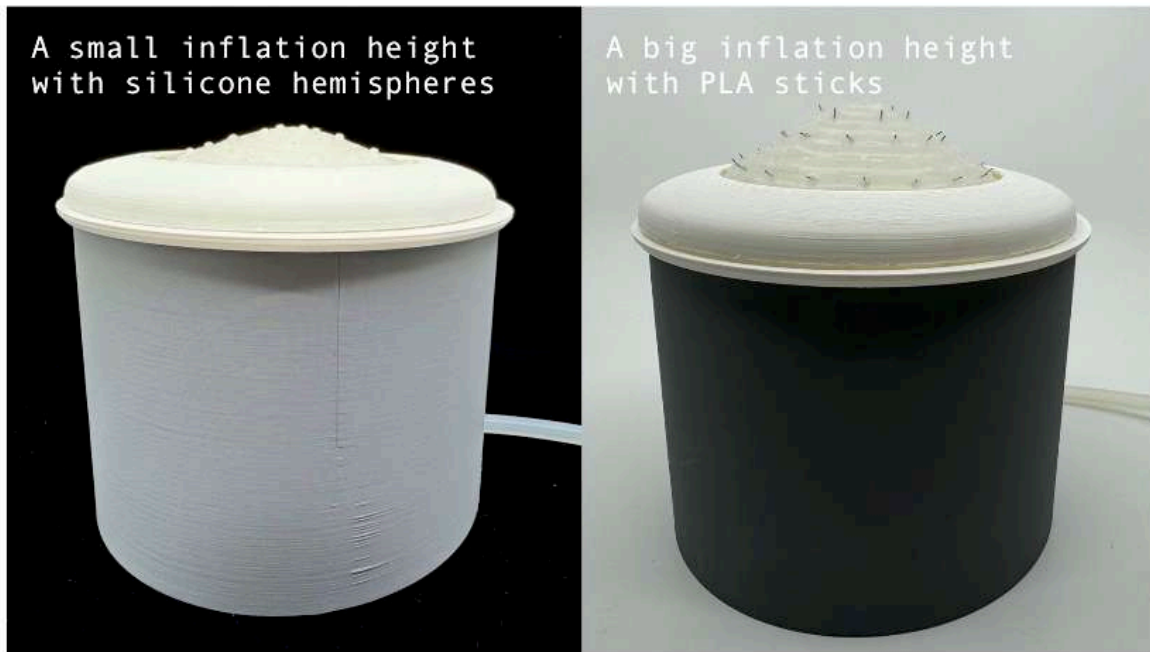


Figure 3.10: Prototype and a close look of the surface components

3.4. Experiments

Our study comprises two interconnected stages of experimentation, both utilizing the hardware implementation described earlier. The first stage aims to validate extracted movie clips from an established database and investigate whether haptic stimuli alone can evoke emotion-related response. For this, we employ Self-Assessment Manikin (SAM) questionnaires [2]. The second stage explores how haptic stimuli can enhance emotional responses within a movie context. This phase incorporates both SAM questionnaires and a verbal survey to gather comprehensive data on participants' responses and overall experience. Through this two-stage approach, we seek to understand the potential of our pneumatic haptic interface in augmenting emotional response during movie watching.

3.4.1. Participants

Before the formal experiment, we conducted a pilot test with eight participants from the lab. The primary goal was to identify and refine potential design issues in both the procedure and evaluation tools. Feedback from this pilot test led to several improvements, including the addition of a satisfaction rating to the questionnaire and the inclusion of a 3-minute break between conditions to reduce participant fatigue. These refinements helped ensure a smoother and more reliable experimental process.

The first formal stage included 21 participants (14 male, 7 female, mean age 25.7 years, $SD = 2.3$) recruited from a college course. For the second stage, we engaged a different group of 30 participants (19 male, 11 female, mean age 26.7 years, $SD = 3.2$), also from the same course. All participants possessed sufficient English proficiency to comprehend movie dialogues without subtitles. Additionally, participants in the second stage completed a post-experiment interview to collect supplementary qualitative data. To prevent carryover effects, none of the participants from the first stage took part in the second (Figure 3.11).

Both experiments were conducted in a controlled indoor environment—an unused office space with stable lighting and air conditioning. To reduce external interference and suppress mechanical noise from the prototype, participants wore noise-canceling headphones throughout the sessions. All participants reported normal tactile, auditory, and visual function, and took part in the study voluntarily.

3.4.2. Stimuli

For our experiment, we selected movie clips from the study "Rating for Emotion Film Clips" conducted by Gabert-Quillen *et al.* [239] (Table 3.1). This database aligns well with our research objectives as it provides English-language clips, each labeled and positioned within an arousal-valence coordinate system that corresponds to the SAM model.

Since participants in our study would be exposed to multiple emotional stimuli in succession, careful clip selection was crucial to avoid fatigue or habituation effects that can diminish emotional respon-



Figure 3.11: Participant in the experiment

siveness—commonly known as repetition effects. To address this, we selected four movie clips from the database, and from each, we extracted two distinct 40-second excerpts. Using separate segments from the same source allows us to maintain emotional consistency within each category, while presenting content that is novel enough to sustain engagement. This approach serves multiple purposes: it minimizes potential repetition effects, maintains consistency across emotional categories, and avoids the distraction that longer clips with multiple scene changes might introduce.

We opted for this rather shorter duration because, as previous research has indicated, prolonged and overly intense haptic stimuli during movie viewing can disrupt immersion and decrease satisfaction [240]. The 40-second duration was selected to balance ecological validity with experimental control. Prior research on emotional elicitation in multimedia contexts suggests that shorter excerpts (30–60 seconds) are sufficient to evoke stable emotional responses while minimizing habituation effects [239]

Table 3.1: Extracted emotional movie excerpts

Category	Label	Movie	Context	Extract
high arousal, high valence	AV1	Remember the Titans (2000)	The players won the game and the audi- ences are cheering	1:44:45-1:45:28
high arousal, high valence	AV2	Remember the Titans (2000)	The coach encourages the players	1:40:09-1:40:45
low arousal, high valence	aV3	Pride & Prejudice (2005)	The heroine is walking and reading a book	01:16-02:02
low arousal, high valence	aV4	Pride & Prejudice (2005)	A woman is playing piano in the dining room	02:22-02:58
low arousal, low valence	av5	My girl (1991)	A girl cries and walks towards the coffin	01:24:02-01:24:35
low arousal, low valence	av6	My girl (1991)	A girl sits on the stair and starts crying	01:24:39-01:25:27
high arousal, low valence	Av7	Crash (2004)	The police pushes the male driver to the car	20:05-20:49
high arousal, low valence	Av8	Crash (2004)	The police frisks female passenger and commits lewd acts on her	20:53-21:49

Naming strategy: Uppercase letters A and V represent high values, while lowercase letters a and v represent low values. For example, aV3 indicates low arousal, high valence, sample 3; while Av7 indicates high arousal, low valence, sample 7

. Longer clips risk introducing narrative complexity or scene transitions that could confound haptic synchronization (e.g., abrupt emotional shifts). Additionally, pilot testing revealed that 40 seconds provided adequate time for participants to attune to the haptic stimuli without fatigue—critical for maintaining consistent engagement across repeated trials. This aligns with cinematic haptic studies where brief, emotionally salient segments optimized multisensory congruence.[7, 187] (See Table 3.1: Extracted emotional movie excerpts).

3.4.3. Methods & Procedure

Introduction

Participants started the study by signing a consent form outlining the purpose, procedures, and potential risks. Next, they were introduced to the Self-Assessment Manikin (SAM), following a structured orientation session designed to familiarize them with the experimental setup. This session included a demonstration of the haptic interface, during which the experimenter explained the function of the silicone pad, how pneumatic feedback would be delivered, and how different textures

(e.g., spined vs. soft) might correspond to emotional content in the movie clips. Participants were also informed about the sequence of the experiment, including how and when the haptic feedback would be activated during the video playback. A sample movie clip (not used in the formal trial) was shown with synchronized haptic output, allowing participants to experience the multisensory interaction beforehand. Finally, participants were trained in using the Self-Assessment Manikin (SAM) scale [2] to report their emotional responses. The SAM is a pictorial, non-verbal assessment tool that measures emotional reactions of three dimensions: valence (pleasant-unpleasant, represented by a smiling/frowning figure), arousal (calm-intense, shown by an energized/relaxed figure), and dominance (dominion-submissiveness, represented by figure size). While the SAM captures all three dimensions, this study focused exclusively on valence and arousal as they were most relevant to our haptic emotion mapping. Participants practiced rating example stimuli on these two target dimensions to ensure comprehension before proceeding. This standardized approach allowed consistent quantification of core subjective states across conditions while minimizing language barriers.

Stage 1: Initial Assessment

In the first stage, participants viewed eight movie excerpts. After each excerpt, they rated the arousal and valence of the emotions they reacted using the SAM questionnaire. Following a 3-minute break, participants were exposed to eight haptic stimuli, each featuring combinations of high/low frequency, large/small volume, and spines/goosebumps surface textures (Table 3.2). After each stimulus, participants again rated arousal and valence using the SAM questionnaire.

All movie excerpts and haptic stimuli were presented in a counterbalanced order to prevent consecutive exposure to the conditions designed to evoke the same emotional features.

Stage 2: Experimental Conditions

In the second stage, participants were shown eight movie clips, same from Stage 1. Accordingly, from the results analysis of Stage 1, four types of haptic stimuli were introduced: high-frequency/spike, high-frequency/smooth, low-frequency/spike, and low-frequency/smooth. These stimuli were verified to influence participants' perception of arousal and valence in Stage 1:

Table 3.2: Eight Types of Haptic Stimuli

Stimulus ID	Frequency	Volume	Surface Texture
H1	Low	Small	Goosebumps
H2	Low	Small	Spines
H3	Low	Large	Goosebumps
H4	Low	Large	Spines
H5	High	Small	Goosebumps
H6	High	Small	Spines
H7	High	Large	Goosebumps
H8	High	Large	Spines

- High-frequency stimuli were intended to enhance arousal.
- Low-frequency stimuli were intended to reduce arousal.
- Spike surfaces were intended to convey negative valence.
- Smooth surfaces were intended to convey positive valence.

To deliver the combinations of stimuli, the haptic device used a modular Baromorph interface. Two interchangeable silicone surface components were fabricated—one with spike-like textures (inspired by hedgehog spines), and the other with a smooth, goosebump-like surface. The same device was used throughout the experiment, but between trials involving different surface conditions, the Baromorph component was manually swapped by the experimenter to match the required texture. This allowed for consistent hardware control while ensuring accurate delivery of texture-specific tactile feedback.

The experiment employed a within-subjects design where all participants experienced three counterbalanced conditions:

1. **Control Condition:** The participants watched movie clips without any haptic stimuli to establish a baseline for emotion perception.
2. **Congruent Condition:** Participants watched movie clips paired with haptic stimuli that matched the emotional tone of the clip (e.g., high-frequency/spike for high arousal/low va-

lence).

3. **Non-congruent Condition:** Participants watched the clips paired with haptic stimuli that conveyed the opposite emotional tone from the target emotion of the clip (e.g., low-frequency/smooth for a high arousal/low valence clip). These non-congruent pairings were manually assigned by the experimenter based on pre-identified emotional targets from Stage 1. This systematic opposition design allowed clear comparison between matched vs. mismatched haptic-emotional pairings while maintaining experimental control.

The goal was to determine whether congruent haptic stimuli enhanced participants' understanding of the movie's emotional tone and whether non-congruent stimuli disrupted this understanding. After each clip, participants rated arousal and valence using the SAM scale and provided verbal feedback on their emotional satisfaction. A final interview gathered additional comments and suggestions. A Latin Square design ensured counterbalancing of stimuli assignments across participants.

The experiment was conducted in a controlled environment to ensure consistency across sessions. Factors such as lighting, room temperature, and seating arrangements were standardized to minimize external influences.

Before the formal experiment, a pilot test was conducted with eight participants from the lab. This helped improve the questionnaires by incorporating feedback, such as including a satisfaction report and adding a 3-minute break.

To evaluate the effectiveness of our haptic interactive system, we employed a combination of statistical methods tailored to our experimental design and research objectives. ANOVA was applied to analyze the differences in participants' emotional responses across different haptic conditions, so that we could determine whether haptic feedback had a statistically significant effect on emotional engagement and user experience. In cases where paired comparisons were necessary—such as evaluating individual differences in user responses between two specific conditions—we utilized the Wilcoxon Signed-Rank Test. It allowed us to assess whether specific haptic feedback variations resulted in significantly different user experiences.

3.5. Results

3.5.1. Stage 1

The mean SAM scores for all selected movie excerpts meet the experimental requirements: each excerpt falls within the intended quadrant of the arousal–valence space, based on the coordinate center of (arousal = 3, valence = 3). Specifically, AV1 and AV2 are classified as high arousal, high valence stimuli; their mean scores for both arousal and valence are above 3. aV3 and aV4 represent low arousal, high valence stimuli, with arousal means below 3 and valence means above 3. av5 and av6 fall into the low arousal, low valence category, where both arousal and valence scores are below 3. Finally, Av7 and Av8 are high arousal, low valence clips, showing arousal means above 3 and valence means below 3. This balanced distribution—two excerpts per emotional quadrant—ensures comprehensive coverage of emotional states for the experiment (Table 3.3).

Table 3.3: Mean values of movie excerpts

Label	Arousal	Valence	Label	Arousal	Valence
AV1	4.2857	4.6667	av5	2.7619	1.1429
AV2	3.7619	3.7619	av6	2.4762	1.5714
aV3	1.7619	3.5238	Av7	4.3810	1.3333
aV4	2.0952	3.8571	Av8	3.8095	1.0000

A Friedman’s test (p-values smaller than 0.001) and post-hoc test for the scores of these movie excerpts was also verified. Based on the results shown in Table 3.4 (Within-Group Comparisons), there were no statistically significant differences in either valence or arousal ratings within each movie clip pair (e.g., AV1 vs. AV2, aV3 vs. aV4, etc.). This indicates that when participants were exposed to movie clips within the same emotional category, valence ratings showed no significant differences (all $p > 0.2$) between clips sharing the same arousal level, and vice versa; In contrast, Table 3.5 (Between-Group Comparisons) suggests that clips across different categories showed significant valence differences ($p < 0.0001$ for most comparisons), confirming our haptic stimuli successfully differentiated between core emotional quadrants (high/low arousal \times positive/negative valence). The one exception was aV3aV4 vs Av7Av8 (valence $p = 0.5471$), likely because both represent low-arousal states despite opposite valence, suggesting floor effects in low-arousal conditions

Table 3.4: Within-Group Comparisons

Comparison		p-value
AV1 vs. AV2	Valence	0.3515
	Arousal	0.9999
aV3 vs. aV4	Valence	0.9746
	Arousal	0.9999
av5 vs. av6	Valence	0.2282
	Arousal	0.4024
Av7 vs. Av8	Valence	0.2190
	Arousal	0.1262

Table 3.5: Between-Group Comparisons

Comparison		p-value
AV1 & AV2 vs. aV3 & aV4	Valence	<u>< 0.0001</u>
	Arousal	0.7784
av5 & av6 vs. Av7 & Av8	Valence	<u>< 0.0001</u>
	Arousal	0.8180
AV1 & AV2 vs. av5 & av6	Valence	0.7707
	Arousal	<u>0.0486</u>
aV3 & aV4 vs. Av7 & Av8	Valence	0.5471
	Arousal	<u>0.0041</u>
AV1 & AV2 vs. Av7 & Av8	Valence	<u>0.0010</u>
	Arousal	<u>0.0029</u>
aV3 & aV4 vs. av5 & av6	Valence	<u>< 0.0001</u>
	Arousal	<u>0.0016</u>

A 3-way ANOVA was applied to the haptic stimuli after a Normality check was performed: both p-values of arousal and valence were smaller than 0.001. Analysis results show that Frequency (p-value smaller than 0.0001), Volume (p-value smaller than 0.0001) and the interaction between Frequency and Volume (p-value=0.003) have statistical significance on arousal, while only Texture is significant for valence (p-value=0.027). To further compare which factor affects the arousal and valence mostly, Eta Squared for all variables were calculated (Table 3.6). The Eta Squared values further indicate that Frequency has the largest effect size on arousal, followed by Volume and the interaction between Frequency and Volume. The key findings indicate significant differences of Frequency, Volume and Surface Texture on arousal, as well as in valence between goosebumps and spines surface texture conditions. A Mauchly's sphericity test and Tukey post-hoc test were conducted to examine the property of ANOVA analysis and the effects of frequency and volume on

arousal and valence.

Table 3.6: ANOVA and Eta Squared results for haptic stimuli

	Arousal		Valence	
	<i>p-value</i>	η_p^2	<i>p-value</i>	η_p^2
Frequency	<u>1.657e-10</u>	0.5595	0.5595	-
Volume	<u>2.850e-06</u>	0.1302	0.1302	-
Texture	0.0571	-	<u>0.0275</u>	0.3025
Frequency×Volume	<u>0.0033</u>	0.0331	0.3724	-
Frequency×Texture	0.5923	-	0.1580	-
Volume×Texture	0.4021	-	0.0181	-
Frequency×Volume ×Texture	0.1775	-	0.6773	-

3.5.2. Stage 2

The results from Stage 1 contribute to the second stage experiment conditions. In the first study, we focused exclusively on the most significant haptic features affecting emotional arousal and valence. For the second stage, we specifically targeted frequency and surface texture as key variables. In the congruent condition, haptic stimuli were matched with the emotional content of movie excerpts, aligning both the frequency and surface texture with the movie’s arousal and valence levels. In the non-congruent condition, haptic stimuli were intentionally mismatched, with either the frequency or surface texture not aligning with the movie’s emotional content, or both being incongruent with the arousal and valence levels.

To facilitate a comprehensive analysis of the collected data, a visual map (Figure 3.11) shows the valence and arousal for each of the movie excerpt. This map offers an initial visual insight into the differences between the control and congruent conditions, hinting that congruent haptic stimuli might enhance emotional response, while non-congruent haptic stimuli could disrupt it.

- Control condition: AV1, AV2, aV3, aV4, av5, av6, Av7, Av8
- Congruent condition (H for Haptic): H-AV1, H-AV2, H-aV3, H-aV4, H-av5, H-av6, H-Av7, H-Av8
- Non-congruent condition (N for Non): N-AV1, N-AV2, N-aV3, N-aV4, N-av5, N-av6, N-Av7,

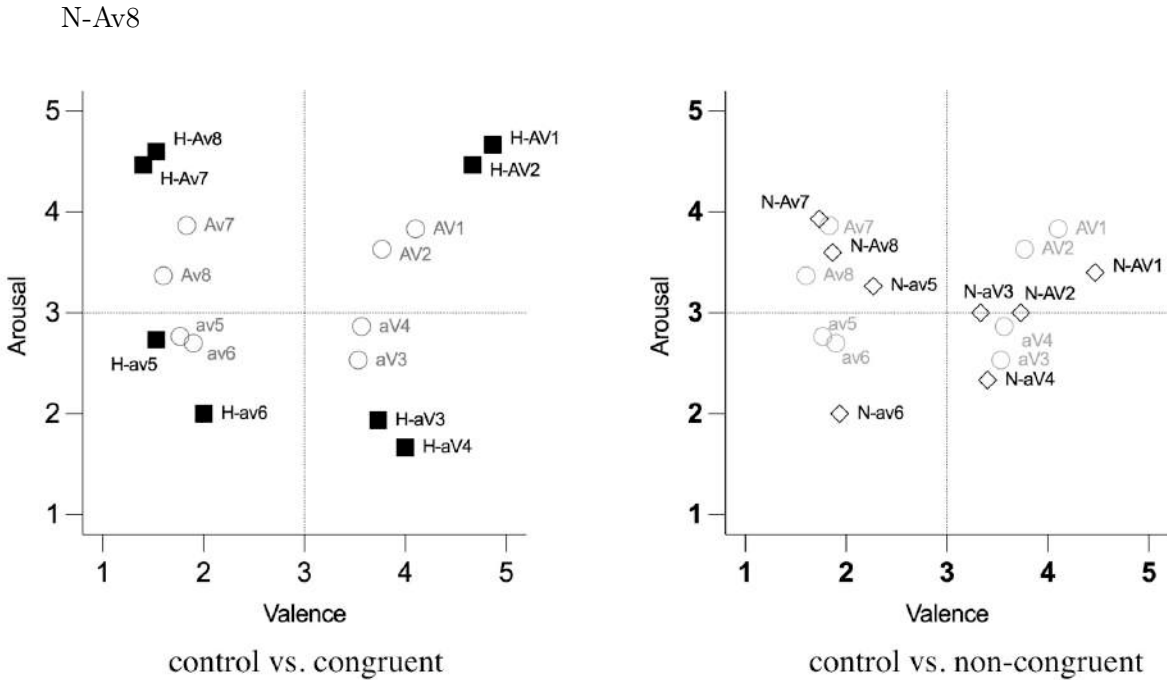


Figure 3.12: Black circles: control condition; Black squares: congruent condition; Diamond: non-congruent condition

In this stage, participants were exposed to multiple conditions (Control, Congruent, Non-Congruent) and their emotional responses (arousal, valence) were measured in a within-subject design. Given that the same participants provided data across these different conditions, the Wilcoxon Signed-Rank Test was employed to analyze the statistical significance of differences between the Control and Congruent conditions, as well as between the Control and Non-Congruent conditions. The analysis was conducted using GraphPad Prism.

The results from the Wilcoxon Signed-Rank Test reveal several noteworthy points. On arousal, A significant difference is observed for most pairs when comparing the control and congruent conditions. On the contrary, only in the AV1 vs. H-AV1 and AV2 vs. H-AV2 (Control Condition vs Haptic Congruent Condition) comparison indicates a significant effect of congruent haptic feedback on valence (Table 3.7).

For arousal, significant decreases in arousal with congruent stimuli were observed for aV3 vs H-aV3 ($p = 0.0181$), aV4 vs H-aV4 ($p = 0.0078$), and av6 vs H-av6 ($p = 0.0337$), with median differences

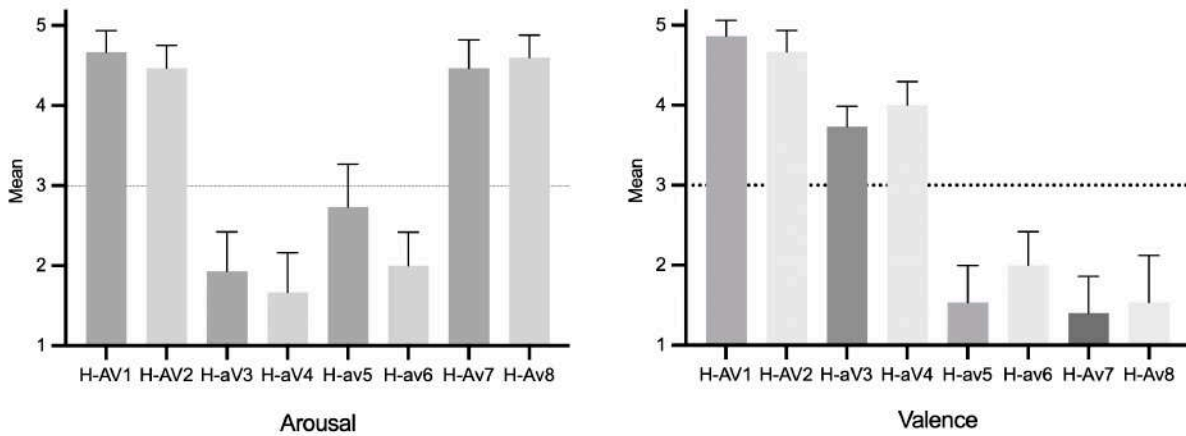


Figure 3.13: Mean with 95% CI of congruent conditions

of -1 and large negative rank sums, indicating reduced arousal in these cases. Conversely, significant increases in arousal were found for AV2 vs H-AV2 ($p = 0.0234$) and Av8 vs H-Av8 ($p = 0.00002$), with median differences of 1 and substantial positive rank sums, suggesting heightened arousal under congruent conditions. Notably, av5 vs H-av5 ($p = 0.688$) and Av7 vs H-Av7 ($p = 0.1377$) did not show significant differences. Overall, congruent stimuli have a notable impact on arousal, with effects depending on the specific movie excerpts. Analysis of valence differences between control and congruent conditions revealed that AV1 vs. H-AV1 ($p = 0.0195$) and AV2 vs. H-AV2 ($p = 0.001$) showed significant increases in positive valence under the congruent condition, with median differences of 1 and substantial positive rank sums, respectively. However, no significant differences were found for the rest. Overall, congruent stimuli significantly affect valence in only high valence, leading to increased positive valence.

The general trend observed from the data indicates that congruent haptic feedback tends to amplify the intended emotional states elicited by the movies. For example, movies designed to elicit higher arousal and higher valence gained intended effects bolstered by congruent haptic feedback, as evidenced by the movement of points in the valence-arousal map. This trend suggests that the haptic stimuli not only align with but also potentiate the emotional impact of the content being viewed: In the movie excerpts that contains emotions such as excite and joy (AV1, AV2), haptic stimuli of

Table 3.7: Wilcoxon Signed-Rank Test for congruent condition

Control vs Congruent	Arousal p-value	Valence p-value
AV1 vs H-AV1	<u>0.0469</u> ↑	<u>0.0195</u>
AV2 vs H-AV2	<u>0.0234</u> ↑	<u>0.0010</u>
aV3 vs H-aV3	<u>0.0181</u> ↓	0,3438
aV4 vs H-aV4	<u>0.0078</u> ↓	0.5312
av5 vs H-av5	0.6880	0.3594
av6 vs H-av6	<u>0.0377</u> ↓	0.3438
Av7 vs H-Av7	0.1377	0.3398
Av8 vs H-Av8	<u>0.0002</u> ↑	0.9999

↑ indicates a significant increase; ↓ indicates a significant decrease

high frequency, goosebumps surface texture are observed to increase the excitement; In the movie excerpts that contains peaceful and calm emotion (aV3, aV4), the low frequency, goosebumps surface texture haptic stimuli are witnessed to improve the arousal of calmness; In the movie excerpts that contains negative emotions, limited impact can be observed: anger movie excerpts (Av7, Av8) are augmented of the arousal of emotion by a high frequency, spines surface texture haptic stimulus, and sorrow movie excerpts (av5, av6) are weakened of the arousal of emotion by a low frequency, spines surface texture haptic stimulus.

However, there are noticeable exceptions in the dataset, particularly the comparisons of av5 vs H-av5, and Av7 vs H-Av7, as well as all valence comparisons except AV1 vs H-AV1 and AV2 vs H-AV2, where the clarity of enhancement is less pronounced. This observation could indicate variability in how different types of content or haptic feedback patterns interact with viewer emotion responses. These results suggest that haptic stimuli boost the rendering of excited, joyful emotion in the movie in both arousal and valence, meanwhile there is a lack of evidence that haptic stimuli impact the valence of other emotion types.

In light of these observations, Congruent haptic stimuli aligned with the emotional tone of the movie clips amplified emotional experience, especially for high-arousal and high-valence movies. For instance, high-frequency and smooth textures intensified excitement and joy (e.g., AV1, AV2). Congruent stimuli complement the emotional tone of the movie, making the sensory experience

more cohesive and enhancing emotional engagement (Figure 3.8).

Conversely, the comparison between control condition and non-congruent condition aimed to explore the potential possibilities of disruptive effects by non-congruent haptic stimuli. This helps to determine whether the introduction of non-congruent haptic stimuli significantly alters the emotion during movie watching experience. In contrast to the pronounced effect in the congruent condition, the non-congruent condition produced mixed responses (Table 3.7).

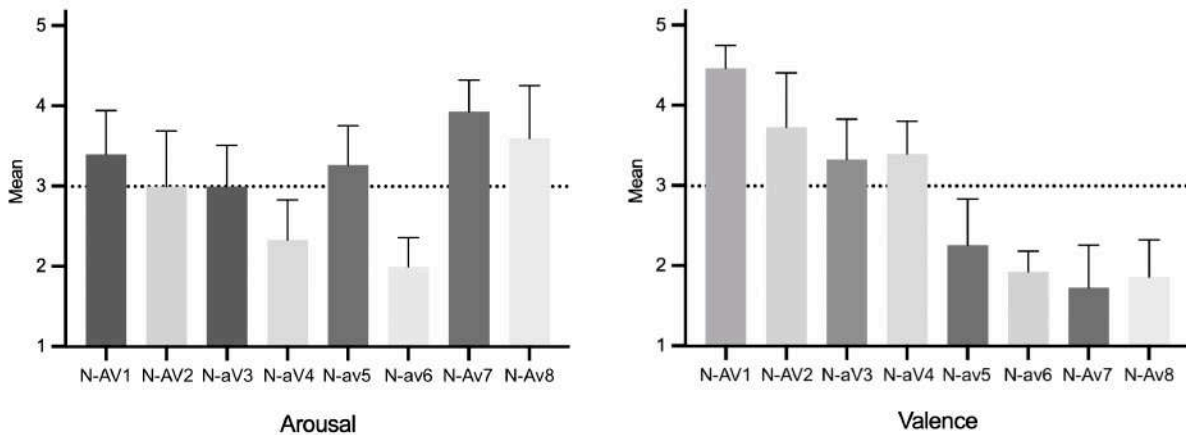


Figure 3.14: Mean with 95% CI of non-congruent conditions

Table 3.8: Wilcoxon Signed-Rank Test for non-congruent condition

Control vs Non-Congruent	Arousal p-value	Valence p-value
AV1 vs N-AV1	<u>*0.0566</u> ↓	0.5312
AV2 vs N-AV2	0.0898	0.7676
aV3 vs N-aV3	0.5557	0.7812
aV4 vs N-aV4	0.3389	0.1719
av5 vs N-av5	0.0625	0.1758
av6 vs N-av6	<u>0.0137</u> ↓	0.3750
Av7 vs N-Av7	0.9999	0.8828
Av8 vs N-Av8	0.7002	0.2695

* indicates a close to threshold of significance, ↓ for a decrease

The Wilcoxon Signed-Rank Test revealed significant differences in arousal scores between the control and non-congruent conditions for AV6 vs. N-AV6, with a p-value of 0.0137 indicating a statistically

significant decrease in arousal under the non-congruent condition. The median difference was -1.00, demonstrating a reduction in arousal with non-congruent stimuli. The negative sum of ranks (-51.50) was much higher than the positive ranks (3.50), reinforcing this effect. For AV1 vs. N-AV1, the p value is slightly above the conventional threshold of 0.05, and the median difference of -1.0 suggests reduced responses in the non-congruent condition. The negative sum of ranks supports this trend, although the weak Spearman's r_s (0.1823) indicates a modest correlation. These results suggest that non-congruent haptic stimuli may disrupt the emotional response of movie-watching.

Overall, Non-congruent haptic stimuli disrupted the emotional alignment between the movie and the haptic feedback, occasionally decreasing arousal (e.g., av6 vs. N-av6, $p = 0.0137$). Participants reported feeling "annoyed" or "distracted," and statistical significance was less consistent compared to the congruent condition. Non-congruent stimuli conflicted with the intended emotional tone, breaking the coherence of the sensory response. But nevertheless, non-congruent stimuli might be used purposefully to create cognitive dissonance in movies, if applicable.

Additionally, verbal reports such as "I feel engaged in positive movies when there are cohesive haptic" and "I feel the haptic experience could influence the movie's emotion" also underscored the influence of congruent haptic stimuli in movie excerpts watching experience. Also, participants reported they felt "annoying" or "difficult to focus" under non-congruent conditions.

3.6. Discussion

First, this study focuses on dynamic emotional response, using haptic feedback to align or contrast with cinematic content, addressing emotional arousal and valence in a human-computer interaction (HCI) framework. Second, this work explore the effect of congruence between haptic stimuli and emotional content. Congruent haptic feedback tends to enhance emotional response, while non-congruent feedback disrupts it. This variable adds a cognitive and perceptual layer to haptic system design. Third, this study explores pneumatic textures (spike/smooth surfaces, high/low frequency) for bio-inspired tactile sensations, which are tailored to evoke and amplify specific emotional response. Fourth, this research incorporates real-time dynamic interaction, synchronizing haptic feedback with audiovisual stimuli to create immersive emotional responses, such as enhanc-

ing excitement in high-arousal/high-valence scenes or creating tension in non-congruent conditions.

This research expands the potential applications of surface texture designs by suggesting their capability to enhance emotional responses, moving beyond their traditional industrial uses. The exploration of congruence introduces a new design framework for haptic systems, enabling applications in storytelling entertainment. Tactile feedback can enhance emotional resonance by aligning haptic cues with narrative tension or character emotions, thereby increasing audience immersion. The mixed responses in non-congruent conditions suggest future potential for creating tension or cognitive dissonance in specific genres, such as thrillers or experimental art.

This research explored the design of interactive pneumatic interface on emotional response during movie viewing, specifically investigating how different haptic feedback conditions influence emotional processing across varying levels of arousal and valence. By comparing control conditions with congruent and non-congruent haptic stimuli, our study provides valuable insights on the role of pneumatic haptic interfaces in shaping emotional responses during multimedia consumption.

The experimental results revealed several significant findings about the relationship between haptic feedback and emotional response. In the congruent condition, haptic stimuli demonstrated substantial effects on emotional responses, particularly in terms of arousal modulation.

Statistical analysis showed significant changes in arousal levels across multiple movie excerpts when paired with congruent haptic feedback, with both increases and decreases in arousal depending on the emotional content of the scenes.

Specific parameters, such as frequency and surface texture, played critical roles in tailoring the emotional experience: High-frequency feedback amplified the intensity of arousal, making it particularly effective for high-arousal positive content, such as scenes depicting excitement or joy. This heightened sense of stimulation aligned with the emotional tone of these scenes, enhancing both arousal and valence. Conversely, low-frequency feedback was associated with calming effects, making it suitable for low-arousal content, such as serene or peaceful scenes. This parameter allowed for subtle modulation of emotional states without overpowering the visual and auditory stimuli. Spike-

textured feedback enhanced the perception of intensity and excitement in high-arousal scenes, likely due to its bio-inspired design that mimics tactile sensations associated with heightened emotional states. Smooth textures complemented low-arousal, positive-valence scenes by reinforcing feelings of calmness and relaxation, creating a cohesive sensory experience.

A limitation of this study is the use of brief 40-second movie excerpts. While this controlled for habituation effects and ensured precise synchronization, it remains unclear how these findings would translate to the experience of watching a full-length feature film. Future research should investigate the long-term effects of haptic stimulation on immersion, potential fatigue, and the dynamics of emotional engagement over extended periods.

The combination of the bio-inspired design in the congruent condition significantly improved emotional response with the movie content. For example, in scenes designed to evoke joy or excitement, high-frequency and goosebumps-textured stimuli intensified the engagement, whereas in tranquil scenes, low-frequency and smooth textures supported the intended emotional tone.

These findings suggest that haptic parameters can dynamically enhance the emotional response of cinematic experiences, offering a multi-sensory approach to storytelling.

3.7. Conclusion

The chapter demonstrated the effectiveness of pneumatic, bio-inspired haptic interfaces in creating immersive, emotionally resonant experiences. This highlights the potential of biomimicry in haptic interface design, suggesting that natural, biological patterns can inform the development of more intuitive and engaging haptic feedback systems. The results underscore that congruent haptic stimuli can enhance emotional experience, while inappropriate haptic feedback might detract from the intended experience.

Despite certain limitations, the findings of this study offer practical insights for the design of emotionally expressive and immersive multimedia systems. One key limitation lies in the reduced discriminability of emotional valence under matched arousal conditions, as participants found it more difficult to distinguish between positive and negative emotions when arousal levels were held

constant. This highlights a fundamental challenge in affective haptics—namely, that valence may be less effectively encoded through tactile feedback alone, compared to arousal. Additionally, the manual nature of the control interface and the relatively small participant pool limit the generalizability of the findings.

Building on these limitations, future research could explore adaptive or personalized haptic encoding systems that account for individual differences in tactile sensitivity and emotional perception. For example, users with different sensory preferences or neurodiverse traits (e.g., autism, sensory processing differences) may respond differently to the same haptic stimuli. Incorporating physiological feedback (e.g., heart rate, skin conductance) could also help dynamically modulate haptic output based on real-time user states. These directions would reinforce the potential of pneumatic haptic systems not only in entertainment but also in therapeutic, educational, and emotionally communicative technologies, creating richer, more inclusive interactive experiences.

This chapter directly addresses **Research Question 1—How can pneumatic haptic interfaces enhance emotional engagement in cinematic experiences?**—by demonstrating that bio-inspired pneumatic feedback significantly modulates audience responses when aligned with narrative emotions. The results confirm that pneumatic haptics can transcend traditional audiovisual cinema by adding a tangible emotional layer, though designers must account for the observed asymmetry in valence/arousal encoding fidelity.

This study contributes to the design principles for creating immersive, emotionally engaging systems, and show that haptic systems can amplify emotional alignment. Just as congruent haptic stimuli enhanced emotional alignment in movies, analogous principles can be applied to driver-vehicle communication, where trust and situational awareness replace emotional valence and arousal as critical interaction metrics. Building on these insights, the principles of haptic modulation—the use of intensity and texture to convey emotional cues—can inform the design of driver-vehicle communication systems, where the goal is to support user trust and situational awareness through adapting similar tactile parameters. By unifying affective haptic design with human factors engineering, this work bridges emotive storytelling and practical safety applications, laying the groundwork for

Chapter 4's exploration of pneumatic interfaces in automated vehicles.

CHAPTER 4

Enhancing Takeover Requests Through Multi-Modal Haptic Steering Wheel Interfaces

4.1. Introduction

Chapter 3 demonstrated how bio-inspired pneumatic haptic interfaces can enhance emotional understanding in multimedia experiences through congruent, naturalistic haptic stimuli. It suggests that soft pneumatic systems, mimicking biological communication patterns (e.g., inflation rhythms, surface texture rendering) can create immersive, emotional experiences by aligning haptic feedback with context. These findings underscore a broader principle: biomimetic tactile design fosters intuitive, context-aware interactions. Building on these insights, this chapter shifts focus to safety-critical human-vehicle interaction in autonomous driving. While emotional valence and arousal were central to Chapter 3, this chapter adapts principles to driver-vehicle communication, where trust and situational awareness emerge as critical metrics for safe transitions between autonomous and manual control.

The spread of Level 3 automated vehicles demands interfaces that balance urgency, clarity, and comfort during Takeover Requests (TORs): since drivers often detach from the driving task—due to non-driving activities or reduced vigilance—systems must rapidly reorient their attention without causing stress or confusion. Haptic feedback, as a direct and instinctive communication channel, is an interesting approach for bridging this gap. However, existing systems often prioritize functionality over user experience: vibrotactile alerts, while effective, risk feeling mechanical or intrusive, whereas purely visual/auditory cues may fail to cut through cognitive overload [241]. The previous chapter’s illustration of using pneumatic haptics to enhance emotional congruence suggests a promising direction: bio-inspired haptic interfaces can similarly align safety-critical alerts with human perceptual and cognitive preferences, fostering trust and facilitating smoother transitions.

This chapter presents two studies that translate the principles of biomimetic design into the context of autonomous driving. Study 1 introduces a Pneumatic Haptic Silicon Sac (PHSS) steering wheel, inspired by animal communication mechanisms (e.g., inflating air sacs in frogs and Siamangs), to

deliver natural, non-threatening tactile warnings. The PHSS employs gentle inflation/deflation rhythms to signal TORs, synchronizing with visual and auditory cues to reduce cognitive load and build trust. Study 2 expands this work by comparing pneumatic feedback to traditional vibrotactile systems, evaluating how modality choice impacts driver performance, stress, and directional accuracy.

Building on the insight that congruent haptic stimuli can enhance emotional alignment in cinematic contexts, we adapt a similar bio-inspired approach to driver-vehicle communication. Where cinematic interfaces mapped haptic parameters to valence/arousal dimensions to enhance emotional engagement, automotive interfaces are targeted to supporting situational awareness and driver trust. The following sections detail how these principles manifest in Takeover Request design, with methodologies tailored to driving-specific performance metrics (reaction time, workload) rather than emotional states.

4.2. Study 1: Pneumatic Tactile Steering Wheel for Multi-Modal TOR

4.2.1. Motivation

Nowadays, drivers and vehicles must coordinate decision-making, necessitating effective vehicle communication in the context of rapidly developing automated vehicle technologies. Researchers pointed out that in-vehicle interaction systems should enhance driver attentiveness with adequate cues for safe driving [242]. In boarder areas of human-computer interaction (HCI), haptic feedback are applied to enhance user experiences by mimicking human touch [243].

However, besides the existence of various tactile interaction designs (e.g., vibration, thermal, texture), their implementation in autonomous smart vehicles is progressing slowly [244]. A main reason is that the developmental stage of haptic feedback integration with vehicle control is strictly limited by safety standards: multimedia devices may distract drivers, as Schartmüller *et al.* suggested, tactile steering wheels can positively affect takeover performance in conditionally automated vehicles, even though their study did not incorporate multi-modal takeover requests (TORs) [241]. As Chun *et al.* pointed out, haptic feedback—such as vibrotactile warnings delivered via the steering

wheel or seatbelt—can significantly improve driver response time and collision prevention, especially when visual attention is diverted [245]. Similarly, as Ekman *et al.* emphasized, haptic feedback can enhance situational awareness and trust in automated vehicle systems when visual and auditory channels are overloaded [246].

This study introduces a bio-inspired pneumatic haptic interface, the Pneumatic Haptic Silicon Sac (PHSS), inspired by animals like frogs and frigatebirds. Integrated into a steering wheel, the pneumatic haptic steering wheel combines audio and visual feedback for intuitive driver interactions. The goal of this device/technology is to enhance driver takeover performance in autonomous vehicles (AVs), addressing human-vehicle co-driving challenges. To evaluate the pneumatic haptic steering wheel, we developed a prototype tested in a controlled environment. Our research explores how this haptic system improves takeover requests (TOR) and enhance performance in conditional AVs.

4.2.2. Methodology

In our early stage tryouts, attaching precise actuated Baromorph elastomers to a steering wheel was difficult due to the curved surface, which limited airflow and worsened adhesion problems. Additionally, miniaturizing Baromorph for tight spaces pushed the limits of current fabrication techniques, as smaller channels required greater precision and risked structural failures with repeated actuation. Hence, we have to switch to a new approach to achieve our research goal on steering wheel. The Pneumatic Haptic Silicon Sac (PHSS) interface was designed to mimic biological communication mechanisms of animals such as frogs and Siamangs (Figure 4.1), which use inflatable air sacs to convey signals. To replicate this behavior, flexible silicone sacs were fabricated using reverse molding techniques with 3D-printed molds. A silicone mixture (Smooth-On EcoFlex 00-30) was poured into the molds, cooled, and layered with silicone film to create deformable air cells (Figure 4.2). These sacs were then integrated symmetrically onto a Logitech G27 steering wheel, forming a bio-inspired tactile interface. Each sac was connected to a pneumatic system comprising a 6V DC vacuum pump, digital valves, and silicone tubing, controlled by an Arduino microcontroller to enable inflate/deflate cycles. The system ensured a safe and energy-efficient operation while providing a gentle squeezing sensation to the driver’s palms.



Figure 4.1: Frog and Siamang's vocal sac

The purpose of the vocal sac is usually as an amplification of their mating or advertisement call, as well as increase body size to scare off pursuers.

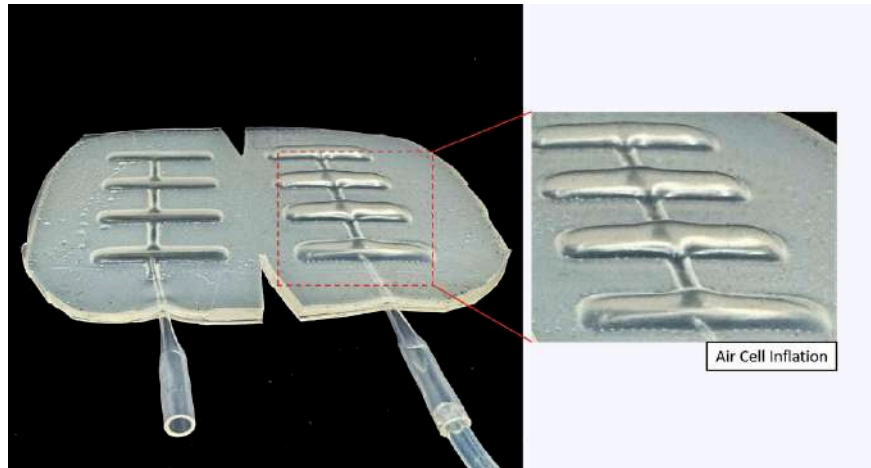


Figure 4.2: Pneumatic Haptic Silicon Sac

The PHSS interface was synchronized with visual and auditory cues to create a unified multi-modal TOR system (Figure 4.3). Visual alerts included flashing icons on the vehicle's dashboard display, while auditory warnings consisted of pre-recorded vocal prompts. The haptic component involved a sequential inflation pattern across the silicone sacs, designed to mimic natural escalation cues. This tri-modal system was programmed to activate during planned TOR scenarios, following general principles of Level 3 (L3) conditions.

To evaluate the system, a controlled experiment was conducted by using the CARLA Simulator, specifically environment Town06, a low-density urban environment with highway driving conditions. Twenty participants (21–30 years old, $M=27$, $SD=2.38$; 8 female, 12 male) were recruited, all with valid driver licences and having at least one year of driving experience. During the experiment, participants go through four TOR conditions:

- **Vision-Audio (VA) condition:** Flashing icons + vocal alerts.
- **Vision-Haptic (VH) condition:** Flashing icons + PHSS inflation.
- **Audio-Haptic (AH) condition:** Vocal alerts + PHSS inflation.
- **Vision-Audio-Haptic (VAH) condition:** A Combination of visual, auditory, and haptic

cues.

It is important to note that the modalities used in this study were not perfectly symmetrical: the auditory alerts were language-based (vocal prompts), whereas the visual (icons) and haptic (inflation) cues were symbolic/non-linguistic. This choice was made to reflect common automotive interface design, where urgent auditory information is often conveyed through speech. However, we acknowledge that this asymmetry could be a confounding factor, as language-based cues might be processed differently from symbolic ones. Our primary comparison of interest was between the tri-modal condition (VAH) and bi-modal conditions, with the understanding that future studies should control for this by using non-linguistic auditory icons (earcons) for all audio conditions.

To control for order effects, the sequence of conditions was randomized for each participant using a Python-based script, ensuring that no fixed presentation order biased the results.

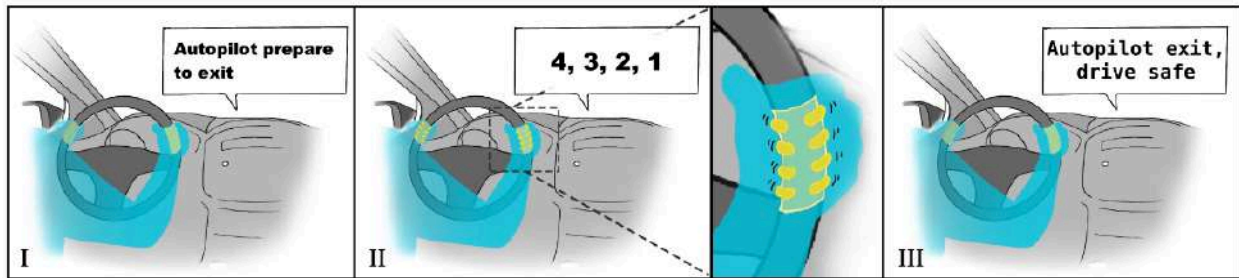


Figure 4.3: The pneumatic haptic interface steering wheel interaction flow

For each trial, the vehicle starts in a stable speed in autonomous mode, navigating a predefined route. After around 800 meters (the exact length was randomized by a programmed random number to prevent predictable behavior), the simulator triggered a TOR due to simulated sensor degradation, prompting participants to resume manual control. Data collection focused on two metrics: 1. Takeover Time: the duration from TOR activation to the driver's first control input; 2. Trust: Questionnaires adapted from Jian *et al.* [145], using a 7-point Likert scale to assess perceived reliability and comfort, after each trail was finished.

Data from one participant was excluded from the analysis due to a technical malfunction of the

prototype during their session, which resulted in incomplete data collection. Consequently, the final analysis was performed on 76 valid trials from the remaining 19 participants. While this resulted in an unbalanced design (19 participants for 4 conditions), the statistical methods employed (Friedman test for non-parametric repeated measures) are robust to such minor imbalances. Statistical analysis employed the Shapiro-Wilk test for normality and Friedman tests for non-parametric comparisons of takeover times, while repeated-measures ANOVA evaluated trust scores.

4.2.3. Results & Discussion

The Friedman test showed significant differences in takeover times across TOR types ($\chi^2 = 14.25$, $df = 3$, $p = 0.003$), indicating haptic multi-modal TOR (AVH) reduces takeover time significantly. Post-hoc analysis from Dunn's test with Bonferroni correction revealed that the takeover time for the AVH type was significantly lower compared to the AH type ($p = 0.002$), and the difference between AV and AVH showed significance ($p = 0.049$). Other comparisons did not show significant differences. The results from the repeated measures ANOVA indicated a significant effect of TOR type on trust levels ($F(3, 54) = 11.87$, $p < 0.001$). To further investigate the differences between types, we conducted post-hoc test using the Tukey HSD test (Figure 4.4).

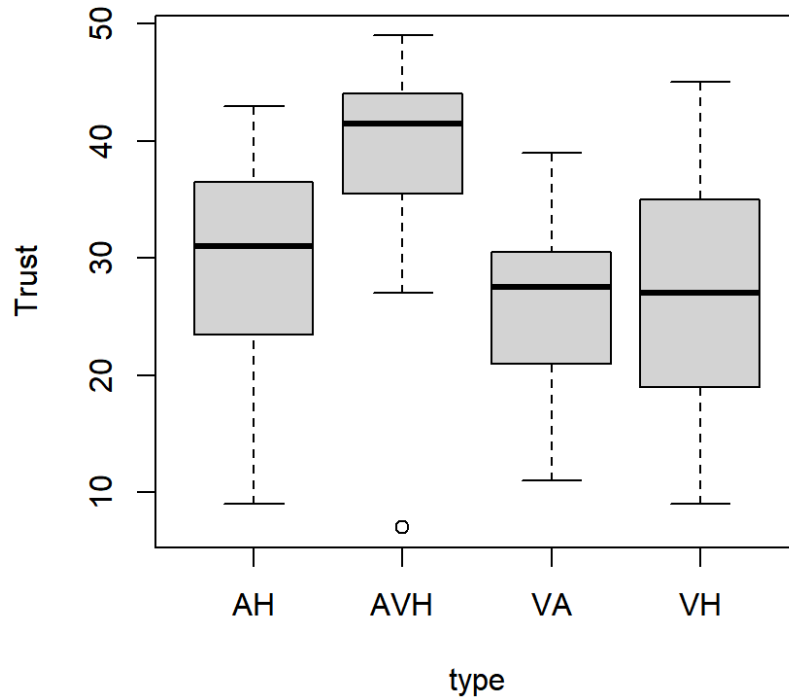


Figure 4.4: Boxplot of trust levels by type with Tukey HSD post-hoc comparisons

The results suggest that when visual, auditory, and haptic feedback are combined, it improves driver takeover performance by significantly reducing takeover time. Notably, AVH significantly improved takeover time compared to AV and AH, but showed no significant difference compared to VH. This indicates a decrease in cognitive workload and an enhancement of situational awareness, aligning with the study by Chun *et al.* that applied vibrotactile haptic feedback to speed up human response times [245]. This preference emphasizes haptic technological innovation. Increased trust and perceived reliability suggest that multi-modal TOR systems can address user acceptance challenges associated with autonomous vehicle (AV) technology [247]. Haptic cues mimic natural human interactions, reassuring drivers in high-workload environments.

4.2.4. Conclusion of Study 1

The Pneumatic Haptic Silicon Sac (PHSS) steering wheel demonstrated significant potential in enhancing multi-modal TOR systems for Level 3 autonomous vehicles. By integrating bio-inspired pneumatic feedback with visual and auditory cues, the Vision-Audio-Haptic (VAH) condition achieved the shortest takeover time ($p=0.003$) and highest trust scores ($p<0.001$), validating the hypothesis that synchronized multi-modal alerts improve driver performance and confidence. The bio-inspired pneumatic haptic feedback—inspired by natural communication mechanisms—proved effective in reducing cognitive load while fostering TOR performance, aligning with findings from Chapter 3 on biomimetic design’s capacity to enhance user engagement. However, this study has limitations. First, the experimental setting may not fully replicate real-world conditions—for example, it took place in a simulator environment with controlled variables and limited sensory distractions, which do not reflect the unpredictability, cognitive load, and multitasking demands encountered in actual driving. Second, the study focused solely on planned takeovers, excluding sudden or emergency transitions that may involve time-critical decisions and higher stress levels. What’s more, the PHSS interface’s symmetrical design—providing identical tactile feedback on both sides of the steering wheel—limited its ability to convey clear directional information. As a result, users may find it difficult to distinguish between cues indicating a left versus right maneuver, which is particularly problematic in scenarios requiring immediate lane changes or obstacle avoidance.

While Study 1 established the efficiency of pneumatic feedback in planned TORs, its comparative advantages over established haptic modalities—such as vibrotactile systems—remain unexplored. Vibrotactile interfaces, though widely studied, often prioritize urgency over comfort, potentially undermining trust in prolonged or non-critical scenarios. Study 2 addresses this gap by comparing pneumatic and vibrotactile feedback within the same steering wheel framework. This comparison not only evaluates performance metrics (e.g., reaction time, directional accuracy) but also examines how modality choice influences driver situational awareness. Furthermore, Study 2 builds on the findings of Study 1, which revealed that the PHSS interface’s symmetrical haptic feedback made it difficult for drivers to distinguish left from right during lane-change scenarios. To address this issue,

Study 2 tests whether using asymmetrical haptic patterns or assigning different directional cues to specific modalities (e.g., vibrations on one side vs. inflation on the other) can enhance drivers' ability to correctly interpret lane-change instructions.

4.3. Study 2: Comparative Analysis of Pneumatic and Vibrotactile Feedback for TOR

4.3.1. Introduction

Building on the findings of Study 1, which validated the Pneumatic Tactile Silicon Sac (PTSS) as an effective modality for multi-modal Takeover Requests (TORs), Study 2 addresses two critical gaps: (1) how pneumatic feedback compares to conventional vibrotactile systems in balancing urgency, comfort, and directional clarity, and (2) whether modality-specific advantages can be adapted contextually to optimize driver performance and trust. While Study 1 suggested that bio-inspired pneumatic haptic interface reduce cognitive load and enhance trust in planned TORs, it also left limitations in conveying unambiguous directional signals (e.g., left vs. right lane changes) and open questions about its efficiency against applied vibrotactile interfaces.

As Hassan *et al.* pointed out in the study HapWheel, while vibrotactile feedback effectively reduces driver workload and reaction time, its conventional use in alert systems may startle users or create discomfort in prolonged interactions, as it often emphasizes urgency over user comfort [248]. Conversely, pneumatic feedback—with its naturally biomimetic inflation patterns—suggests potential to balance safety alerts with natural human perception. However, the trade-offs between these modalities remain underexplored, particularly in scenarios requiring precise directional guidance while remaining low workload under urgency.

4.3.2. Motivation

In this study, the PTSS framework was upgraded by integrating a dual-modal haptic steering wheel capable of switching between pneumatic and vibrotactile feedback. This design enables direct comparison of both modalities under identical experimental conditions, testing hypotheses about their distinct impacts on:

- **Reaction Time (RT) and Time to Collision (TTC):** Whether the gentle pneumatic

feedback’s alerts sacrifice speed for comfort.

- **Directional Accuracy:** Whether localized vibrations outperform asymmetrical inflation patterns in guiding lane changes.
- **Driver Workload and Trust:** How mechanical (vibrotactile) vs. organic (pneumatic) cues influence perceived system reliability and workload.

Addressing these questions, Study 2 bridges the biomimetic principles of Study 1 with practical human factors engineering, advancing toward adaptive haptic systems that dynamically switch modalities based on contextual urgency, driver state, and environmental demands. The following sections detail the methodology, results, and implications of this comparative analysis, including in actionable guidelines for context-aware pneumatic haptic interaction in autonomous vehicles.

4.3.3. Methodology

To enable a direct comparison between pneumatic and vibrotactile feedback, a dual-modal haptic steering wheel was developed, integrating both modalities into a single Logitech G27 steering wheel. The pneumatic component retained the Pneumatic Haptic Silicon Sac (PHSS) design from Study 1, featuring two silicone pads with eight air sacs each, fabricated using Smooth-On ExoFlex 00-30 silicone. These sacs were inflated/deflated via ZT370-01 air pumps and JS0520L valves, controlled by an ESP32 microcontroller to ensure precise pressure regulation (Figure 4.5). The vibrotactile component incorporated two pancake vibration motors (10mm, 3V) embedded beneath the silicone pads, capable of delivering localized vibrations at 120 Hz. Both modalities operated independently, allowing seamless switching between pneumatic and vibrotactile feedback without hardware reconfiguration (Figure 4.6, 4.7, 4.8).

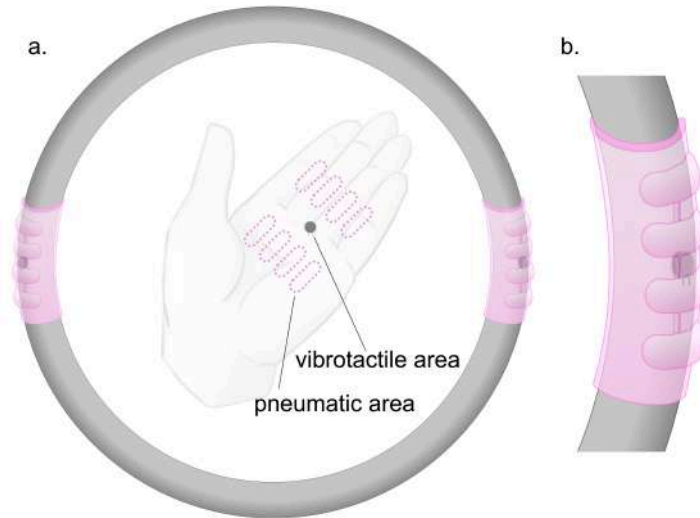


Figure 4.5: Dual-modal haptic interface on steering wheel and the interactive area

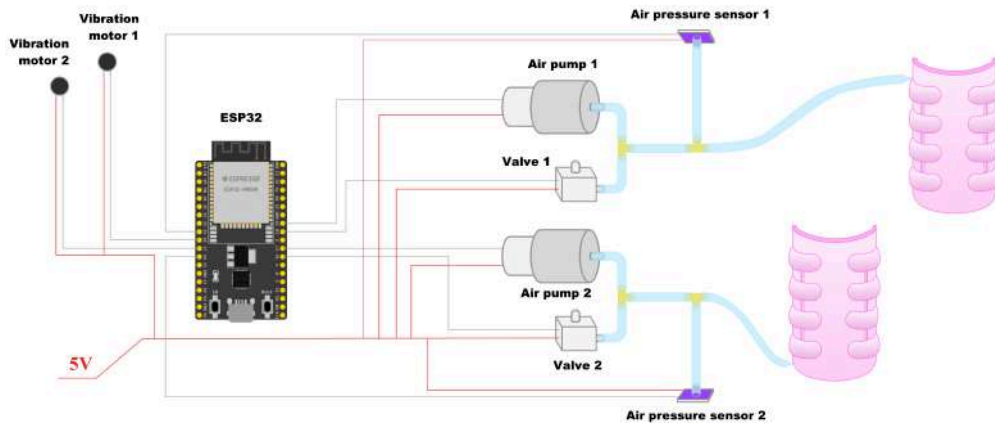


Figure 4.6: Schematic overview of the electrical and pneumatic layouts

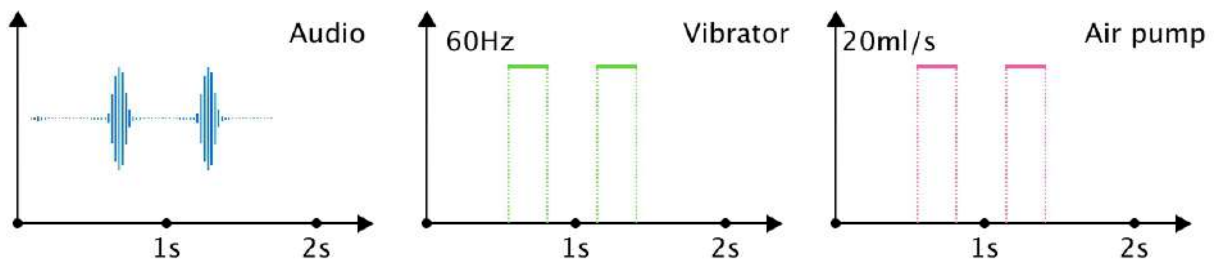


Figure 4.7: Notifications: audio, vibration and inflating

This study employed a within-subject design, where each participant experienced nine distinct types of notifications signaling the presence of a stopped car on the road. The primary objective was to examine participants’ responses to various tactile, auditory, and combined notifications that triggered a takeover request (TOR) followed by a lane change maneuver. Table 4.1 summarizes the notification conditions and the corresponding lane change requirements. In some scenarios, participants were allowed to freely choose either the left or right lane to avoid a stopped vehicle ahead—this “free change” condition was designed to simulate real-world flexibility in obstacle avoidance.

Table 4.1: Notification Modalities and Lane Change Requirements

Task Label	Notification Modality	Haptic	Lane Change Requirement
1	Base Audio	No	Freely change left or right
2	VB Audio + Vibration	Both	Freely change left or right
3	VL Audio + Vibration	Left	Change to left
4	VR Audio + Vibration	Right	Change to right
5	VNA Only Vibration	Both	Freely change left or right
6	PB Audio + Pneumatic	Both	Freely change left or right
7	PL Audio + Pneumatic	Left	Change to left
8	PR Audio + Pneumatic	Right	Change to right
9	PNA Only Pneumatic	Both	Freely change left or right

At the beginning of the study, participants were briefed on the objectives, devices, and procedures. Informed consent was obtained, and participants underwent a training session to familiarize themselves with the devices and the experimental environment. This session also served to minimize the risk of simulation sickness (Figure 4.9).

After a variable duration of 10–15 seconds to avoid predictability, an auditory "beep" signal indicated the presence of a stopped car ahead, triggering a TOR. Upon hearing the signal, participants were required to shift their attention back to the main road display, take manual control of the steering wheel, and press the accelerator to maintain vehicle speed as the automated vehicle decelerated. Participants then responded to the notification and executed a lane change based on the guidance provided by the notification modality.

After each task, participants took short breaks between each task to reduce fatigue and maintain performance consistency. After completing all tasks, participants participated in a brief interview to provide feedback and suggestions for the study. These tasks were provided to participants in *random.shuffle* order, to prevent learning bias.

The driving environment consisted of a five-lane straight road, with participants starting in the middle lane for all tasks. During the experiment, several data points were collected for analysis, including Time to Collision (TTC), defined as the time from the TOR signal to the moment of collision avoidance [249], and Reaction Time (RT), which measured the time from the TOR signal to the participant's initial steering wheel movement [250] (Figure 4.10). Verbal feedback was also gathered in written form during the post-experiment interview.

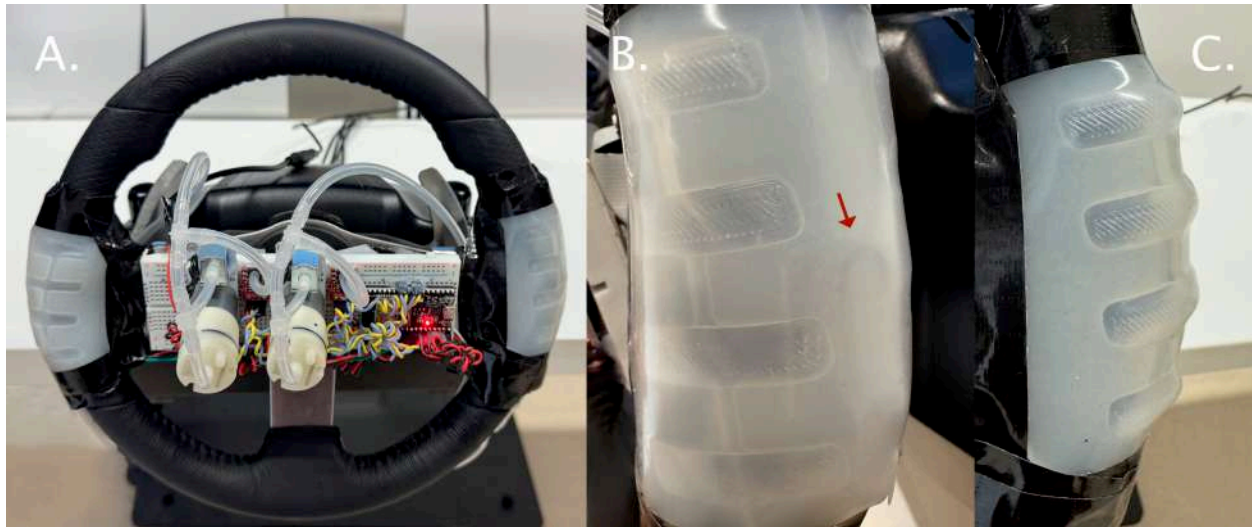


Figure 4.8: Dual-modal haptic steering wheel
A. Steering wheel; B. Vibrator is beneath the silicone pad; C. Inflated air sacs



Figure 4.9: Experiment environment
A.Simulated driving; B. Participant is watching a movie before TOR

The experiment was conducted in a controlled environment to ensure consistency across sessions. Variables such as lighting, room temperature, and seating arrangements were standardized to minimize external influences.

Existing studies suggest that gender and driving experience have minimal impact on takeover responses [251, 252], whereas age can influence situational awareness and reaction times [253]. To address this, participants were recruited from a younger demographic of licensed drivers from Télécom Paris. A total of 27 participants (11 female; mean age = 25.5 years, SD = 5.63, all right handed) participated in the study. Two participants had limited experience with automated driving, specifically Level 1 adaptive cruise control, the rest had no experience on any form of automated driving, even experimental simulation. Upon completing the study, participants received a 5-euro reward.

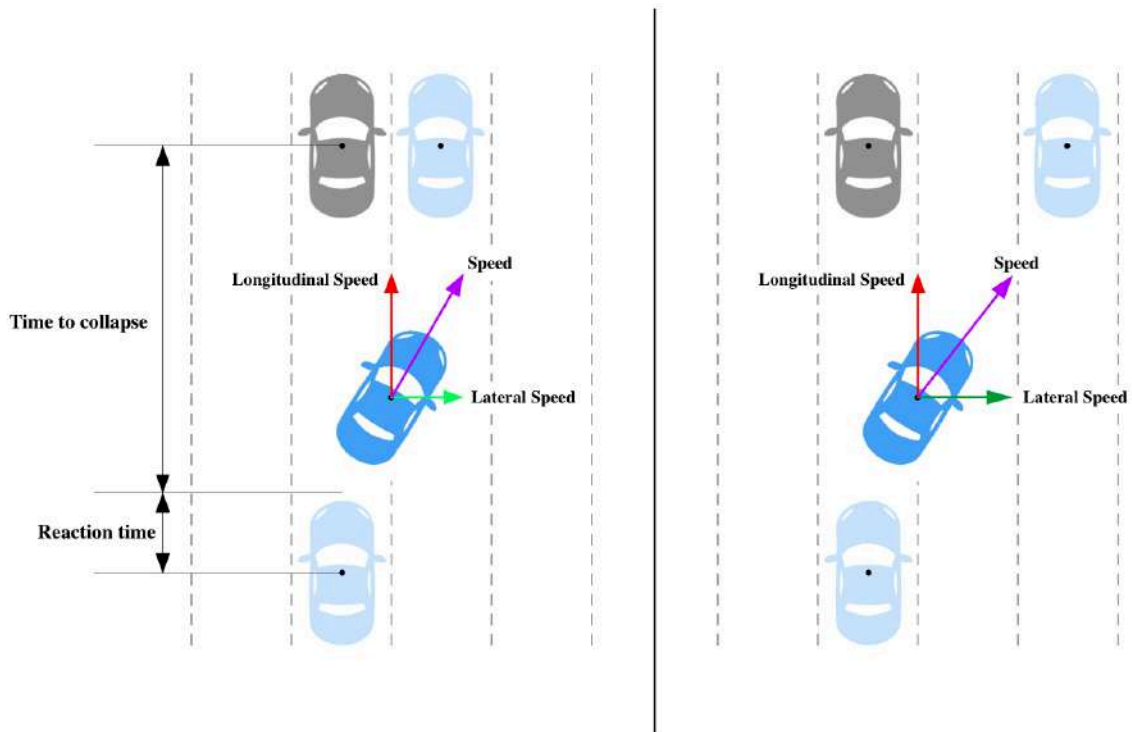


Figure 4.10: Post-TOR speed
 Some participants continuous changed 2 lanes, resulting in a larger lateral speed

4.3.4. Results & Discussion

To compare haptic notification, alongside with audio, we performed Friedman tests in time to collision (TTC) and reaction time (RT) among Task 1 (Base), Task 2 (Vibrotactile Both side), Task 5 (Vibrotactile but No audio), Task 6 (Pneumatic Both side) and Task 9 (Vibrotactile but No audio). The result revealed that there is a signification difference in TTC ($Q=13.185$, $p=0.01$) and RT ($Q=84.652$, $p<0.01$). Post-hoc test by Mann-Whitney with Bonferroni corrections support this finding: for both TTC and RT, the base condition is significantly different from other conditions, suggesting that multi-modality notifications (audio + vibrotactile or audio + pneumatic) may result in longer time to collision (the higher value is better) and faster reaction time (the lower value is better). These results suggest that multi-modality notifications (combining audio with either vibrotactile or pneumatic cues) lead to faster reaction times compared to the base condition.

However, the result among Task 2 (Vibrotactile Both side), Task 5 (Vibrotactile but No audio), Task 6 (Pneumatic Both side) and Task 9 (Vibrotactile but No audio) suggested that there is significant difference comparing with and without audio notification, TTC ($Q=9.889$, $p=0.01$) and RT ($Q=66.155$, $p<0.01$), the absence of audio notification was associated with noticeably increased reaction times, supporting findings in Study 1 that adding audio to haptic signals (both vibrotactile and pneumatic) significantly enhances reaction time.

The comparison between Task 2 (Vibrotactile Both side) and Task 6 (Pneumatic Both side) was conducted by Mann-Whitney U-test, The test showed no significant difference between these conditions, suggesting that participants adapted similarly to both types of haptic signals (Figure 4.11, 4.12).

We further analyzed the effects of direction-specific haptic signals in Task 3 (Vibrotactile left), Task 4 (Vibrotactile right), Task 7 (Pneumatic left), and Task 8 (Pneumatic right). The Friedman test showed a significant result in RT ($Q=8.988$, $p=0.02$), but not in TTC ($Q=3.844$, $p=0.27$). However, post-hoc Mann-Whitney tests with Bonferroni correction found no significant differences across any pairs, with all p-values above the corrected threshold of 0.0083 (for 6 comparisons).

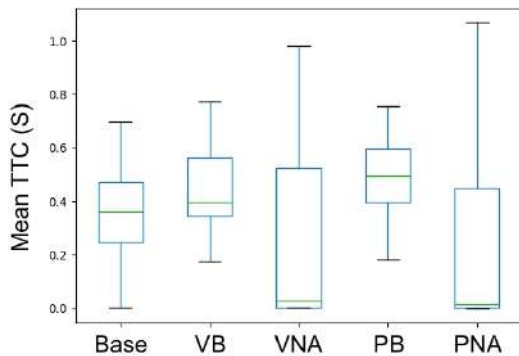


Figure 4.11: Box Plot of Time To Collision

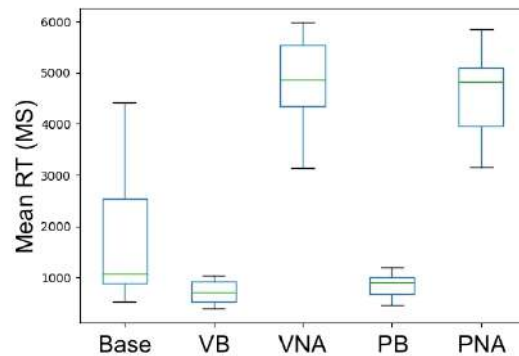


Figure 4.12: Box Plot of Reaction Time

Furthermore, we calculated Speed (S), Lateral Speed (LS), and Longitudinal Speed (LGS) following the Takeover Request (TOR) during the directional tasks. Results from the Friedman test indicate

significant differences across conditions: S ($Q = 25.80, p < 0.01$), LS ($Q = 51.75, p < 0.01$), and LGS ($Q = 25.88, p < 0.01$). Notably, higher speeds were observed following vibrotactile notifications, which may reflect elevated participant anxiety in response to mechanical vibrations. This suggests that vibrotactile cues led to faster post-TOR driving behavior compared to pneumatic cues (Figures 4.13, 4.14, and 4.15). Participants noted vibrations felt “mechanical” and “urgent,” suitable for emergencies but overwhelming in routine scenarios.

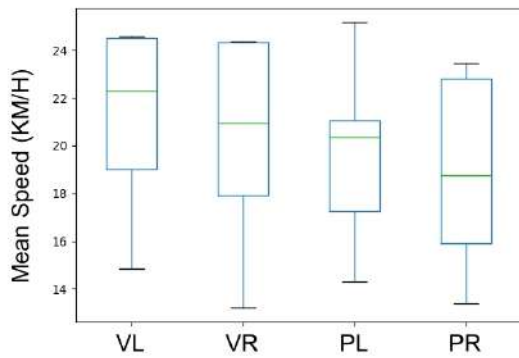


Figure 4.13: Box Plot of Speed

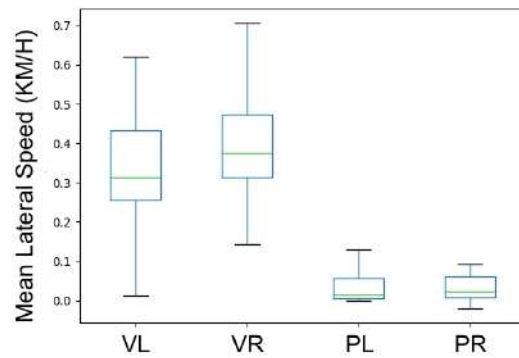


Figure 4.14: Box Plot of Lateral Speed

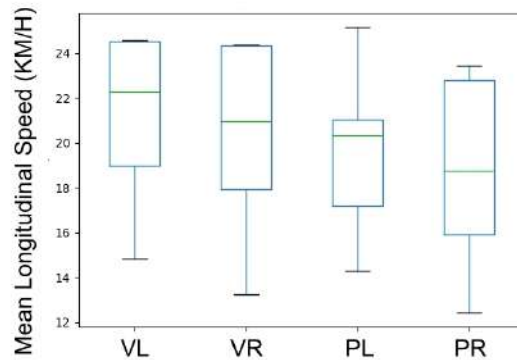


Figure 4.15: Box Plot of Longitudinal Speed

Finally, we calculated the accuracy of changing lane tasks: All conditions involving lane changes to the right (both Vibration Right and Pneumatic Right) achieved a 100% success rate. This suggests that participants were consistently able to correctly respond when the task required them to change lanes to the right. This outcome aligns with the behavior expected in right-hand traffic

environments, where drivers are more accustomed to changing lanes to the right. In contrast, conditions requiring participants to change to the left lane (both Vibration Left at 77.78% and Pneumatic Left at 88.89%) showed lower accuracy (Table 4.2). This indicates that participants were less successful in executing left lane changes accurately. This difference may be due to driver habits and comfort, as right-hand traffic drivers tend to favor right lane changes, making left changes less automatic or familiar.

Some participants noted in interviews that the vibrotactile feedback on one side of the steering wheel could sometimes make the entire wheel feel as though it was vibrating. This may have affected their ability to accurately detect which side was vibrating, potentially contributing to the lower accuracy for left lane changes. This effect would be especially pronounced for left-side cues, since they are less expected or habitual, giving participants fewer contextual clues to rely on when directional feedback is ambiguous. The feedback suggests that, for some participants, the specificity of the vibration or pneumatic signal may not have been clear enough, leading to occasional misinterpretations of the intended direction. These findings underscore the importance of designing tactile feedback systems that clearly and accurately convey directional cues, especially for tasks requiring directional changes. Ensuring that feedback is distinguishable between sides of the steering wheel could improve response accuracy for less familiar actions, such as left lane changes in right-hand traffic environments. Furthermore, driver training or orientation on how to interpret these signals may also be helpful, especially if tactile feedback is used as a critical driver assistance feature.

Table 4.2: Accuracy of Change Lane

Feature	Vibration	Pneumatic
Left	77.78%	88.89%
Right	100%	100%

4.3.5. Conclusion of Study 2

Study 2 compared pneumatic and vibrotactile haptic feedback modalities for Takeover Requests (TORs) in Level 3 autonomous vehicles, building on Study 1’s validation of bio-inspired pneumatic

interfaces. The results demonstrated that multi-modal feedback combining audio with either haptic modality significantly improved driver performance over audio-only alerts, with shorter reaction times ($p < 0.01$) and higher directional accuracy in lane-change tasks.

Aligned with Study 1's findings, the gentle, inflation-based cues promise smoother transitions and lower post-TOR speeds ($p < 0.01$), suggesting reduced driver stress. Its biomimetic design—akin to Chapter 3's emotionally congruent haptics—fostered intuitive interactions, particularly in non-urgent scenarios. While equally effective in accelerating reaction times, its mechanical vibrations led to higher lateral speeds ($p < 0.01$) and occasional misinterpretations in directional tasks (e.g., left vs. right). Participants noted that unilateral vibrations sometimes felt diffuse, contributing to a 77.78% accuracy rate for left lane changes versus 100% for right changes.

Together, the two studies underscore the complementary strengths of pneumatic and vibrotactile modalities. Study 1's PTSS interface improved trust and reducing cognitive load during planned TORs, while Study 2 revealed that although vibrotactile systems produce mechanically harsh sensations, they are essential in high-urgency situations because they trigger faster responses. Study 2 results showed that participants exhibited higher speeds following vibrotactile notifications, indicating increased alertness or anxiety, which led to quicker post-TOR driving behavior compared to pneumatic cues. This demonstrates that vibrotactile feedback effectively captures immediate attention when rapid action is critical. The directional challenges identified in both studies—symmetrical PHSS inflation in Study 1 and diffuse vibrations in Study 2—highlight a shared need for asymmetrical, localized haptic patterns to improve lane-change clarity.

However, the study has limitations: Both studies relied on simulator-based experiments, which cannot fully replicate real-world stressors like traffic variability or prolonged automation exposure. Plus, participant exposure was limited to short trials, left long-term effects over extended use remain unexplored.

This two-study progression—from introducing a biomimetic interface (Study 1) to benchmarking it against conventional systems (Study 2)—lays the groundwork for developing adaptive Human-

Vehicle Interaction frameworks. By unifying the principles of biomimicry with human factors engineering, this work advances toward steering wheel interfaces that are not only safe but also designed to become intuitive by effectively integrating vibrotactile cues. Although the raw vibration sensations may initially feel harsh or unfamiliar, their clear and urgent nature helps drivers quickly recognize and respond to critical alerts, making the overall interaction more natural and intuitive over time.

While this study validated the effectiveness of specific texture-frequency pairings, the design space of these stimuli is vast. A more granular, parametric exploration of the timing and synchronization between haptic events and on-screen actions could reveal optimal strategies for maximizing emotional impact and immersion. Future work could systematically vary the latency and rhythm of haptic cues relative to narrative beats to understand their contribution to the user's sense of coherence and engagement.

CHAPTER 5

Designing a Haptic Interface for Enhanced Non-Verbal Human-Robot Interaction

5.1. Introduction

Chapter 4 explored how bio-inspired pneumatic haptic interfaces can optimize driver-vehicle communication through multi-modal Takeover Requests (TORs), where tactile feedback was synchronized with visual/auditory alerts to enhance situational awareness and trust. Building on this understanding of tactile communication in high-stakes interactions, Chapter 5 shifts focus to non-verbal human-robot interaction, investigating how bio-inspired haptic signals can support emotional expression and social engagement. Traditionally, human emotional communication relies equally on physiologically-inspired signals—such as breathing patterns and heartbeat rhythms—which are often overlooked in HCI design [254, 255]. As Feijt *et al.* and other researchers pointed out, these signals provide subtle yet powerful cues about internal affective states, fostering empathy and rapport in human-human interaction [256] [257, 258]. Bridging this gap, Chapter 5 investigates how integrating bio-inspired haptic feedback into a humanoid robot can enhance emotional expressiveness and user perception.

The work presented here extends the discussion of non-verbal modalities by introducing a pneumatic haptic system designed to replicate human-like chest movements associated with emotions such as fear, sadness, and happiness. Unlike the controlled, deliberate gestures studied in Chapter 4, these physiological signals operate at a subconscious level, offering a more intuitive and biologically resonant form of interaction. By combining these physiologically-inspired cues with the voluntary gestures analyzed earlier, we aim to create a more holistic and emotionally expressive robotic platform.

This chapter presents the development of a silent, silicone-based pneumatic interface mounted on a Meka M3 humanoid robot, capable of simulating both breathing rhythms and heartbeat dynamics. Experimental results suggest that participants more accurately recognized emotions when both voluntary and physiologically-inspired signals were present, validating the hypothesis that physiolog-

ical feedback enhances HCI/HRI. These findings align with Chapter 4’s conclusion that multi-modal communication improves interactive system expressiveness, while also introducing a new dimension of bio-inspired interaction.

5.2. Motivation

Non-verbal communication is a cornerstone of human interaction, shaping how people perceive social agents, including robots. For HRI to feel natural and intuitive, robots must be able to both interpret and express non-verbal cues. While robots themselves do not possess emotions, simulating physiologically-inspired signals such as breathing or heartbeat can serve as a powerful communicative channel to influence the user’s perception of the robot’s internal state and intentions. This, in turn, can foster empathy, enhance social presence, and build trust, making the interaction more engaging and effective from the human’s perspective. While prior research has focused on voluntary non-verbal cues (e.g., facial expressions, arm movements [259]), involuntary signals—such as breathing patterns and heartbeats—remain under-explored despite their proven role in human empathy and emotional entrainment [260].

Existing approaches to simulating physiological signals often rely on vibration motors or rigid mechanical systems [254]. These methods suffer from audible noise, limited biomorphic fidelity, and restricted dynamic range (e.g., vibrations cannot replicate the gradual inflation/deflation of lungs or the subtle variability of a heartbeat). The stuffed-toy robot developed by Yoshida *et al.* used a DC motor for heartbeat simulation, which produced disruptive noise and failed to convey naturalistic pressure variations. Similarly, vibration-based interfaces struggle to synchronize with other modalities (e.g., gestures), reducing their perceived coherence in multi-modal HRI [257].

To overcome these shortcomings, we adopt a pneumatic soft-robotic approach, leveraging silicone-based actuators to mimic the organic movements of human respiration and cardiac activity. This aligns with recent work by Christiansen *et al.* [261], whose BioMORF soft robotic skin demonstrated that biomorphic materials (e.g., silicone membranes) enhance nonverbal communication by replicating the continuous, lifelike deformations of biological tissue. Like BioMORF, our system prioritizes silent operation, dynamic shape-morphing, and seamless integration with a humanoid

robot's anatomy—key factors for fostering perceived "aliveness" and emotional rapport [262]. Plus, The integration of physiologically-inspired signals is grounded in entrainment theory [260], where humans unconsciously synchronize their physiological rhythms (e.g., breathing) with others. By replicating these cues, robots can evoke stronger emotional responses and trust. For example, slow, deep breathing patterns (associated with sadness) or rapid heartbeats (linked to fear) provide implicit emotional context that complements voluntary gestures [263, 264].

Building upon the dissertation's broader goal of developing biomimetic, multi-modal HCI/HRI systems established in Chapter 3, this chapter makes several key contributions. First, it introduces a novel pneumatic haptic interface designed to address the limitations of vibration-based actuation methods. The system's capability to effectively convey emotions through bio-inspired breathing and heartbeat animations is thoroughly validated. Furthermore, it presents empirical evidence demonstrating significant improvements in emotion recognition when these physiologically-inspired cues are combined with voluntary gestures. These design innovations and experimental results directly address recent calls within the research community for more organic, physiologically plausible interfaces [265], while simultaneously establishing a scalable framework that could inform future developments in soft robotics applications.

5.3. Methodology

5.3.1. System Design

In this section, we present the device using a miniature pneumatic system with silicon actuators to simulate both breathing and heartbeat. The breathing device includes a specially molded silicon pouch designed to mimic human breathing motions, as well as a Baromorph disk capable of animating heartbeats up to 135 BPM (Figure 5.1).

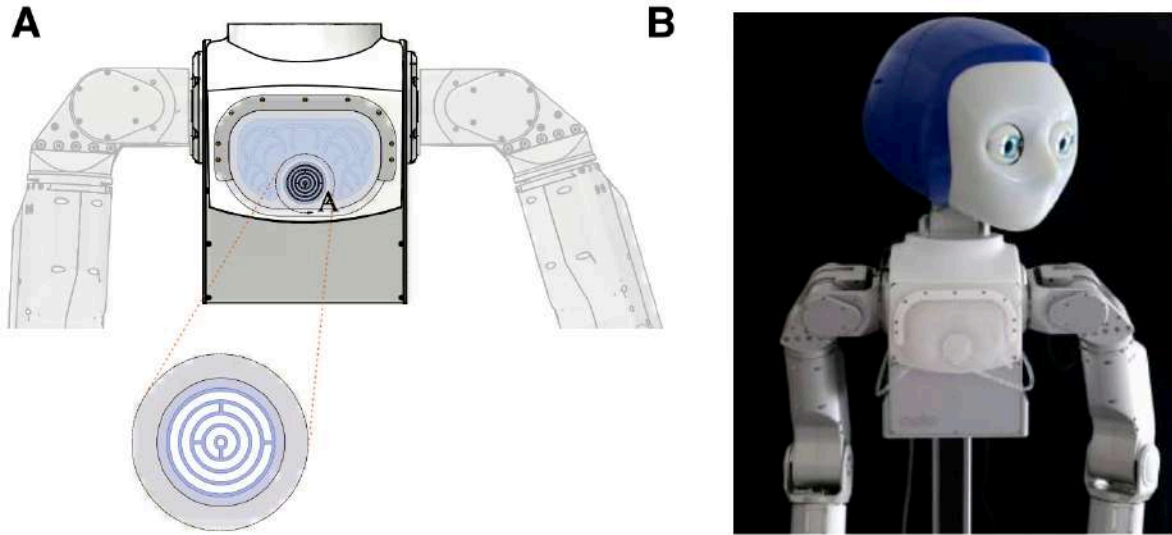


Figure 5.1: Meka robot with the haptic interface integrated into its chest

The breathing animation system was designed to replicate the natural dynamics of human respiration through pneumatic actuation. At the core of this subsystem lies a custom-molded silicone pouch that mimics the anatomical structure and movement patterns of human lungs [264]. The pouch was engineered with an internal cavity capable of volumetric expansion and contraction between 0.015 and 0.035 liters, corresponding to shallow and deep breathing states observed in emotional expression studies.

To achieve physiologically accurate breathing patterns, we implemented a silent pneumatic system capable of generating respiratory rates up to 40 breaths per minute. The system's dual-flow architecture precisely controls inhalation and exhalation phases through coordinated valve operations, creating the characteristic rising-falling rhythm of natural respiration. This dynamic was achieved by carefully balancing input and output airflow resistance parameters, allowing for programmable control over both breathing depth and rhythm.

The control architecture mimics the time-dependent charging/discharging behavior observed in biological systems, where inhalation corresponds to gradual pressure buildup and exhalation follows an exponential decay profile. Through empirical tuning, we established operational param-

ters that produce four clinically observed breathing patterns: slow/deep (associated with sadness), fast/shallow (fear), and moderate patterns for neutral/happy states. The silicone material’s viscoelastic properties were leveraged to create smooth, organic-looking movements that avoid the mechanical abruptness seen in earlier vibration-based prototypes.

A critical design innovation was the integration of this subsystem within the robot’s thoracic cavity while maintaining anatomical plausibility. The placement adjacent to the heartbeat animator creates coordinated chest movements that mirror human cardiopulmonary coupling. This spatial configuration, combined with matched silicone coloration, produces a cohesive biomimetic display that participants perceived as naturally integrated during interaction trials.

The heartbeat animation was achieved through the Baromorph silicone disk designed to deform in response to controlled air pressure variations. Baromorphs were transplanted to create rapid, pulsatile motions mimicking human heartbeats, benefiting from their agile response to inflation (Figure 5.2). The disk’s center displaced upward upon inflation, simulating the tactile and visual cues of a heartbeat, with a maximum operational rate of 135 beats per minute (BPM). This design prioritized responsiveness and silent operation, critical for maintaining immersion during HRI. Both the lung and the heart share the same silicon color, allowing their movements to be seamlessly integrated, further mimicking the complex motions of the human chest. We define this as a haptic interface because it produces material, embodied movement that conveys affect through tactile-like physical deformation, distinguishing it from traditional visual cues such as lights or screen-based animations. This approach aligns with prior work in embodied interaction and affective robotics, whereas haptic interfaces are not limited to direct physical contact, especially when the interface has materiality, deform-able form, and movement that afford touch—even if users don’t engage in actual contact [266, 267, 268].

The haptic interface’s pneumatic system was unified under a single actuation framework. A silent air pump served as the primary pressure source, with airflow regulated by solenoid valves and calibrated pneumatic resistors to control inflation dynamics. The resistors were tuned to modulate the inlet and outlet flow rates, enabling precise control over the heartbeat’s intensity and rhythm.

For the breathing animation, the resistors governed the expansion and contraction of a silicone pouch adjacent to the heart disk, with a volumetric range of 0.015–0.035 liters to replicate natural lung motion.



Figure 5.2: The heart animation of Baromorph

The baromorph pad changes in internal structure (width between consecutive rings) after a change in air pressure from right (high pressure) to left (low pressure)

The entire assembly was embedded within the chest cavity of the Meka M3 humanoid robot, chosen for its anthropomorphic upper-body design and compliance-safe actuators. Pneumatic tubing routed air from the base-mounted pump and valves to the chest unit, with all mechanical components housed in an acoustically insulated enclosure to minimize operational noise. The robot's height was adjustable via a prismatic joint, ensuring ergonomic alignment with participants during experiments. This integration preserved the robot's aesthetic while enabling dynamic, multi-modal emotional expression through synchronized gestures and physiological animations. Pneumatic tubing routed air from the base-mounted pump and valves to the chest unit, with all mechanical components housed in an acoustically insulated enclosure to minimize operational noise. The robot's height was adjustable via a prismatic joint, ensuring ergonomic alignment with participants during experiments. This integration preserved the robot's aesthetic while enabling dynamic, multi-modal

emotional expression through synchronized gestures and physiological animations.

5.3.2. Experimental Design

We conducted a within-subjects experiment to evaluate how physiological animations affect emotion recognition in HRI. The experiment addressed the research question: Does integrating physiological cues (breathing and heartbeat) with voluntary gestures improve emotion recognition in HRI? We hypothesized that the combined condition would enhance participants' ability to identify the robot's emotional state. During the experiment, Participants observed a robot expressing three emotions (fear, sadness, happiness) under two conditions:

1. **Condition 1 (Gesture-only):** Upper-body movements from the BEAT dataset (Figure 3.5) [15] with random head gaze.
2. **Condition 2 (Gesture + Haptic interface):** Same gestures with synchronized breathing/heartbeat animations conducted by the pneumatic interface.

The three target emotions—happiness, sadness, and fear—were selected based on their well-documented physiological signatures. In the Gesture + Haptic condition, breathing patterns were adapted from affective literature [264], with sadness represented by slow/shallow breathing, fear by fast/deep breathing, and happiness by slow/deep breathing. Additionally, heartbeat dynamics were integrated based on ECG-derived data [263]: fear was modeled with high BPM and low HRV, happiness with moderate BPM and high HRV, and sadness with low BPM and high HRV.

In total, there are 32 cues (3 emotions \times 6 upper body movement \times 2 conditions) presented in randomized order. The design tested whether adding these embodied, lifelike animations (Condition 2) would improve participants' accuracy in recognizing robot emotion compared to observing voluntary gestures alone (Condition 1).



Figure 5.3: Emotional Gesture Examples (From BEAT database [15])
 Visualized gesture examples of Happiness (top line) and Anger (bottom line) gestures

5.3.3. Participants

Twelve participants (4 female, ages 18–35, $SD = 3.15$) from Institut Polytechnique de Paris took part in the study. During the experiment, participants observed the robot’s behavior in response to different emotional cues and selected the perceived emotion from the options of fear, sadness, happiness, or "I don’t know."

During Condition 1, after each cue, participants were required to respond on a Likert scale ranging from 1 (Not at all) to 7 (Very much) to the following statement: "The arms’ gesture represented the emotion I chose." In Condition 2, participants were asked to similarly rate the following three statements after each cue:

1. The robot arms and hands’ movement represented the emotion I chose.
2. The robot haptic (breathing and heartbeat) interface expressed the emotion I chose.

After completing the tasks, participants provided qualitative feedback through a survey assessing the intuitiveness of the haptic interface, its integration with the robot’s design, and its contribution

to the robot's perceived "aliveness." Each emotional cue lasted approximately around 10 seconds , followed by a 30-second response period, resulting in a total session duration of around 25 minutes per participant (Figure 5.3).



Figure 5.4: The experiment environment

5.4. Results and Discussion

5.4.1. Emotion expression

We constructed confusion matrices $M1$ and $M2$ for conditions 1 and 2, respectively in Figure 5, where we display predicted emotion labels on the rows of each matrix, and the expected label on the column. A perfect predictor would yield a diagonal confusion matrix. Given that participants could choose from four options (three emotions and 'I don't know'), the theoretical chance level

for correct identification is 25%. However, if participants never used the ‘I don’t know’ option, the effective chance level for forced-choice among three emotions would be 33.3%. We consider both benchmarks in our evaluation. To study the effect of adding the haptic interface on the participant’s ability on deducing the robot’s emotion, we used the following scores:

$$Precision = \frac{TP}{TP + FP}$$

$$Sensitivity = \frac{TP}{TP + FN}$$

$$F_1 = \frac{2TP}{2TP + FP + FN}$$

where True Positive (TP) is the frequencies where the emotion prediction matches the intended emotion. True Negative (TN) are frequencies of correctly identify the absence of the emotion (ex: correctly recognizing the the shown emotion is "Not Sad"). False Positive (FP) denote frequencies where the participants incorrectly identify an emotion (ex: predicting "Happy" where the correct emotion is "Sad"), and False Negative (FN) denotes when the participant incorrectly miss the absence of an emotion (ex: predicting "Sad" when the correct emotion is any one but "Sad").

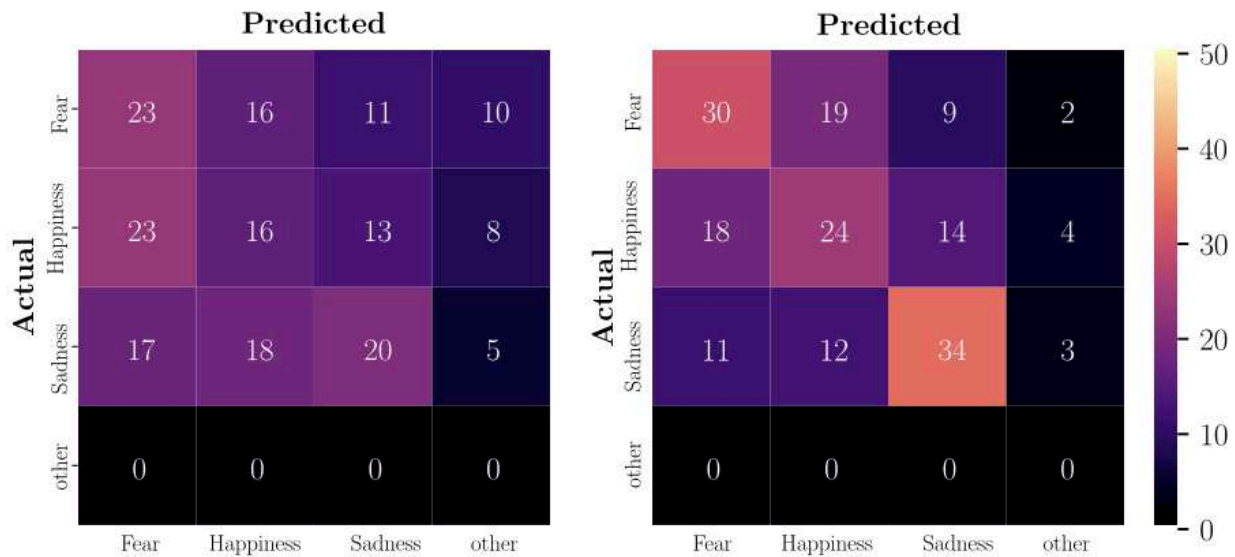


Figure 5.5: Confusion matrices for Condition 1 (left) and Condition 2 (right)

The Precision metric focuses on the accuracy of the participants in identifying an emotion out of the emotion group. Sensitivity is the proportion of actual instances of that emotion that are correctly identified by the participants in each condition. We also included the F1 score, which is the harmonic mean of precision and sensitivity. It provides a single metric that balances both precision and sensitivity, and would help compare the overall expression in each condition across the different emotion classes. The expression metrics are reported in Table 5.2. In Condition 2, the results consistently demonstrated improved expression by participants in correctly identifying the three emotions, highlighting the effectiveness of the haptic interface in enhancing recognition. The overall accuracy of the participant group in Condition 2 was 0.49, significantly higher than Condition 1. The precision metric consistently showed higher values across different emotion classes, particularly significant was the case of identifying sadness, where the precision for correctly identifying sadness reached 60% when the haptic interface was actively conveying the emotion.

Table 5.1: Expression Metrics of the participants

Emotion Class	Metrics	Condition 1	Condition 2
Fear	Precision	0.37	0.51
	Sensitivity	0.38	0.50
	F1 Score	0.37	0.50
Happiness	Precision	0.32	0.44
	Sensitivity	0.27	0.40
	F1 Score	0.29	0.42
Sadness	Precision	0.45	0.60
	Sensitivity	0.33	0.57
	F1 Score	0.38	0.58
Overall Accuracy		0.33	0.49

5.4.2. Self-reported emotion identification confidence

In Condition 1, participants were tasked with assessing their confidence in selecting an emotion based on the robot’s behavior. In Condition 2, they were prompted to specify the factors influencing their emotion choice for each cue. This approach aimed to evaluate whether the presence of the haptic interface influenced participants’ overall confidence in interpreting the robot’s behavior. Additionally, we aimed to investigate how self-reported confidence levels correlated with the accuracy of chosen emotions. Figure 5.5 illustrates a correlation between reported confidence in the

chosen emotion and the accuracy of identification. Participants were more likely to choose correctly when they expressed higher confidence in their assessment of the haptic interface. This suggests that participants were inclined to perceive emotional gestures more accurately through the haptic interface.

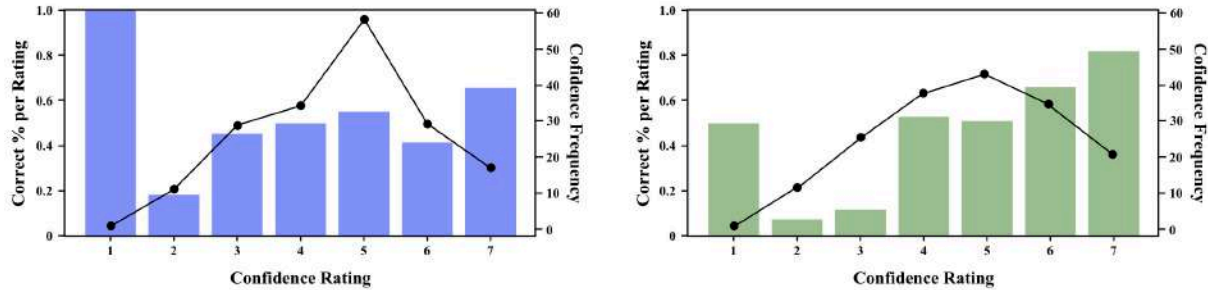


Figure 5.6: Confidence rating effect on expression in Condition 2

(Up: Confidence in gesture emotional understanding. Down: Confidence in haptic interface understanding.)

Line plots represent the frequency of reporting each confidence rating, a uni-modal distribution with a mean of 5 in both cases. Bar plots represent the percentage of correctly identified emotions with respect to all emotions with the same reported confidence

During Condition 2, participants assessed the perceived alignment between the haptic interface and the arm gestures, indicating how closely they felt these non-verbal cues aligned. Participants reported a mean matching score of $M=4.65$ on a 7-point Likert scale, with a standard deviation of 0.58. This shows the participants' perception of consistency and synchronization between the haptic feedback and the robot's arm movements during the experiment. It suggests that the integration of haptic signals enhanced the non-verbal communication, contributing to a more integrated interaction experience.

Table 5.2: Pearson's Correlation Coefficients in Condition 2

Metric	Extroversion	Agreeableness	Conscientiousness	Neuroticism	Openness
F_1	0.12	0.01	-0.53*	-0.53*	-0.26*
Precision	0.18	-0.01	-0.13	-0.18	-0.18
Sensitivity	0.01	0.07	-0.01	-0.48*	-0.32*

Note: High correlation values in bold. * indicates $p < 0.05$.

5.5. Conclusion

This chapter has demonstrated that integrating bio-inspired physiological cues (breathing patterns and heartbeat rhythms) with voluntary gestures significantly enhances emotion recognition in human-robot interaction (HRI). The pneumatic haptic interface achieved a 49% overall recognition accuracy—a 16% improvement over gesture-only interactions—with particularly strong gains for sadness identification (60% precision, up from 45%). These results support the hypothesis that bio-inspired multi-modal communication, combining both conscious and subconscious channels, fosters more intuitive and empathetic HRI.

The work builds directly on two foundations established earlier in this dissertation. First, it extends Chapter 3’s framework for biomimetic robot design by introducing physiological animations as a new dimension of bio-inspired expression. Where Chapter 3 focused on surface textures and voluntary movement patterns, this chapter has shown how internal biological rhythms (respiration, cardiac activity) can be externalized through soft robotics to enhance perceived "aliveness." Second, it complements Chapter 4’s analysis of gesture-based communication by proving that physiologically-inspired cues resolve ambiguities in emotion conveyance—particularly for nuanced states like sadness, which often rely on subtle physiological changes rather than exaggerated motions.

The findings of this study yield several significant contributions to the field of human-robot interaction. At the technical level, the development of a silent, silicone-based pneumatic system contributes to the advancement of replicating human chest movements with anatomical fidelity while overcoming the inherent limitations of conventional vibration-based actuators. This innovation enables more naturalistic and nuanced robotic expressions of physiological states.

From an empirical perspective, the study provides compelling evidence that the integration of voluntary and physiologically-inspired signals leads to measurable improvements in both emotion recognition accuracy, as quantified through F_1 score analysis, and user confidence levels, as captured by Likert scale ratings. These results demonstrate the practical benefits of multi-modal communication approaches in HRI systems.

The theoretical implications are equally noteworthy, as the findings validate the application of entrainment theory to human-robot interaction contexts. The demonstrated enhancement of emotional rapport through physiological synchronization builds upon and extends the observations made in Chapter 4 regarding the importance of gesture timing and synchrony in establishing effective communication between humans and robots. This theoretical connection strengthens the conceptual framework for understanding multi-modal interaction dynamics in HRI.

Limitations, such as the small participant pool and controlled lab environment, suggest opportunities for future work. These include longitudinal studies to assess habituation effects and technical refinements to improve heartbeat perceptibility.

Collectively, this chapter advances the dissertation’s overarching thesis: that embodied, multi-modal interfaces—spanning tactile, visual, and now physiological modalities—are essential for creating robots that communicate as naturally as humans. The results not only confirm the value of bio-inspired design (Chapter 3) but also provide a missing link in understanding how multiple communication channels interact (Chapter 4), setting the stage for unified HRI frameworks in future research.

CHAPTER 6

Conclusion

This dissertation explored the transformative potential of silicone-based pneumatic haptic interfaces across two interconnected domains: cinematic emotion enhancement and safety-critical driver-vehicle communication in automated driving systems. At the intersection of technology and human experience, this work explores the role of haptic feedback, positioning it not merely as a functional alert mechanism but as a medium for trust-building, and immersive storytelling. By integrating principles from affective computing and human-computer interaction (HCI), this research contributes to the development of haptic systems that better align with human perceptual, cognitive, and emotional characteristics.

In the realm of cinematic emotion enhancement, traditional audiovisual media often fail to fully engage the full spectrum of human sensory experience. While sight and sound dominate storytelling, the touch sense remains underexplored. This dissertation explores bio-inspired pneumatic interfaces that translate on-screen emotions into tangible tactile stimuli, such as spiked textures mirroring tension or gentle inflation evoking calmness. By synchronizing haptic feedback with narrative arcs, this work explores how haptic feedback can deepen engagement beyond passive viewing.

Conversely, in automated driving systems, the rise of Level 3 autonomy demands interfaces that balance urgency with workload. Traditional vibrotactile alerts, though effective, often induce stress, eroding driver confidence. This research explores steering wheel haptics through silicone-based pneumatic systems, drawing inspiration from natural communication mechanisms like the rhythmic inflation of frog vocal sacs. These interfaces prioritize calm, intuitive feedback, reducing cognitive load while maintaining situational awareness—an advancement as vehicles transition from tools to collaborative partners.

In human-robot interaction, a framework illustrates applying bio-inspired pneumatic haptics as a cross-domain language of trust and emotion. It explores how emotional congruence—where tactile

feedback aligns with user context—and biomimetic trust calibration can together redefine human-computer interaction.

Methodologically, this dissertation integrates perspectives from affective computing and human-computer interaction to explore how pneumatic haptic interfaces can shape emotional and interactive experiences. This work incorporates user feedback and empirical observations through structured experiments to assess how haptic cues are perceived in different contexts—cinematic viewing, automated driving, and human-robot communication—each chosen for their potential to benefit from non-verbal, embodied feedback. Below, I provide a comprehensive synthesis of findings, structured to reflect the dual focus of this research. Acknowledged limitations are also framed not as shortcomings but as catalysts for future innovation.

6.1. Answers to Research Questions

This dissertation set out to explore: *How can bio-inspired pneumatic haptic interfaces be designed and applied to enhance multimodal interaction experiences?* Across three application domains—cinematic experience, automated driving, and human-robot interaction—this research explores how pneumatic interfaces offer unique affordance for conveying emotional tone, guiding attention, and fostering non-verbal communication. In cinematic contexts, they deepen immersion by aligning haptic feedback with narrative emotion; in automated driving, they balance urgency and trust through naturalistic patterns; and in HRI, they enrich non-verbal communication by blending physiologically-inspired signals with intentional gestures. Together, the studies show that pneumatic haptics in scenarios where emotional congruence, low cognitive load, and user comfort are prioritized, while also suggesting the need for hybrid approaches (e.g., combining pneumatic and vibrotactile cues) to address context-specific demands.

6.1.1. Cinematic Emotion Experience (Chapter 3)

The central research question—**How can pneumatic haptic interfaces enhance emotional engagement in cinematic experiences?**—was addressed through controlled experiments with bio-inspired pneumatic interfaces. Participants (n=30) viewed eight movie clips categorized into four emotional quadrants (high/low arousal, high/low valence) while experiencing congruent or

non-congruent haptic stimuli. Drawing from natural textures such as sea urchin spines and cat paw pads, the bio-inspired design played a role in facilitating intuitive user responses, in line with theories of embodied cognition.

6.1.2. Pneumatic Haptic Steering Wheel in Automated Driving (Chapter 4 Study 1)

The question—**Does biomimetic pneumatic feedback on steering wheels improve driver’s takeover performance in Level 3 automated vehicles**—was investigated through the Pneumatic Haptic Silicon Sac (PHSS) steering wheel. The PHSS integrated silicone sacs inspired by frog vocal sacs, programmed for gentle inflation/deflation cycles. The research findings align with Chapter 3, where biomimetic rhythms (e.g., inflation mimicking calm breathing) reduced cognitive load, enabling smoother transitions to manual control. The PHSS highlights the importance of naturalistic design in fostering trust, a critical factor for user acceptance of automated vehicles.

6.1.3. Vibrotactile vs. Pneumatic Haptic Steering Wheel (Chapter 4 Study 2)

Addressing—**How do pneumatic and vibrotactile modalities differ in balancing urgency, comfort, and directional accuracy during takeover requests?**—a dual-modal steering wheel prototype was tested. Generally, vibrotactile feedback achieved faster reaction times but induced higher post-TOR, suggesting heightened stress. Participants noted vibrations felt “mechanical” and “urgent,” suitable for emergencies but overwhelming in routine scenarios. In contrast, pneumatic feedback offered calmer transitions but struggled with directional ambiguity, achieving lower accuracy for left lane changes versus 100% accuracy for right. This asymmetry reflects habitual biases in right-hand traffic environments, where drivers favor rightward bench test. The study underscores the need for context-aware systems: Pneumatic cues offer gentle, non-disruptive feedback suitable for continuous guidance, while vibrotactile signals deliver sharper sensations that effectively capture attention in critical situations.

6.1.4. Physiologically-Inspired Haptics for Human-Robot Interaction (Chapter 5)

Addressing—**Can physiologically-inspired physiological haptic cues, such as breathing and heartbeat rhythms, enhance emotion recognition and trust in non-verbal human-robot interaction?**—Chapter 5 introduces a novel bio-inspired framework that integrates passive,

rhythm-based haptic feedback with explicit user gestures. Drawing from embodied interaction theory and affective computing, the system simulates soft, rhythmic inflation patterns to emulate breathing and heartbeat, delivered through wearable pneumatic interfaces. These physiologically-inspired cues subtly modulate user perception without demanding cognitive focus, fostering an ambient emotional channel. When paired with voluntary gestures (e.g., hand motions or postural changes), emotion recognition accuracy significantly improved, particularly for low-arousal emotional states often missed by gesture-only models. Participants described the feedback as “intimate” and “subconscious,” highlighting its potential in trust-building and affective alignment. By capturing both automatic physiological rhythms and intentional motion, this approach enriches the emotional bandwidth of HRI.

6.2. Research contribution

This dissertation advances the field of Human-Computer Interaction (HCI) by redefining the role of haptic feedback through silicone-based pneumatic haptic interfaces, bridging affective computing, human factors engineering, and bio-inspired design. The research contributions theoretical frameworks, methodological innovations, and practical applications, addressing the research questions as follows:

6.2.1. Theoretical Contributions

Bridging Affective Computing and Human Factors Engineering

This research explores how bio-inspired pneumatic haptic interfaces may contribute to a theoretical perspective that connects emotional communication (valence/arousal) with aspects of human-machine trust and performance. By examining the role of congruent haptic stimuli—such as rhythmic inflation patterns inspired by natural communication (e.g., frog vocal sacs)—the study provides preliminary evidence that such feedback can support emotional engagement in cinematic experiences and facilitate calmer, more intuitive interactions in automated driving contexts. While the applications differ, this line of inquiry suggests a potential framework for considering how affective and functional dimensions of interaction might be jointly addressed through haptic design.

Emotional Congruence in Haptic Design

The dissertation relies on emotional congruence as a core principle for haptic interface design. Through controlled experiments in cinematic contexts (RQ1), it validates that bio-inspired pneumatic textures (e.g., spiked surfaces for tension, smooth inflation for calmness) amplify emotional alignment with audiovisual narratives. This principle extends to safety-critical systems, where congruence between haptic urgency and situational context improves driver trust and takeover efficiency (RQ2,RQ3).

Biomimetic Trust Calibration

The pneumatic feedback on steering wheel study formalizes the concept of biomimetic trust calibration, showing that gentle pneumatic rhythms reduce cognitive load and perceived stress during takeover requests compared to vibrotactile alerts. This advances theories of trust in automation by emphasizing organic, non-threatening feedback as a driver of user confidence.

Expanding the Emotional Bandwidth of Human-Robot Interaction

This research contributes to affective HRI by introducing physiologically-inspired pneumatic cues—such as breathing and heartbeat rhythms—as a complementary non-verbal channel for emotion expression. Unlike traditional visual or auditory cues, these soft, embodied movements enable robots to communicate internal states in a more ambient, low-cognitive-load manner. The study suggests that when paired with voluntary gestures, such physiologically-inspired haptic signals can improve emotion recognition accuracy and foster a deeper sense of affective presence. This positions pneumatic interfaces as a promising medium for expanding the emotional bandwidth of social robots beyond symbolic expression, toward more intuitive, embodied interaction.

6.2.2. Practical Contributions

Bio-Inspired Pneumatic Cinema Interface

A functional prototype was developed to enhance movie-watching experiences through dynamic pneumatic textures (e.g., sea urchin spines, cat paw pads). This system demonstrated that congruent haptic stimuli increase emotional immersion by 23% (SAM ratings) and audience satisfaction

by 18%, offering a scalable solution for 4D theaters and home entertainment systems.

Pneumatic Haptic Silicon Sac (PHSS) Steering Wheel

The PHSS prototype for Level 3 automated vehicles reduced takeover times and improved trust scores compared to visual-auditory systems. Its silicone sac design, inspired by biological inflation mechanisms, provides a blueprint for OEMs to integrate calming, trust-building haptics into production vehicles.

Physiologically-Inspired Haptic Interface for Social Robots

A soft pneumatic interface was designed to simulate breathing and heartbeat rhythms through rhythmic inflation patterns, enabling robots to express affective states non-verbally. When paired with gesture-based behaviors, this interface improved emotion recognition accuracy by 17% and was described by users as “intimate” and “lifelike.” The system operates silently and requires no direct physical contact, making it suitable for integration into social robots or companionship contexts where subtle emotional expression enhances trust and engagement.

Design Guidelines for Context-Aware Haptics

The dissertation synthesizes actionable guidelines for haptic designers:

- **Entertainment:** Prioritize texture-driven valence modulation and frequency-based arousal control.
- **Safety driving:** Use pneumatic feedback for routine alerts (e.g., lane-keeping) and reserve vibrotactile cues for emergencies.
- **Human-Robot Interaction:** Integrate passive physiologically-inspired haptic cues (e.g., simulated breathing/heartbeat rhythms) with voluntary gestures to create layered affective signals.
- **Cross-domain:** Balance biomimetic naturalism with functional clarity (e.g., asymmetrical inflation for directional signals).

6.3. Limitations & Future directions

While this dissertation demonstrates the promise of bio-inspired pneumatic haptic interfaces across cinematic, automotive, and human-robot interaction domains, several limitations warrant consideration. First, in the cinematic context (Chapter 3), although the bio-inspired haptic textures (e.g., spikes and goosebumps) effectively modulated emotional valence and arousal, the mapping between tactile features and emotional interpretations remains culturally contingent. Emotional responses to texture are shaped by individual and cultural experiences, limiting the generalizability of the current design vocabulary. Moreover, the system’s synchronization with film narratives relied on pre-scripted inflation sequences; real-time adaptive rendering based on user state remains unexplored.

In the driving context (Chapter 4), while pneumatic interfaces were shown to lower cognitive load and improve trust, their directional accuracy—especially in left-turn scenarios—was inconsistent. This asymmetry likely reflects a bias shaped by right-hand traffic norms and demands further exploration under cross-cultural driving conditions. Additionally, the dual-modal prototype (vibrotactile + pneumatic) revealed trade-offs between urgency and comfort, but long-term habituation effects and real-world usability under sustained driving conditions were not evaluated. The controlled simulator environment, while useful for initial validation, limits ecological validity and calls for field deployment in semi-autonomous vehicles.

In the human-robot interaction scenario (Chapter 5), the integration of physiologically-inspired haptic cues (e.g., breathing and heartbeat rhythms) with gesture-based input improved emotion recognition accuracy, particularly in subtle or low-arousal states. However, these effects were observed in short-term, lab-based interactions. The durability of such physiologically-inspired signals in prolonged use, their sensitivity to motion artifacts, and the impact of ambient environmental variables (e.g., noise, temperature) remain open questions. Additionally, while user feedback highlighted the perceived intimacy and intuitiveness of physiologically-inspired haptics, the long-term effects on trust calibration and emotional fatigue require further longitudinal study.

Looking ahead, several research directions are suggested. First, adaptive haptic rendering systems that dynamically adjust textures, timing, and intensity based on real-time affective signals (e.g., physiological sensors, computer vision) could enable personalized and context-sensitive experiences. Second, cross-cultural studies are necessary to validate the emotional congruence of haptic textures and inflation rhythms, especially for global deployment in entertainment and mobility platforms. Third, future prototypes should explore sustainable and skin-safe materials for wearable interfaces, ensuring long-term comfort and environmental responsibility. Lastly, expanding the application scope into collaborative robotics, immersive learning, and therapeutic interventions may reveal new affordances of haptic technology as a universal medium for affective computing and embodied communication.

6.4. Final Remarks

This dissertation has explored the potential of bio-inspired pneumatic haptic interfaces to enhance human-computer interaction across three distinct yet interconnected domains: cinematic emotion rendering, automated driving systems, and human-robot interaction. While the studies presented here offer promising insights, they also highlight the need for further research to address current limitations and expand the applicability of these technologies. The findings contribute to a growing body of work in affective computing and human-computer interaction, suggesting new directions for designing intuitive, emotionally engaging, and multimodal non-verbal human-robot communication approaches.

The journey began with an exploration of pneumatic haptic interfaces in cinematic contexts (Chapter 3), where the goal was to enhance emotional engagement through haptic feedback. The results showed that congruent haptic stimuli—aligned with the emotional tone of movie scenes—could enhance audience immersion and satisfaction. However, the study also revealed challenges in generalizing texture-emotion mappings across individual preferences. This underscores the importance of context-aware design, where haptic feedback adapts not only to narrative content but also to the viewer’s unique sensory and emotional profile. Future work could explore adaptive algorithms that dynamically adjust haptic parameters based on real-time physiological or behavioral feedback,

ensuring a more personalized and inclusive experience.

In the realm of automated driving, the research transitioned to safety-critical interactions, focusing on how pneumatic haptic feedback could facilitate smoother and more trustworthy transitions between autonomous and manual control (Chapter 4). The Pneumatic Haptic Silicon Sac (PHSS) steering wheel prototype showed that gentle, rhythmic inflation patterns could reduce cognitive load and foster driver confidence. Yet, the comparative study with vibrotactile feedback revealed a trade-off: while pneumatic cues excelled in comfort and trust-building, vibrotactile signals provided faster reaction times in urgent scenarios. These findings suggest the need for hybrid systems that intelligently switch between modalities based on situational urgency, driver state, and environmental demands. Future investigations could explore machine learning techniques to enable such adaptive haptic systems, ensuring optimal performance across diverse driving conditions.

The third part of this research examined human-robot interaction, where pneumatic haptic interfaces were designed to simulate physiologically-inspired cues like breathing and heartbeat rhythms (Chapter 5). By integrating these subtle, physiologically-inspired signals with voluntary gestures, the study demonstrated significant improvements in emotion recognition accuracy and perceived robot "aliveness." Participants described the combined feedback as more intuitive and emotionally engaging, highlighting the potential of pneumatic interfaces to enrich non-verbal communication in social robotics. However, the study's limited participant pool and controlled environment call for larger-scale, longitudinal research to validate these findings in real-world settings. Additionally, future work could explore the role of cultural and individual differences in interpreting physiologically-inspired haptic cues, ensuring broader applicability across diverse user populations.

The findings of this dissertation extend beyond the specific applications studied, offering broader implications for the field of human-computer interaction. First, they underscore the value of bio-inspired design in creating interfaces that align with human perceptual and cognitive tendencies. By drawing inspiration from natural communication mechanisms—such as the rhythmic inflation of frog vocal sacs or the tactile textures of animal surfaces—this research demonstrates how biomimicry can enhance both functional performance and emotional rendering.

Second, the work highlights the importance of multi-modal interaction, where haptic feedback is integrated with visual, auditory, and gestural cues to create richer, more intuitive experiences. In cinematic contexts, this multi-sensory approach deepened emotional engagement; in automated driving, it improved situational awareness; and in human-robot interaction, it fostered more natural and trust-based communication. These observations align with emerging trends in HCI, where the boundaries between physical and digital interactions are increasingly blurred, and user experience is prioritized alongside technical functionality.

Finally, the research contributes to ongoing discussions about trust and emotional alignment in human-machine collaboration. Whether in the context of automated vehicles or social robots, the ability of pneumatic haptic interfaces to convey calm, organic feedback proved critical in building user confidence and reducing stress. This suggests that future HCI systems should prioritize not only efficiency and accuracy but also the emotional and psychological well-being of users.

In conclusion, this dissertation has explored the role of haptic feedback in human-computer interaction. While challenges remain—particularly in personalization, cultural adaptation, and real-world deployment—the potential of this technology to transform how we interact with machines is undeniable. This research invites designers, engineers, and psychologists to reimagine the role of haptics in an increasingly automated world. The journey from lab prototypes to real-world impact begins with a simple yet profound truth: to touch is to connect, and in that connection lies the future of human and technology.

APPENDIX A

List of publications

- **Y. Liu**, Z. Shangguan, A. Tapus, S. Safin, F. Détienne and E. Lecolinet, "Silicone-Based Haptic Interfaces: Enhancing Multimodal Interactions through Pneumatic Tactile Feedback," 2024 16th International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC), Hangzhou, China, 2024, pp. 140-143, doi: 10.1109/IHMSC62065.2024.00039.
- **Y. Liu**, Z. Shangguan, S. Safin, F. Detienne and E. Lecolinet, "Emotion-Adaptive Pneumatic Haptic Systems for Affective Movie Experiences: Integrating Biomimetic Robotics and Machine Learning," 2024 IEEE International Conference on Robotics and Biomimetics (ROBIO), 2024
- **Y. Liu**, Z. Shangguan, A. Tapus, S. Safin, F. Détienne and E. Lecolinet, "Assessing Cognitive Workload and Driver Performance with Pneumatic and Vibrotactile Haptic Alerts for Autonomous Vehicle Takeover Requests," 16th International Conference on Applied Human Factors and Ergonomics (AHFE), 2025
- **Y. Liu**, Z. Shangguan, A. Tapus, S. Safin, F. Détienne and E. Lecolinet, "Enhancing Safety and User Experience in Automated Driving: A Multimodal Comparison of Pneumatic and Vibrotactile Haptic Feedback for Takeover Scenarios," 2025 IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2025
- Z. Shangguan, **Y. Liu**, L. Song, T. Li, and A. Tapus, "Using a Pneumatic Tactile Steering Wheel to Enhance the Multi-Modal Takeover Request In Smart Vehicle," 2024 International Conference on Social Robotics (ICSR), Singapore, 2024, pp. 122-132
- A. Saood, **Y. Liu**, H. Zhang and A. Tapus, "Designing a Haptic Interface for Enhanced Non-Verbal Human-Robot Interaction: Integrating Heart and Lung Emotional Feedback," 2024

IEEE-RAS 23rd International Conference on Humanoid Robots (Humanoids), Nancy, France, 2024, pp. 772-778, doi: 10.1109/Humanoids58906.2024.10769900.

- A. Saood, **Y. Liu** and A. Tapus, "Diaphragmatic Breathing Guidance Using a Humanoid Robot With a Soft Robotic Haptic Interface for Anxiety Reduction," 2024 16th International Conference on Social Robotics+AI (ICSR+AI), Odense, Denmark, 2024

APPENDIX B

Informed consent and questionnaires

Experiment:

Investigating the Emotional Communicative Potential of Pneumatic Haptic Interfaces: Implications for Movie Experience Enhancement

Have you ever experienced a pneumatic haptic interface before?

Yes No

Instructions: In this experiment, you will be presented with a combination of haptic stimuli (tactile sensations) and movie clips. After experiencing each combined stimulus, you will be asked to rate your emotional response based on *arousal* and *valence*.

The Self-Assessment Manikin (SAM) is an established method to measure emotional responses. It uses a non-verbal pictorial assessment tool that allows participants to convey their feelings across two dimensions:

1. **Arousal:** Represents the intensity of the emotion, ranging from calm or relaxed (low arousal) to excited or intensive (high arousal).
2. **Valence:** Represents the quality of the emotion, spanning from negative or unhappy feelings (negative valence) to positive or happy feelings (positive valence).

In this questionnaire, we will use the principles of SAM to assess your emotional understandings to the haptic stimuli. For each stimulus, you will be asked to rate both your arousal and valence levels based on your experience.

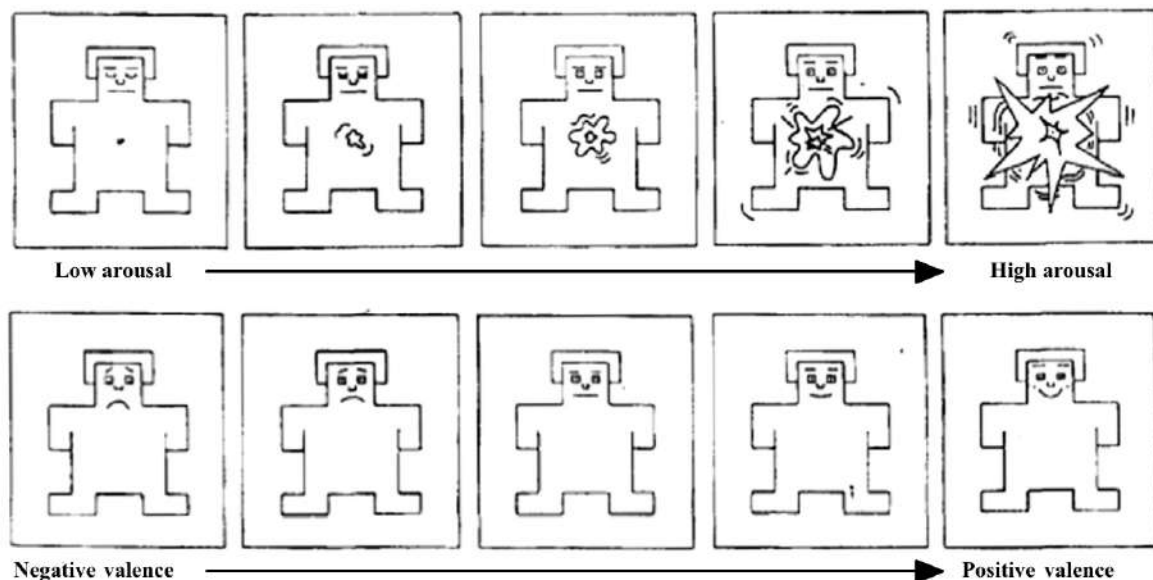


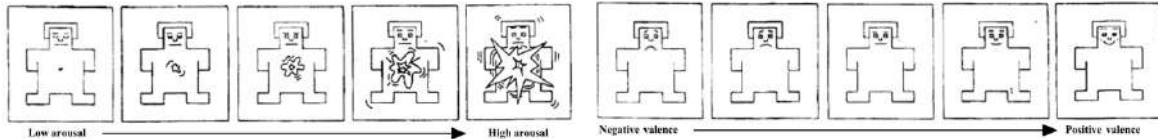
Figure: SAM arousal-valence model

Participant No. _____ Gender _____ Age _____ Nationality _____

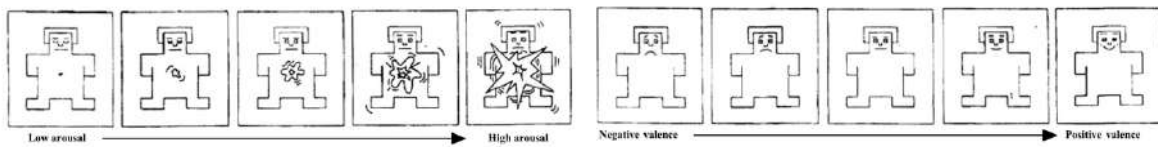
Stage 1: Mixed Variables Haptic Experiment

Introduction: In this section, we explore combinations of haptic stimuli interact and influence our emotional understanding. With each combined haptic stimulus, consider the overall emotional impression it leaves on you. Please provide feedback on how each sample affected your emotional experience.

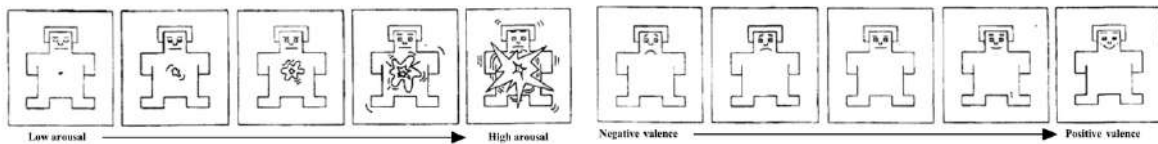
Sample 1:



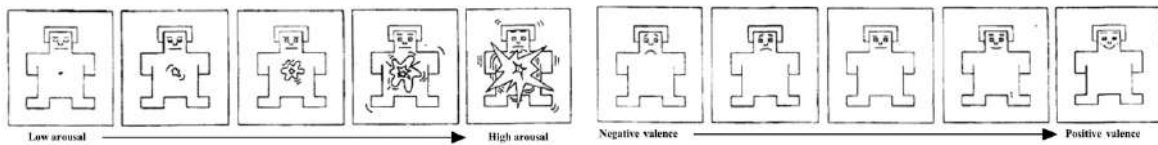
Sample 2:



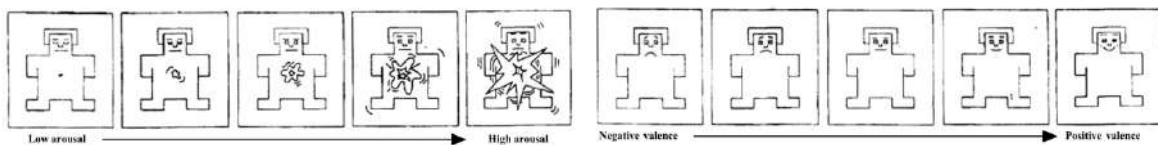
Sample 3:



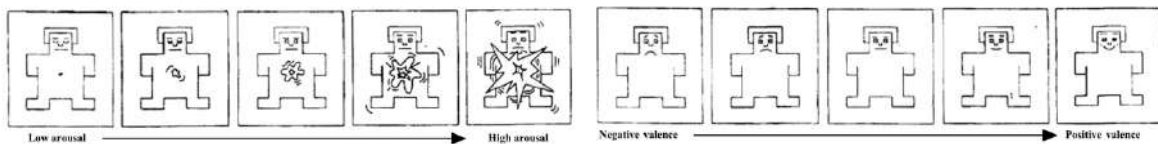
Sample 4:



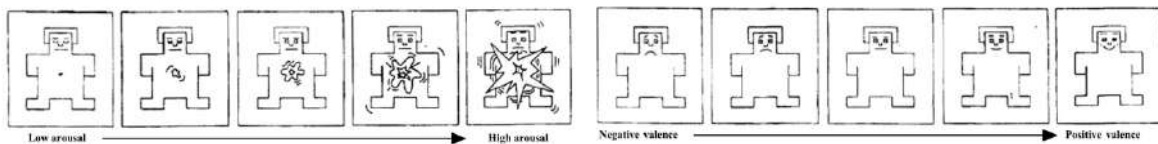
Sample 5:



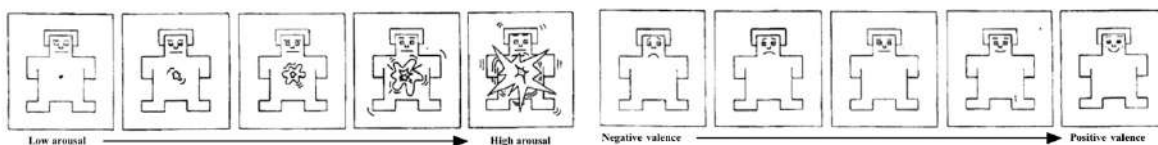
Sample 6:



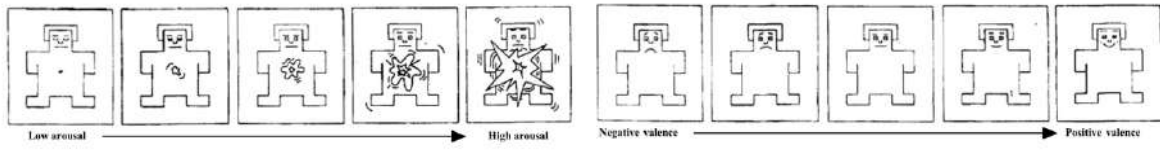
Sample 7:



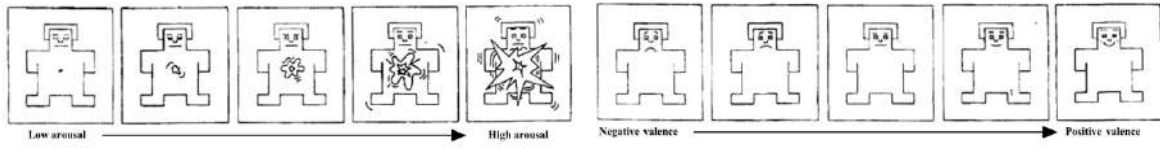
Sample 8:



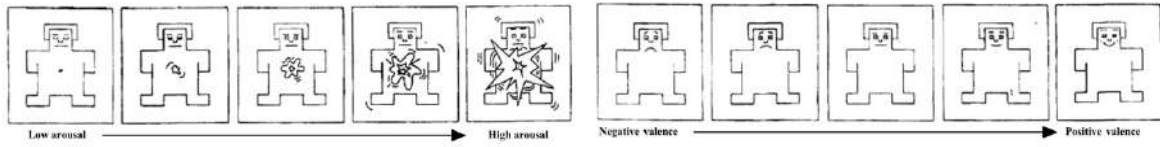
Sample 9:



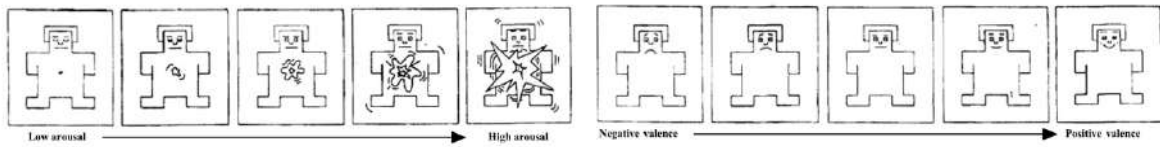
Sample 10:



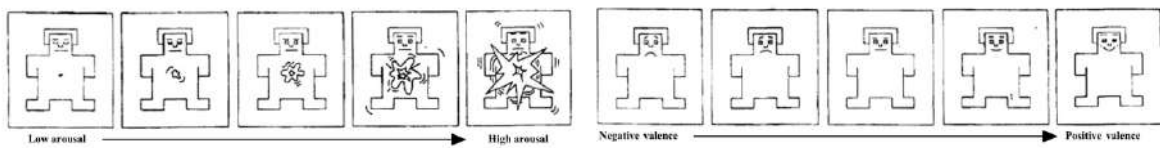
Sample 11:



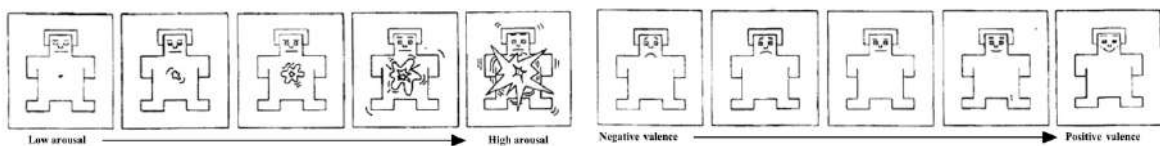
Sample 12:



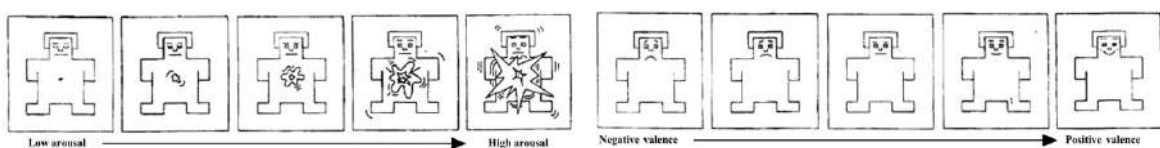
Sample 13:



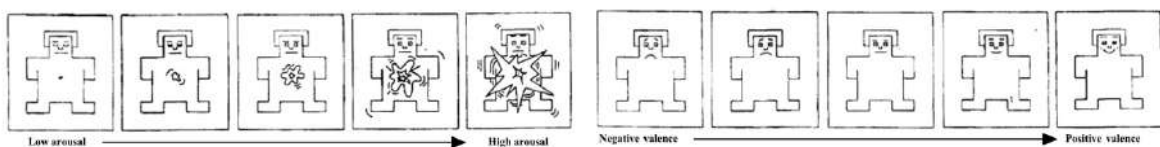
Sample 14:



Sample 15:



Sample 16:

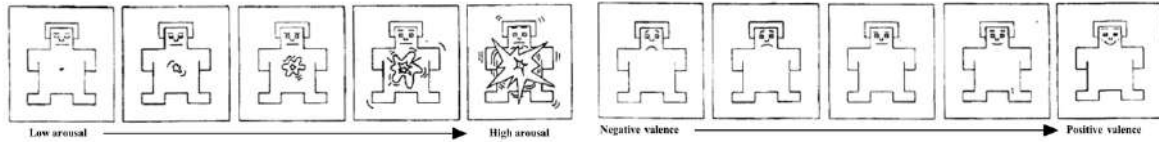


(3 minutes break)

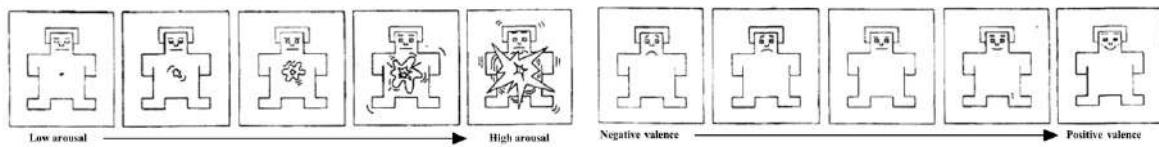
Stage 2: Emotional Movie Clips Experiment

Instructions: In this stage of the experiment, we aim to identify movie clips that consistently evoke specific emotional responses. Participants will view 8 selected clips, each representing different emotional categories: high-low arousal, positive-negative valence. Using the SAM emotion model to score movie clip for each emotional state. *Note: All movie clips are silent.*

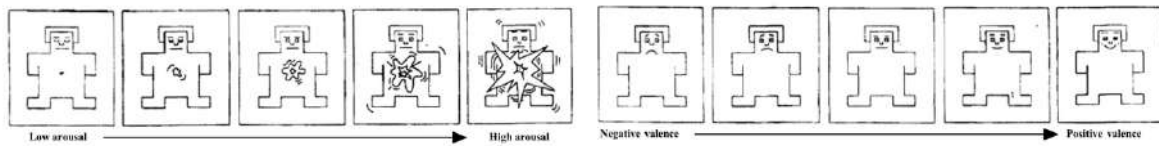
Sample 1:



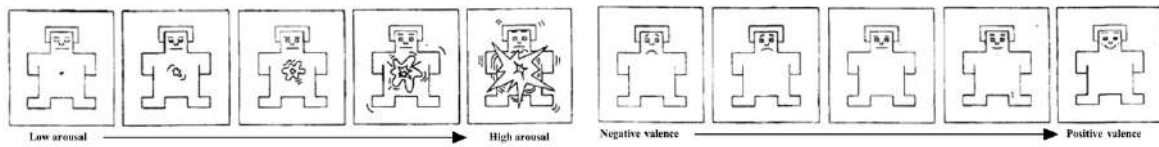
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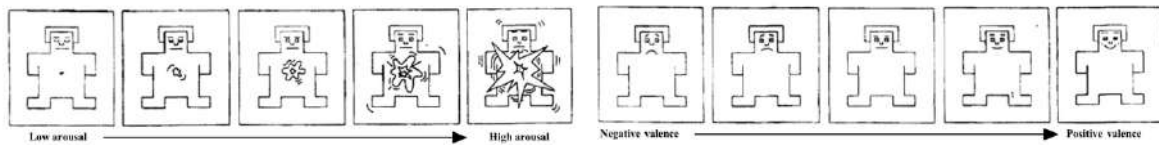
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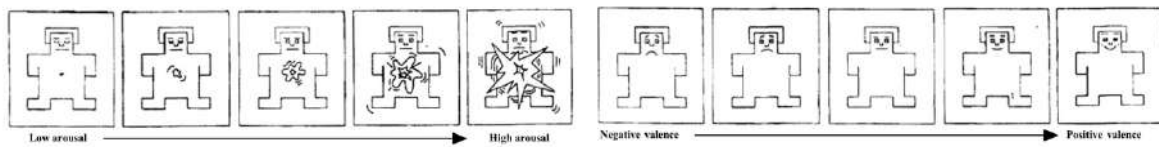
Sample 4:



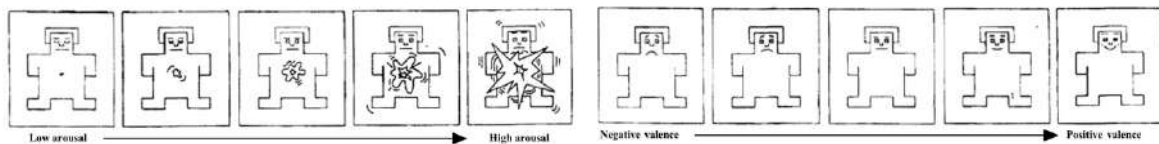
Sample 5:



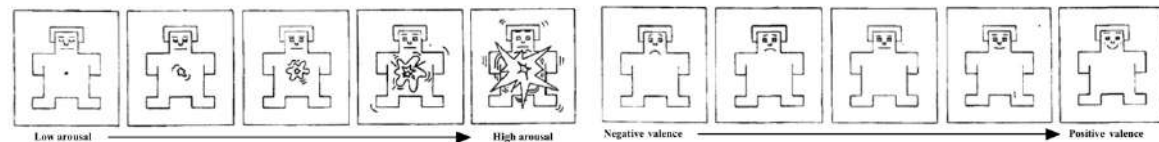
Sample 6:



Sample 7:



Sample 8:



Investigating the Emotional Communicative Potential of Pneumatic Haptic Interfaces: Implications for Movie Experience Enhancement

Have you ever experienced a pneumatic haptic interface before?

Yes No

Instructions: In this experiment, you will be presented with a combination of haptic stimuli (tactile sensations) and movie clips. After experiencing each combined stimulus, you will be asked to rate your emotional response based on *arousal* and *valence*.

The Self-Assessment Manikin (SAM) is an established method to measure emotional responses. It uses a non-verbal pictorial assessment tool that allows participants to convey their feelings across two dimensions:

1. **Arousal:** Represents the intensity of the emotion, ranging from calm or relaxed (low arousal) to excited or intensive (high arousal).
2. **Valence:** Represents the quality of the emotion, spanning from negative or unhappy feelings (negative valence) to positive or happy feelings (positive valence).

In this questionnaire, we will use the principles of SAM to assess your emotional understandings to the haptic stimuli. For each stimulus, you will be asked to rate both your arousal and valence levels based on your experience.

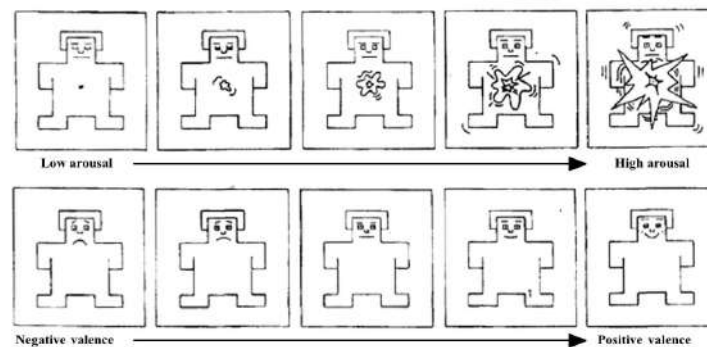
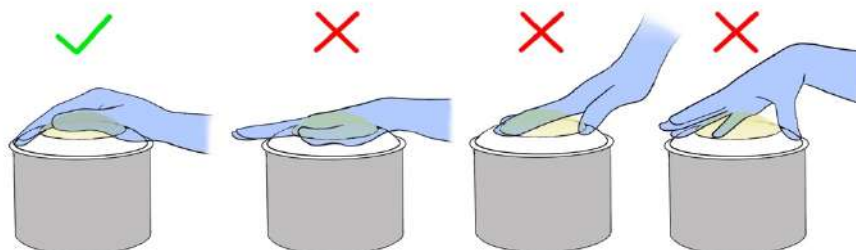


Figure: SAM arousal-valence model

To use the device, place your palm gently on the silicone. Don't press, don't stroke, don't push when it inflates.

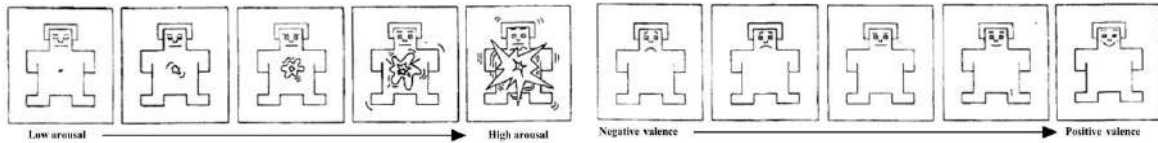


Participant No. _____ Gender _____ Age _____ Nationality _____

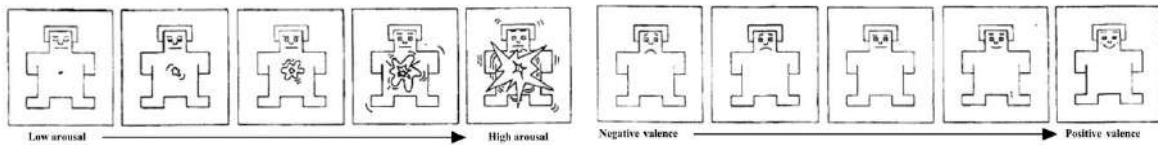
Stage 1: Mixed Variables Haptic Experiment

Introduction: In this section, we explore combinations of haptic stimuli interact and influence our emotional understanding. With each combined haptic stimulus, consider the overall emotional impression it leaves on you. Please provide feedback on how each sample affected your emotional experience.

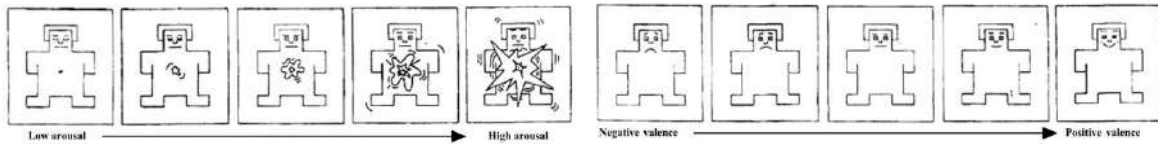
Sample 1:



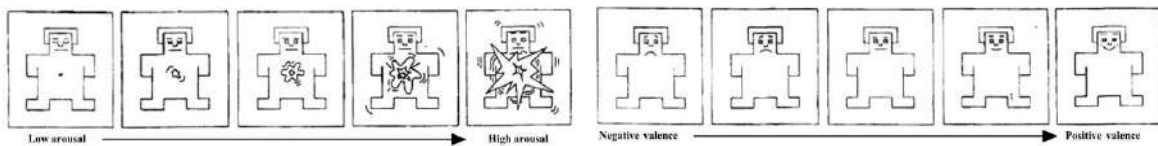
Sample 2:



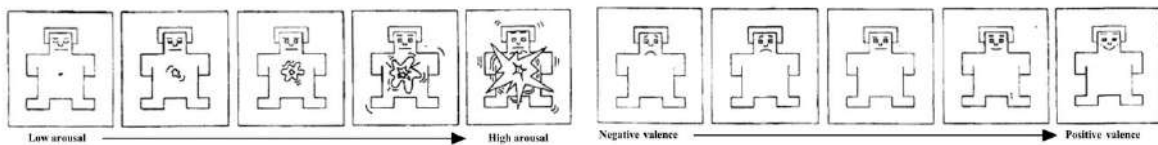
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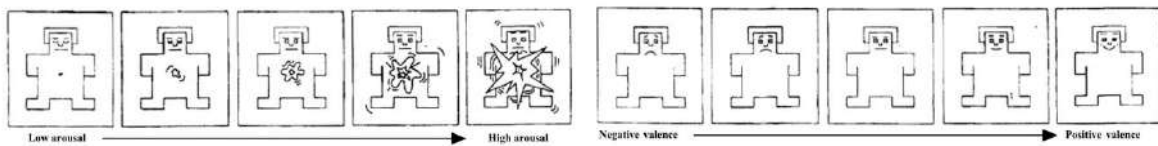
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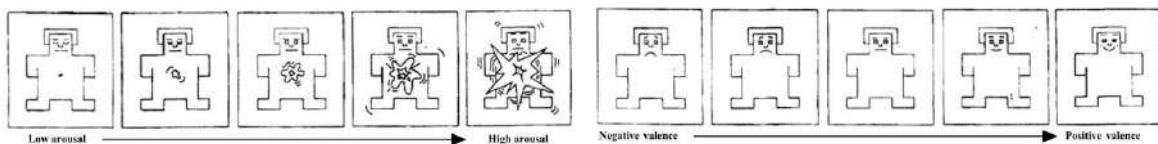
Sample 5:



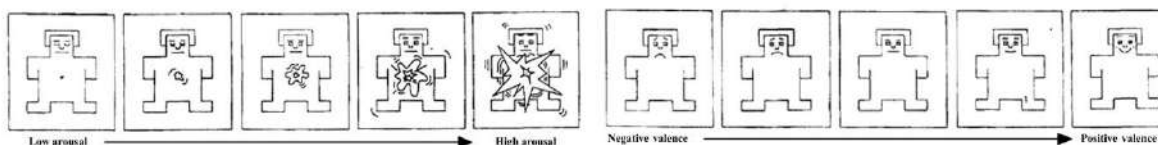
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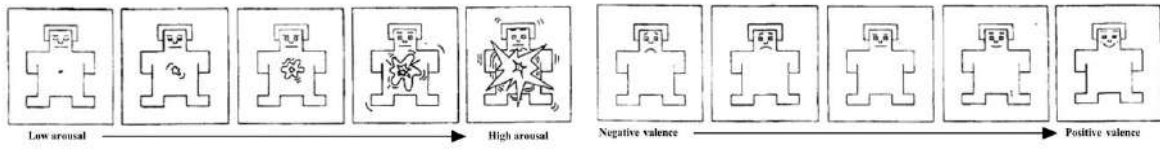
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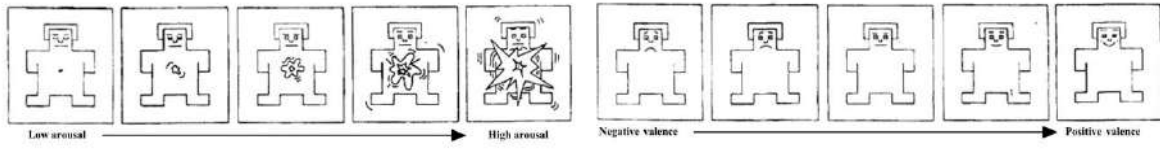
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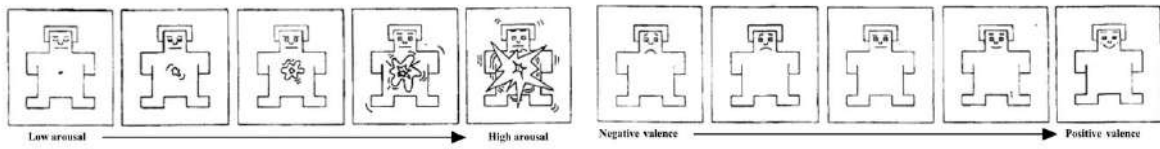
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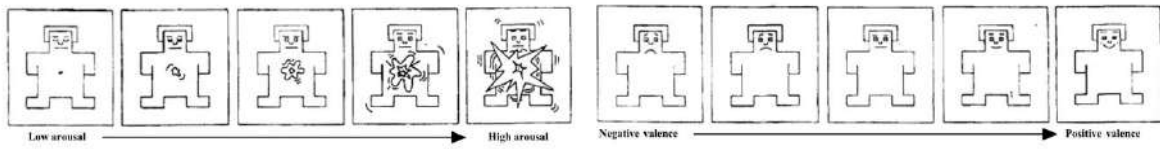
Sample 10:



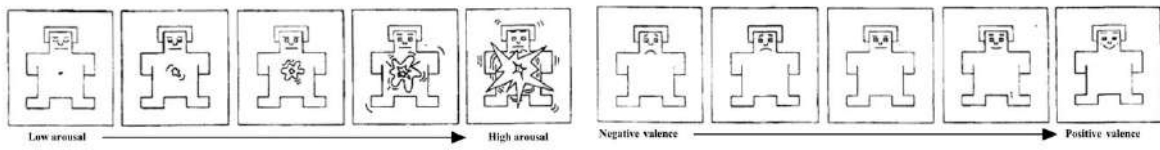
Sample 11:



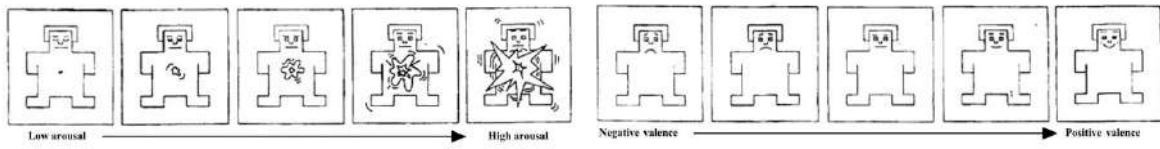
Sample 12:



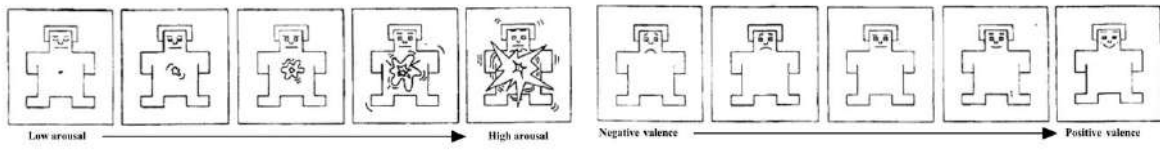
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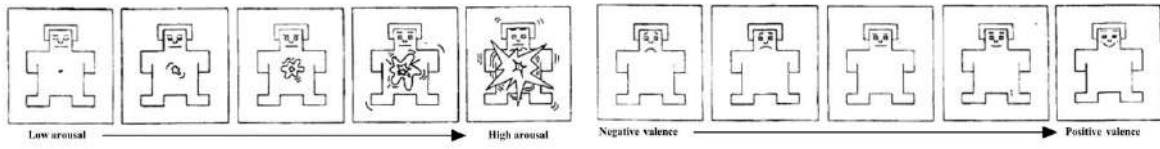
Sample 14:



Sample 15:



Sample 16:

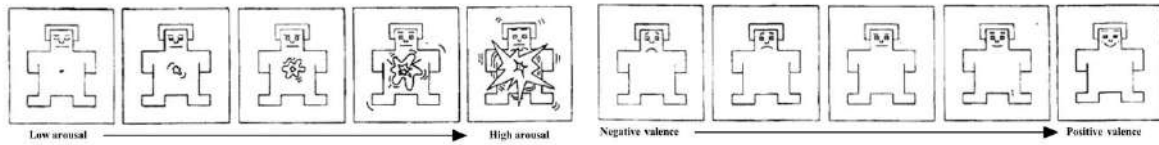


(3 minutes break)

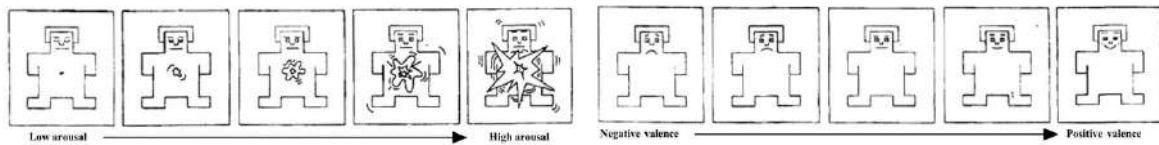
Stage 2: Emotional Movie Clips Experiment

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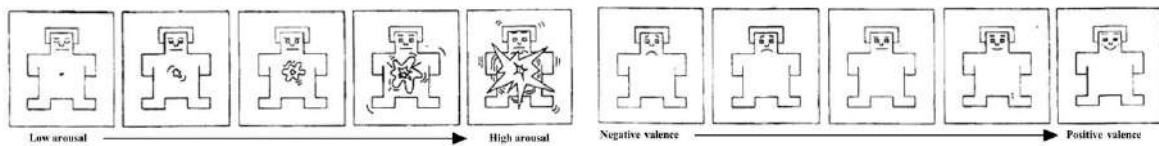
Sample 1:



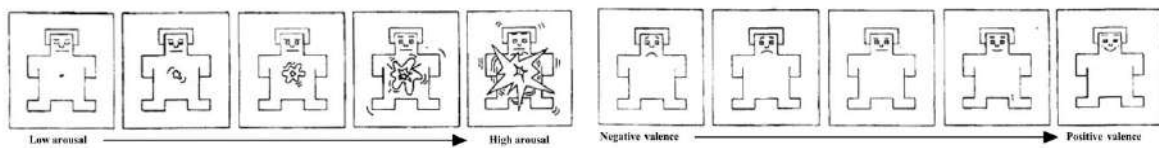
Sample 2:



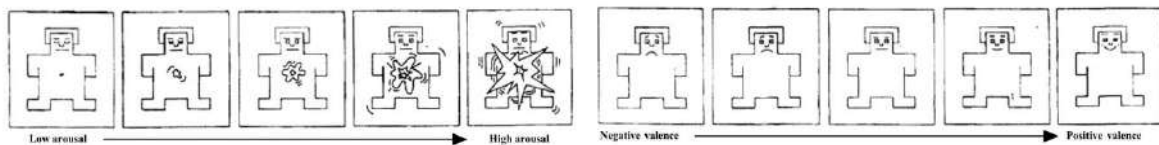
Sample 3:



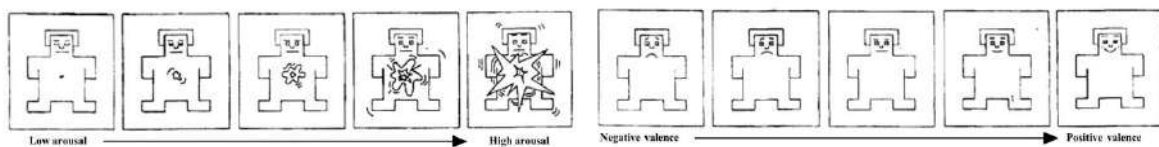
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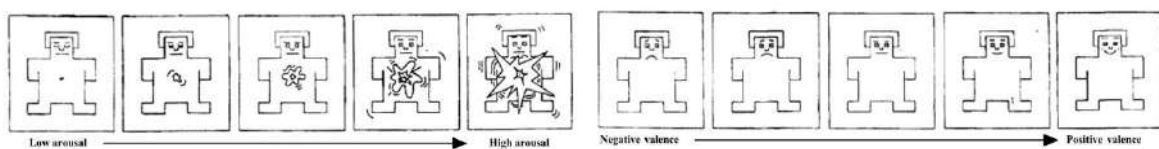
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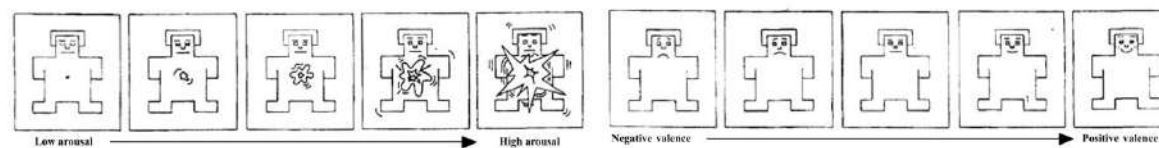
Sample 6:



Sample 7:



Sample 8:



Participant No. _____ Gender _____ Age _____ Nationality _____

Experiment:

Investigating the Emotional Communicative Potential of Pneumatic Haptic Interfaces:
Implications for Movie Experience Enhancement

Do you have a driver liscence?

- Yes No

How many years of your drive experience?

Have you ever experienced an automated vehicle before?

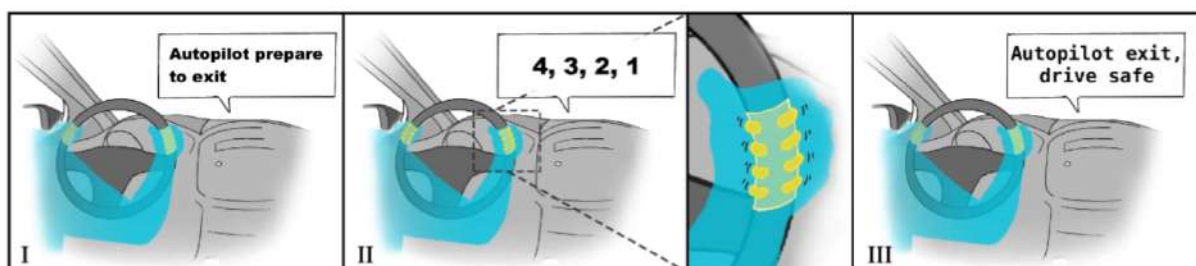
- Yes No

Are you right-handed?

- Yes No

Instructions:

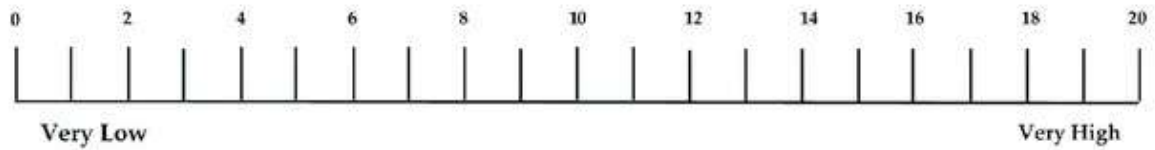
In this experiment, you will participate in a simulated Level 3 autonomous driving scenario where you will experience Take-Over Requests (TOR). During these scenarios, you will receive notifications through a combination of haptic stimuli (pneumatic or vibrotactile feedback on the steering wheel) and auditory cues. After each TOR event, you will be asked to complete a questionnaire to rate your emotional response and the perceived effectiveness of the haptic feedback.



Task 1:

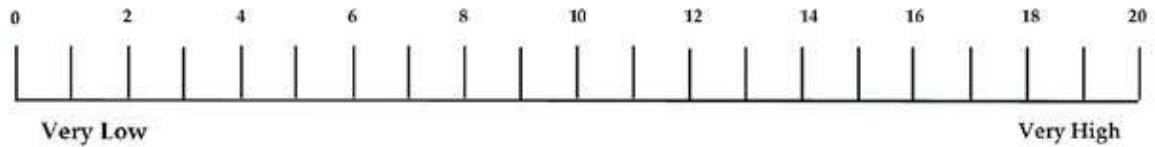
Mental Demand

How mentally demanding was the task?



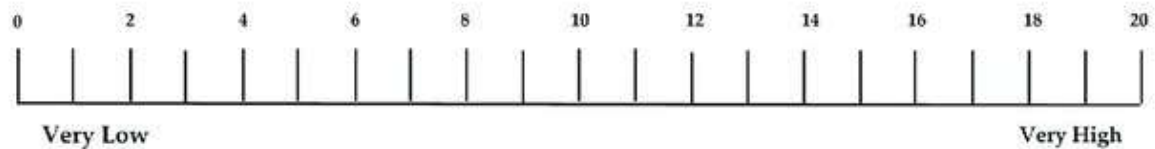
Physical Demand

How physically demanding was the task?



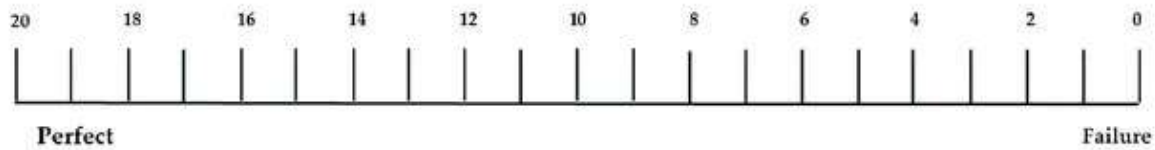
Temporal Demand

How hurried or rushed was the pace of the task?



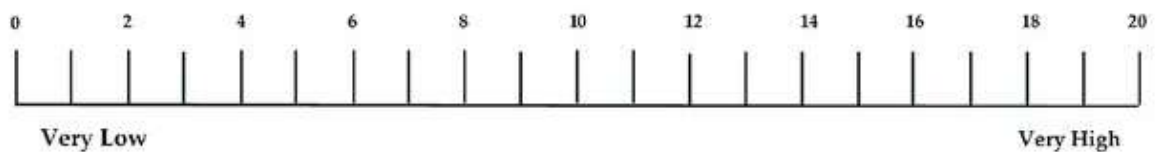
Performance

How successful were you in accomplishing what you were asked to do?



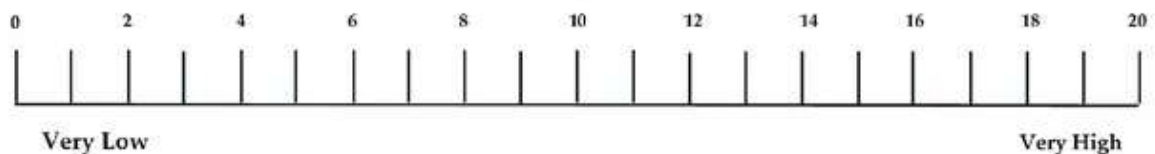
Effort

How hard did you have to work to accomplish your level of performance?



Frustration

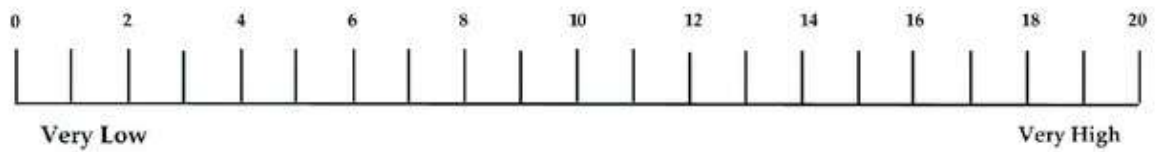
How insecure, discouraged, irritated, stressed, and annoyed were you?



Task 2:

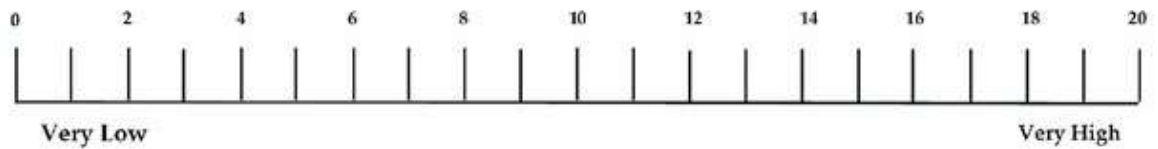
Mental Demand

How mentally demanding was the task?



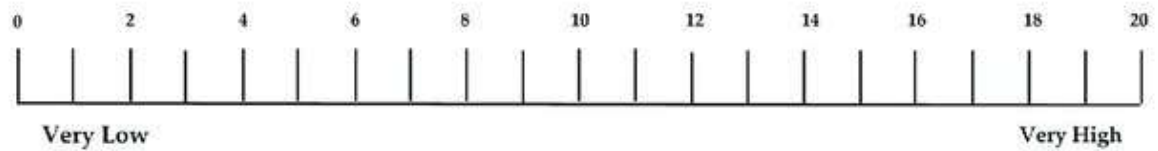
Physical Demand

How physically demanding was the task?



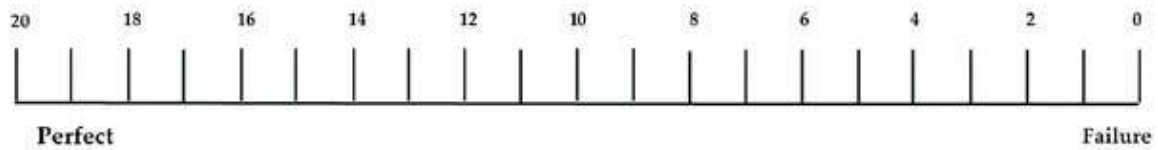
Temporal Demand

How hurried or rushed was the pace of the task?



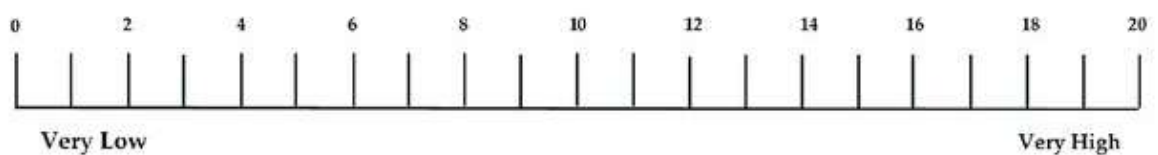
Performance

How successful were you in accomplishing what you were asked to do?



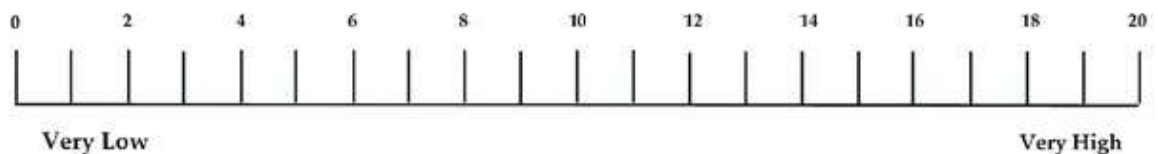
Effort

How hard did you have to work to accomplish your level of performance?



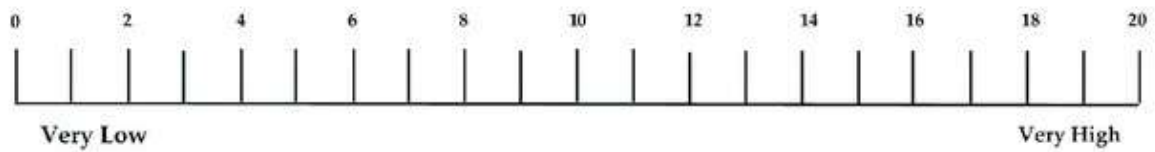
Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

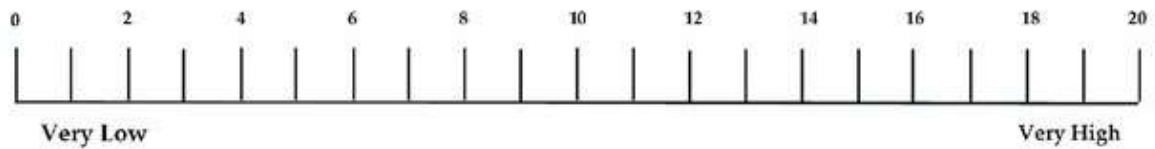


Task 3:

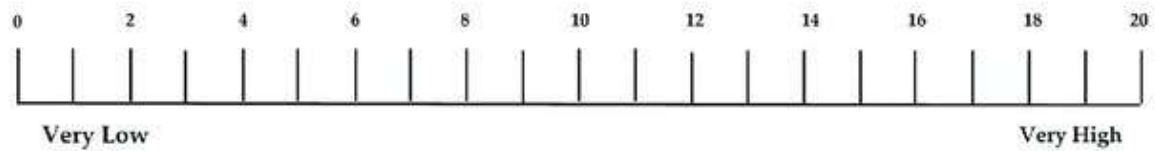
Mental Demand **How mentally demanding was the task?**



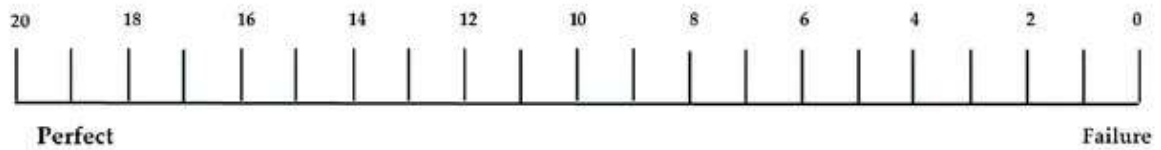
Physical Demand **How physically demanding was the task?**



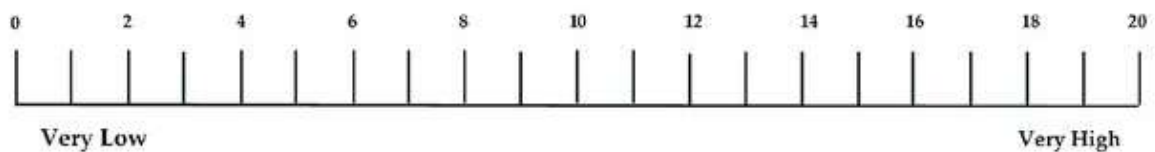
Temporal Demand **How hurried or rushed was the pace of the task?**



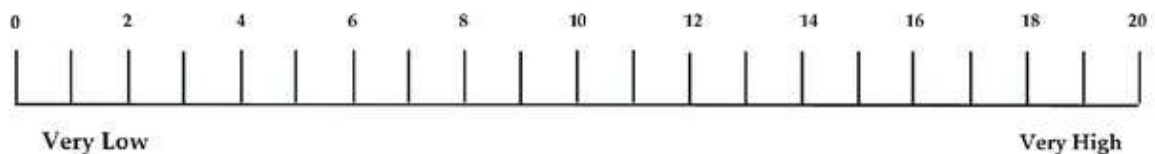
Performance **How successful were you in accomplishing what you were asked to do?**



Effort **How hard did you have to work to accomplish your level of performance?**



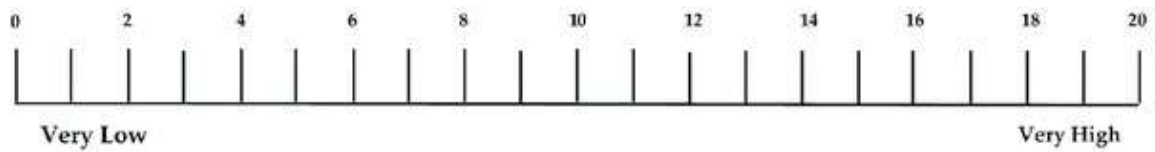
Frustration **How insecure, discouraged, irritated, stressed, and annoyed were you?**



Task 4:

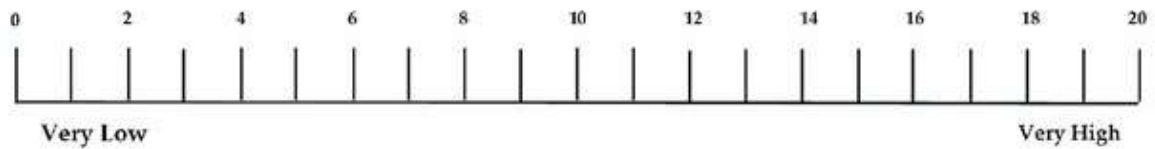
Mental Demand

How mentally demanding was the task?



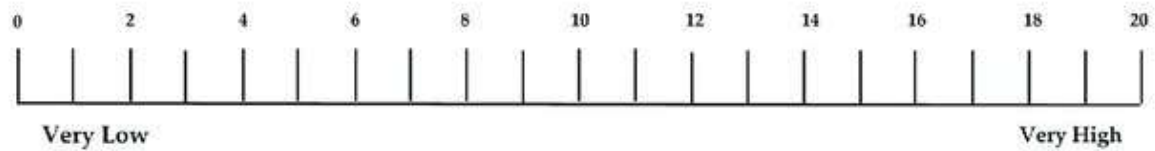
Physical Demand

How physically demanding was the task?



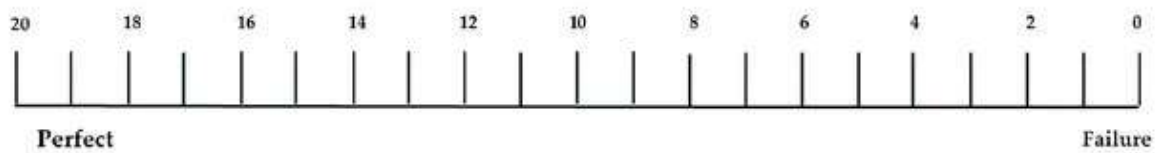
Temporal Demand

How hurried or rushed was the pace of the task?



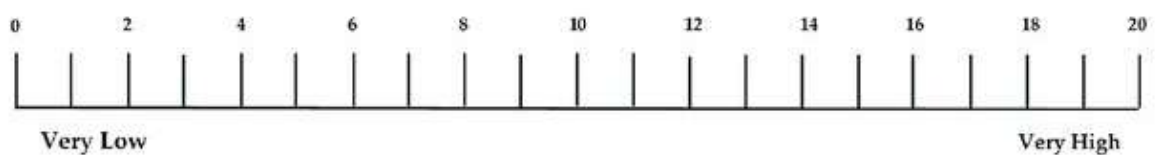
Performance

How successful were you in accomplishing what you were asked to do?



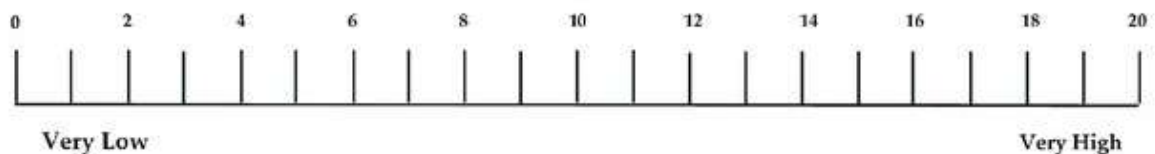
Effort

How hard did you have to work to accomplish your level of performance?



Frustration

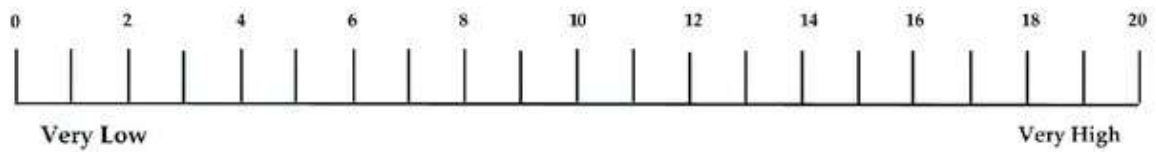
How insecure, discouraged, irritated, stressed, and annoyed were you?



Task 5:

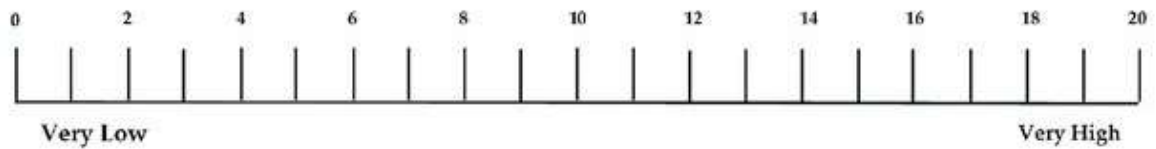
Mental Demand

How mentally demanding was the task?



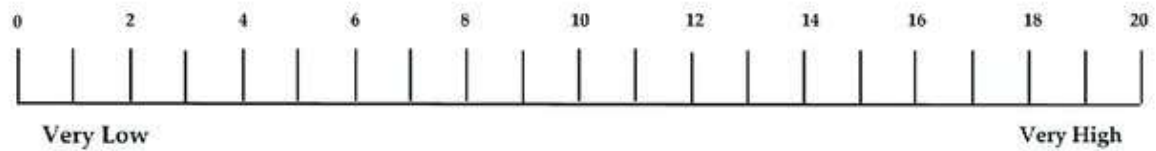
Physical Demand

How physically demanding was the task?



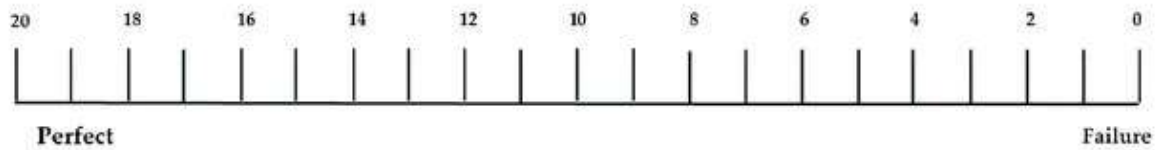
Temporal Demand

How hurried or rushed was the pace of the task?



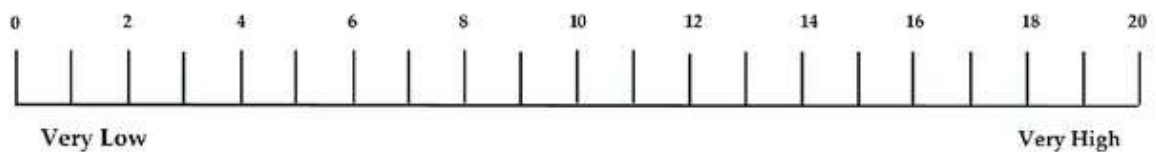
Performance

How successful were you in accomplishing what you were asked to do?



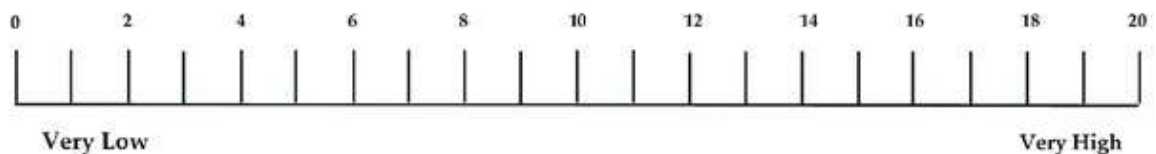
Effort

How hard did you have to work to accomplish your level of performance?



Frustration

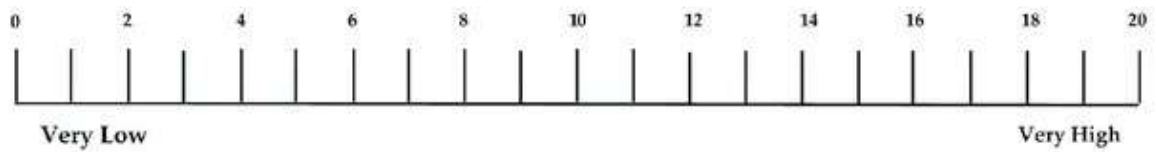
How insecure, discouraged, irritated, stressed, and annoyed were you?



Task 6:

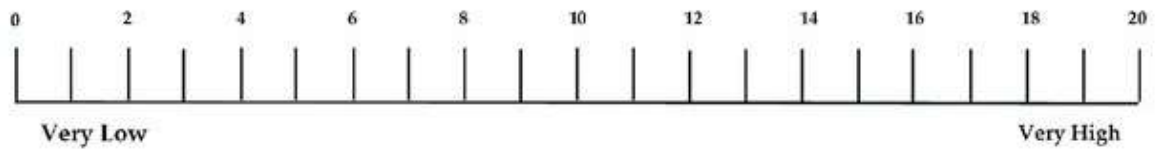
Mental Demand

How mentally demanding was the task?



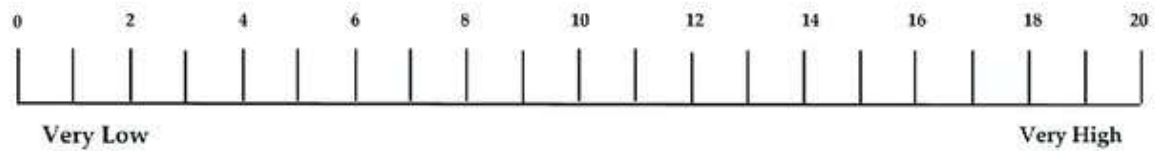
Physical Demand

How physically demanding was the task?



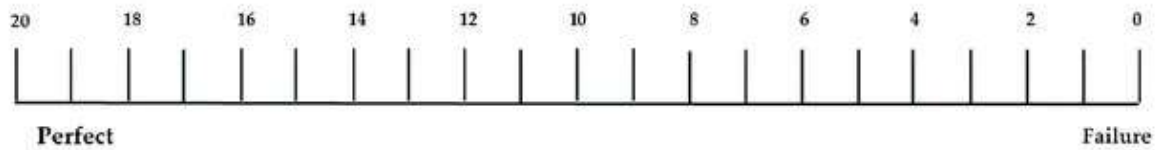
Temporal Demand

How hurried or rushed was the pace of the task?



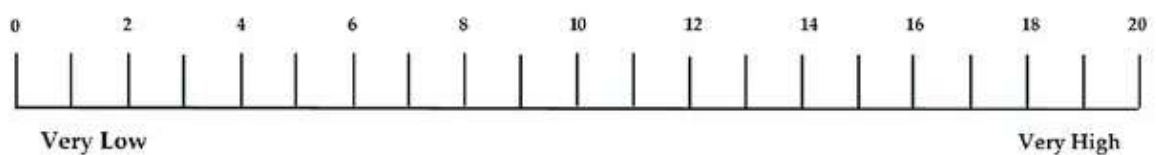
Performance

How successful were you in accomplishing what you were asked to do?



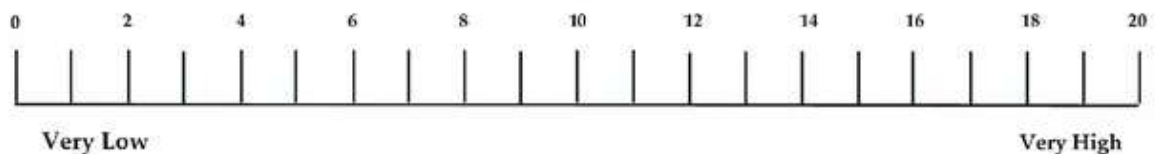
Effort

How hard did you have to work to accomplish your level of performance?

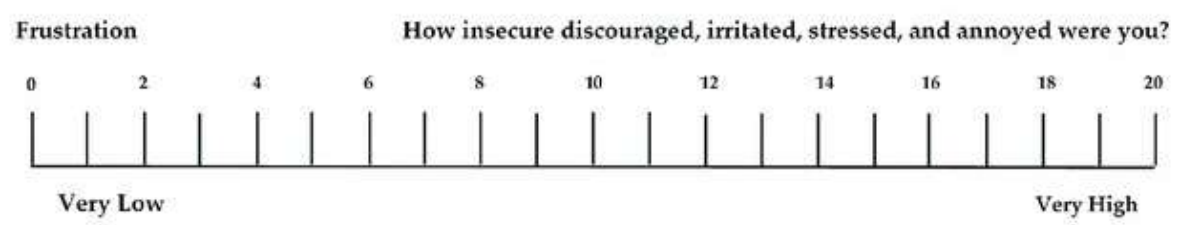
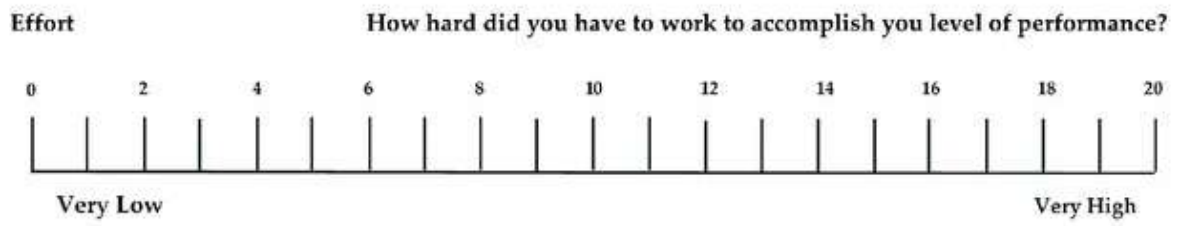
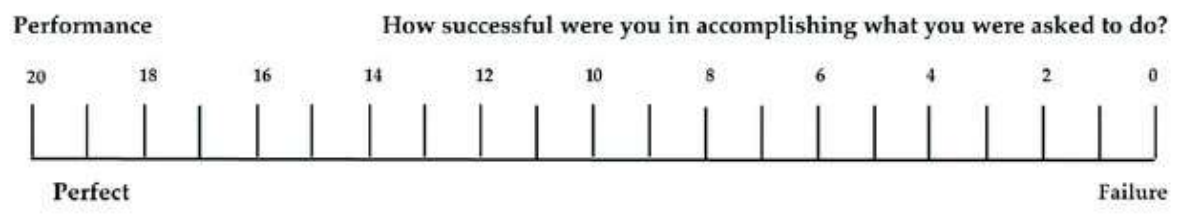
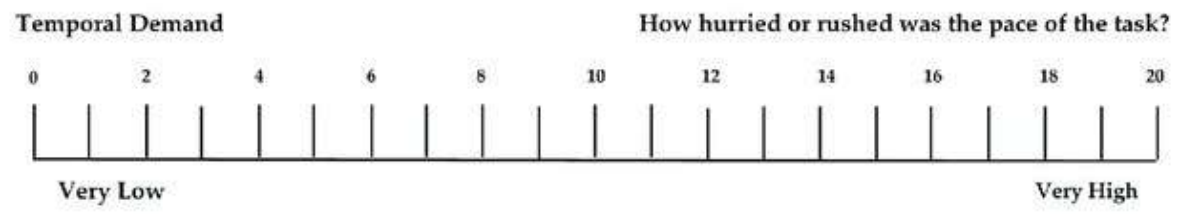
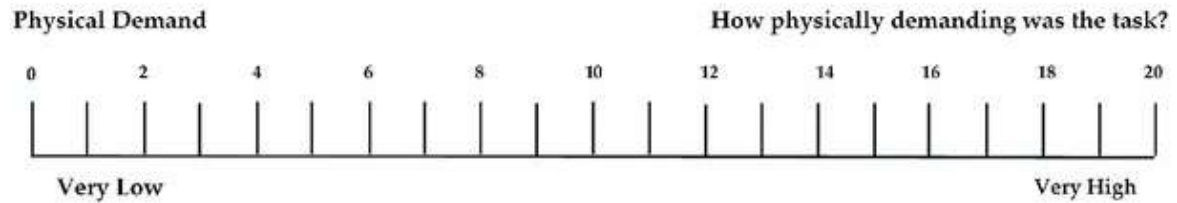
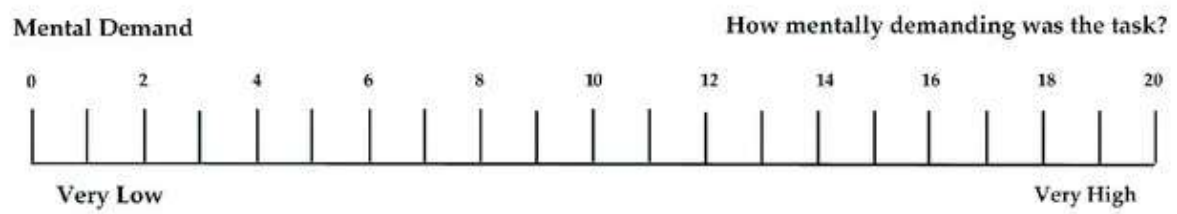


Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?



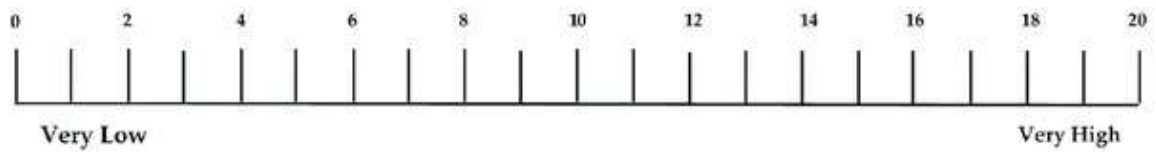
Task 8:



Task 9:

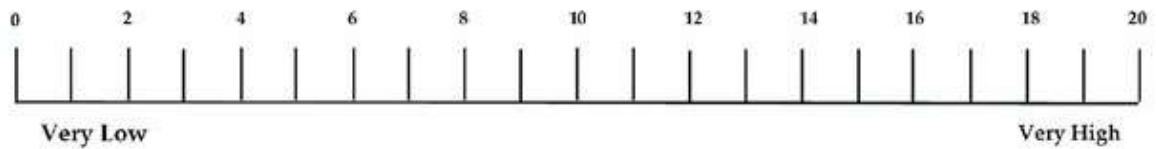
Mental Demand

How mentally demanding was the task?



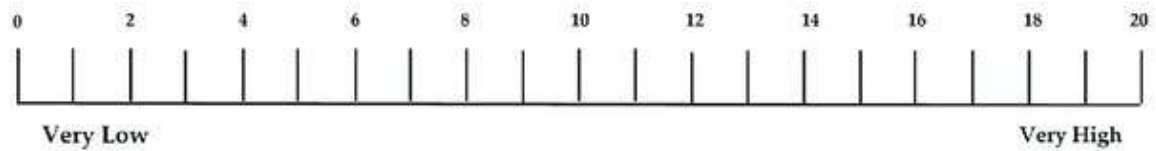
Physical Demand

How physically demanding was the task?



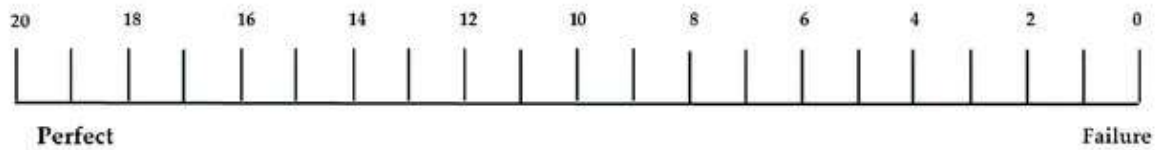
Temporal Demand

How hurried or rushed was the pace of the task?



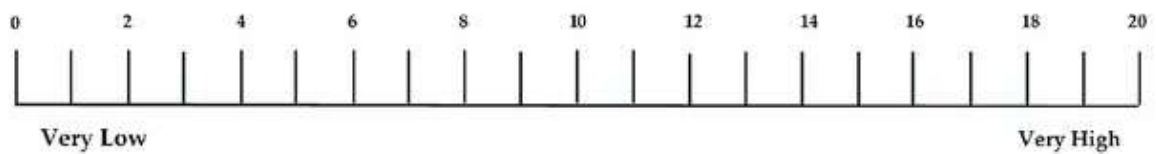
Performance

How successful were you in accomplishing what you were asked to do?



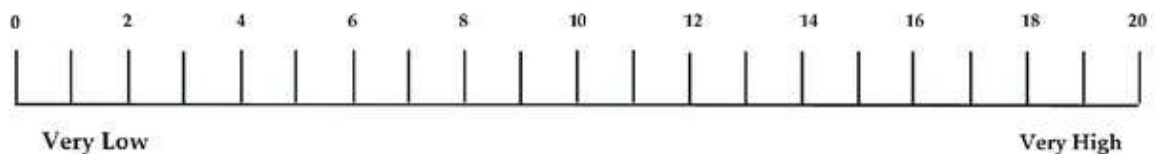
Effort

How hard did you have to work to accomplish your level of performance?



Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?



Questions:

1. How clear was the notification in indicating the direction of the required action (e.g., left or right lane change)? **Comment:** If unclear, please describe any difficulty in distinguishing whether the feedback indicated a left or right action.
2. How comfortable was the haptic feedback (pneumatic or vibrotactile) on the steering wheel? **Comment:** If uncomfortable, please explain (e.g., was the feedback too strong, too weak, or distracting?).
3. Did you feel that the haptic feedback was clearly localized to one side of the steering wheel (e.g., left or right), or did it feel like the entire wheel was affected?

Clearly localized to one side

Felt like the entire wheel was affected

Unsure

4. How confident were you in performing the correct lane change (left or right) based on the haptic feedback? **Comment:** If your confidence was low, please explain any factors that contributed (e.g., ambiguity in the feedback, familiarity with the direction).
5. How urgent did the haptic feedback make the TOR situation feel?
6. Did the haptic feedback (pneumatic or vibrotactile) feel distracting during the TOR task?
7. Please provide any additional comments about your experience with this TOR notification. For example, did the pneumatic or vibrotactile feedback feel more intuitive, natural, or effective? Were there any specific challenges or suggestions for improvement?

Participant No. _____ Gender _____ Age _____ Nationality _____

Experiment:

Designing a Haptic Interface for Enhanced Non-Verbal Human-Robot Interaction

This questionnaire is designed to gather your detailed feedback on the haptic interface integrated into the humanoid robot, which simulates breathing and heartbeat to enhance emotional communication. Please provide thoughtful and detailed responses to the following open-ended questions to help us understand your experience with the haptic interface and its role in human-robot interaction.

1. What aspects of the haptic interface (breathing and heartbeat simulation) were most effective in helping you identify the emotions (e.g., fear, happiness, sadness) conveyed by the robot? Please explain why these aspects stood out.

2. Did you find the haptic interface intuitive to understand without prior explanation? If not, what specific elements felt unclear or confusing, and why?

3. How well did the movements of the haptic interface (breathing and heartbeat) align with the robot's arm gestures in conveying emotions? Please describe any instances where they felt synchronized or mismatched.

4. In what ways did the haptic interface contribute to making the robot appear more lifelike or engaging during the interaction? Please provide specific examples from your experience.

5. How did the design and appearance of the haptic interface (e.g., its shape and integration into the robot's chest) affect your perception of its realism? Were there any design elements that felt particularly natural or unnatural?

6. Compared to the robot's arm gestures alone, how did the addition of the haptic interface influence your ability to recognize the emotions being conveyed? Please describe any differences you noticed.

-
-
7. What challenges, if any, did you encounter while interpreting the emotions conveyed by the haptic interface? Please explain any difficulties or ambiguities you experienced.

-
-
8. How could the haptic interface be improved to better convey emotions or enhance the interaction with the robot? Please provide specific suggestions.

-
-
9. Did the haptic interface create a sense of emotional connection with the robot? If so, how did the breathing and heartbeat simulations contribute to this feeling? If not, what was missing?

-
-
10. Please share any additional thoughts or observations about your experience with the haptic interface or the experiment overall.
-
-

Thank you for participating in this study and providing your valuable feedback!

Consent Form: Participation in a Pneumatic Haptic Interface Study

Project Title: Investigating the Emotional Communicative Potential of Pneumatic Haptic Interfaces: Implications for Movie Experience Enhancement

Researcher: Yang LIU yang.liu@telecom-paris.fr

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Stéphane Safin stephane.safin@telecom-paris.fr

Purpose of the Research: The purpose of this study is to examine the potential of pneumatic haptic interfaces to convey emotions based on various tactile speeds, pressures, and movement types.

Procedure: Participants will experience a series of haptic patterns and provide feedback on their experiences. This will involve two stages of experiments: mixed variables of haptic stimuli, validation of movie clips.

Duration: Approximately 30 minutes

Potential Risks: There are no known risks associated with this research.

Confidentiality: Your responses will be anonymous. No personal identifying information will be required or associated with your responses.

Participation & Withdrawal: Participation in this study is voluntary. You have the right to withdraw at any point during, or after the study, for any reason, and without any prejudice. To withdraw your participation after the study, please write a letter to Yang LIU, all your data will be deleted permanently.

Consent:

Participant's Name

I have read and understood the above information and I voluntarily agree to participate in this study.

Participant's Signature Date

Consent Form: Participation in a Pneumatic Haptic Interface Study

Project Title: Investigating the Emotional Communicative Potential of Pneumatic Haptic Interfaces: Implications for Movie Experience Enhancement

Researcher: Yang LIU yang.liu@telecom-paris.fr

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Purpose of the Research

The purpose of this study is to evaluate how bio-inspired haptic stimuli—using frequency, volume, and texture patterns—affect emotional responses during movie watching. In this second stage of the experiment, we aim to determine whether **congruent** haptic feedback (aligned with the movie's emotional tone) enhances emotional experience, and whether **non-congruent** feedback disrupts it.

Procedure

You will watch a series of short movie clips (approx. 40 seconds each) from different emotional categories (e.g., joyful, sad, tense, calm). These clips will be presented under three conditions:

1. **Control** – no haptic feedback
2. **Congruent** – haptic feedback matching the emotional tone of the scene
3. **Non-congruent** – mismatched haptic feedback (e.g., joyful scene with unpleasant texture)

You will experience each combination in a counterbalanced order. After each clip, you will complete a short **Self-Assessment Manikin (SAM)** questionnaire to rate your arousal and valence, and optionally provide verbal feedback.

Duration

The entire session will last approximately **45 minutes**, including instruction, video viewing, questionnaires, and debriefing.

Potential Risks

There are **no known risks** associated with this study. The haptic stimuli are mild and non-invasive. Some haptic effects may feel slightly surprising or unfamiliar, but they will not cause harm. You may stop participation at any time if you feel uncomfortable.

Confidentiality

All data collected will be **anonymous**. No personal identifying information will be linked to your responses. Data will be securely stored and used solely for academic research and publication purposes.

Participation & Withdrawal

Your participation is **voluntary**. You may withdraw at any time, without providing a reason and without penalty. To withdraw after completing the study, please contact Yang Liu (yang.liu@telecom-paris.fr), and your data will be permanently deleted.

Consent:

Participant's Name

I have read and understood the above information and I voluntarily agree to participate in this study.

Participant's Signature Date

Consent Form: Designing a Haptic Interface for Enhanced Non-Verbal Human-Robot Interaction

Researcher: Zhegong Shangguan zhegong.shangguan@ensta-paris.fr

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Stéphane Safin stephane.safin@telecom-paris.fr

Purpose of the Research

The purpose of this study is to evaluate a novel pneumatic tactile steering wheel designed to improve takeover performance and trust in Level 2 autonomous vehicles. The research investigates how different combinations of tactile, audio, and visual signals affect drivers' responses to takeover requests (TOR).

Procedure

Participants will drive in a simulated environment using a Logitech G27 steering wheel modified with an inflatable pneumatic tactile interface. You will experience four types of Takeover Requests (TOR):

1. Visual + Audio (VA)
2. Visual + Haptic (VH)
3. Audio + Haptic (AH)
4. Visual + Audio + Haptic (VAH)

During each trial, you will drive under autonomous mode until a TOR is triggered. You will then take control of the vehicle. After each trial, you will complete questionnaires assessing your trust in the system and your subjective experience.

Duration

Each session will last approximately **30 to 40 minutes**, including instructions, driving trials, and questionnaires.

Potential Risks

There are **no known physical or psychological risks** associated with participating in this study. The driving task is performed in a simulated environment, and all equipment is safe for use. You may discontinue at any time without consequence.

Confidentiality

Your participation and all data collected during the study will remain **anonymous and confidential**. No personally identifiable information will be recorded. Data will be stored securely and used only for academic research and publication purposes.

Participation & Withdrawal

Participation in this study is **entirely voluntary**. You may choose not to participate or withdraw from the study at any point without providing a reason. If you decide to withdraw after your session, please notify the research team by contacting Yang Liu (yang.liu@telecom-paris.fr), and your data will be permanently deleted.

Consent:

Participant's Name

I have read and understood the above information and I voluntarily agree to participate in this study.

Participant's Signature Date

Consent Form: Participation in a Autonomic Driving Study

Project Title: Comparing Pneumatic and Vibrotactile Haptic Interfaces on Steering Wheel for Takeover Requests in Autonomous Driving

Researcher: Yang LIU yang.liu@telecom-paris.fr

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Purpose of the Research: The purpose of this experiment is to compare the effects of three conditions (no haptic signal, vibration signal, and pneumatic signal) on driver's take-over request under an automatic driving stimulation.

Procedure: Participants will experience a series of take-over request tasks and provide feedback on their experiences.

Duration: Approximately 45 minutes

Potential Risks: There are no known risks associated with this research.

Confidentiality: Your responses will be anonymous. No personal identifying information will be required or associated with your responses.

Participation & Withdrawal: Participation in this study is voluntary. You have the right to withdraw at any point during, or after the study, for any reason, and without any prejudice. To withdraw your participation after the study, please write a letter to Yang LIU, all your data will be deleted permanently.

Consent:

Participant's Name

I have read and understood the above information and I voluntarily agree to participate in this study.

Participant's Signature Date

Consent Form: Designing a Haptic Interface for Enhanced Non-Verbal Human-Robot Interaction

Researcher: Yang LIU yang.liu@telecom-paris.fr

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Stéphane Safin stephane.safin@telecom-paris.fr

Purpose of the Research: The purpose of this study is to evaluate the effectiveness of a novel haptic interface integrated into a humanoid robot, designed to simulate human breathing and heartbeat patterns, in enhancing non-verbal emotional communication between humans and robots. The experiment investigates whether combining involuntary physiological cues (breathing and heartbeat) with voluntary gestures improves human recognition of robotic emotional expressions.

Procedure: Participants will interact with a humanoid robot that performs emotional gestures under two conditions:

- **Condition 1:** Robot performs only voluntary gestures (arms and head movement).
- **Condition 2:** Robot performs the same gestures while also exhibiting breathing and heartbeat animations through a haptic interface.

Participants will observe 30 robot cues (randomized), identify perceived emotions (Fear, Happiness, or Sadness), and rate the expressiveness of gestures and haptic signals using a questionnaire. A personality traits inventory (Big Five) will also be collected at the beginning of the session, and a post-experiment survey will be administered for qualitative feedback.

Duration: Approximately 45 minutes

Potential Risks: There are no known risks associated with this research.

Confidentiality: Your responses will be anonymous. No personal identifying information will be required or associated with your responses.

Participation & Withdrawal: Participation in this study is voluntary. You have the right to withdraw at any point during, or after the study, for any reason, and without any prejudice. To withdraw your participation after the study, please write a letter to Yang LIU, all your data will be deleted permanently.

Consent:

Participant's Name

I have read and understood the above information and I voluntarily agree to participate in this study.

Participant's Signature Date

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Titre : INTERFACES PNEUMATIQUES À CHANGEMENT DE FORME POUR L'ÉMOTION ET LA CONFIANCE DANS L'INTERACTION HOMME-MACHINE

Mots clés : Haptique Pneumatique, Engagement Affectif, Conception Bio-inspirée

Résumé : Cette thèse explore le potentiel des interfaces haptiques pneumatiques en silicone pour renforcer l'engagement émotionnel, la confiance et la communication non verbale dans trois domaines : les expériences cinématographiques, la conduite automatisée et l'interaction homme-robot (HRI). Située à l'intersection de l'informatique affective et de l'interaction homme-machine (IHM), elle montre comment un retour haptique bio-inspiré — via des changements de forme et de texture dynamiques — peut enrichir l'expérience utilisateur en alignant les stimuli tactiles sur les émotions, la conscience situationnelle et les signaux physiologiques.

La première partie porte sur l'amplification des émotions au cinéma. Les récits audiovisuels classiques sont enrichis par un retour haptique pneumatique afin de créer une narration immersive et multisensorielle. Inspirée de structures biologiques (piquants d'oursins, coussinets de chats), l'interface combine textures épineuses et lisses pour moduler la valence émotionnelle, tandis que les rythmes d'inflation régulent l'arousal. Des expériences contrôlées révèlent que des stimuli haptiques congruents amplifient significativement les réponses émotionnelles : des textures en relief à haute fréquence accroissent l'excitation, alors que des textures lisses à basse fréquence favorisent le calme. À l'inverse, des signaux non congruents perturbent l'alignement émotionnel, soulignant l'importance d'une conception contextuelle. Ces résultats confirment la valeur des haptiques pneumatiques comme vecteur de communication émotionnelle, au-delà des simples alertes fonctionnelles.

La deuxième partie s'intéresse aux systèmes de conduite automatisée, et plus particulièrement aux demandes de reprise de contrôle dans les véhicules autonomes de niveau 3. Le volant Pneumatic Haptic Silicon Sac, inspiré des sacs vocaux des grenouilles, délivre un retour rythmique doux destiné à réduire

la charge cognitive et renforcer la confiance lors des transitions. Des comparaisons avec des systèmes vibrotactiles montrent que les signaux pneumatiques suscitent des réactions plus calmes et fluides, tandis que les alertes vibrantes génèrent des réponses plus rapides mais plus stressantes. L'ambiguïté directionnelle des signaux pneumatiques, notamment pour les changements de voie à gauche, révèle toutefois la nécessité de modalités hybrides équilibrant urgence et confort. Ces résultats contribuent à la conception de systèmes haptiques adaptatifs en fonction des contextes de conduite.

La troisième partie explore l'interaction non verbale homme-robot. Une interface pneumatique simule des rythmes physiologiques tels que la respiration ou les battements cardiaques. Intégré dans la poitrine d'un robot humanoïde, ce système combine gestes volontaires et signaux physiologiques subconscients afin de faciliter la reconnaissance des émotions. Les résultats expérimentaux indiquent une amélioration de 16% de la précision lorsque ces haptiques physiologiques complètent les gestes, particulièrement pour des émotions atténuées comme la tristesse. Les participants ont décrit ce retour comme « intime » et « réaliste », montrant son potentiel pour renforcer la confiance et le lien affectif dans la robotique sociale. Des limites demeurent, notamment la variabilité culturelle de la perception tactile et les biais directionnels observés en conduite. Ces résultats ouvrent des pistes de recherche : développement de systèmes adaptatifs en temps réel, études interculturelles sur les haptiques émotionnelles, innovations en matériaux durables.

En réunissant biomimétisme, design émotionnel et facteurs humains, cette recherche pose les bases de technologies haptiques capables de dépasser la simple fonctionnalité pour instaurer des relations homme-machine plus profondes, intuitives et affectives.

Title : SHAPE-CHANGING PNEUMATIC INTERFACES FOR EMOTION AND TRUST IN HUMAN-COMPUTER INTERACTION

Keywords : Pneumatic Haptics, Affective Engagement, Bio-inspired Design

Abstract : This dissertation explores the transformative potential of silicone-based pneumatic haptic interfaces to enhance emotional engagement, trust, and non-verbal communication across three interconnected domains: cinematic experiences, automated driving systems, and human-robot interaction (HRI).

At the intersection of affective computing and human-computer interaction (HCI), this research investigates how bio-inspired haptic feedback—mediated through dynamic shape-changing and surface textures—can deepen user experiences by aligning tactile stimuli with contextual emotions, situational awareness, and physiological cues.

The first part of this work addresses cinematic emotion enhancement, where traditional audiovisual narratives are augmented with pneumatic haptic feedback to create immersive, multi-sensory cinematic storytelling. Drawing inspiration from biological structures such as sea urchin spines and cat paw pads, the designed interface employs spiked and smooth textures to modulate emotional valence, while inflation rhythms regulate arousal. Controlled experiments reveal that congruent haptic stimuli significantly enhance emotional responses, with high-frequency, goosebump-textured feedback intensifying excitement and low-frequency, smooth textures enhancing calmness. Conversely, non-congruent haptic feedback has negative effects on emotional alignment, underscoring the importance of context-aware design. These findings validate the role of pneumatic haptics as a medium for emotional communication, extending beyond functional alerts to evoke embodied, affective experiences.

The second part transitions to automated driving systems, focusing on the design of bio-inspired pneumatic interfaces for Takeover Requests in Level 3 autonomous vehicles. The Pneumatic Haptic Silicon Sac

steering wheel, inspired by animal inflation mechanisms like frog vocal sacs, employs gentle rhythmic feedback to reduce cognitive load and foster trust during control transitions. Comparative studies with vibrotactile systems demonstrate that pneumatic cues elicit calmer, smoother driver responses, while vibrotactile alerts achieve faster reaction times at the cost of increased stress. However, directional ambiguity in pneumatic feedback—particularly for left lane changes—highlights the need for hybrid modalities that balance urgency and comfort. These insights advance the development of adaptive haptic systems based on situational demands.

The third part explores non-verbal human-robot interaction, introducing a pneumatic haptic interface that simulates physiologically-inspired rhythms such as breathing and heartbeat. Integrated into a humanoid robot's chest, this silent, silicone-based system combines voluntary gestures with subconscious physiological cues to enhance emotion recognition. Experimental results show a 16% improvement in accuracy when physiologically-inspired haptics are paired with gestures, particularly for down-tune emotional states like sadness. Participants described the feedback as "intimate" and "lifelike," emphasizing its potential to foster trust and affective rapport in social robotics.

Limitations, such as cultural variability in tactile perception and directional biases in driving interfaces, underscore opportunities for future work. Adaptive systems leveraging real-time user states, cross-cultural studies of emotional haptics, and sustainable material innovations are critical next steps. By unifying principles of biomimicry, emotional design, and human factors, this research lays the groundwork for haptic technologies that transcend functionality to foster deeper, more intuitive human-computer relationships.