Improving mediated touch interaction with multimodality

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Thèse de doctorat

Improving Mediated Touch Interaction with Multimodality

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Improving Mediated Touch Interaction with Multimodality

A dissertation presented

by

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April 2022

Abstract

As one of the most important non-verbal communication channels, touch is widely used for different purposes, from expressing less intimate feelings such as greetings (e.g., shaking hands, embracing, kissing on the cheeks) to more intimate interactions (e.g., holding hands, hugging, kissing). It is a powerful force in human physical and psychological development, shaping social structures and, most importantly, communicating emotions. However, even though current ICT systems enable the use of various non-verbal languages in mediated communication, the support of communicating through the sense of touch is still insufficient. Thus, there is a strong need to improve mediated touch in our daily communication and interaction.

Inspired by the cross-modal interaction of the human perception system, the approach I present in this dissertation is to use *multimodality* to improve mediated touch interaction. This approach contains two directions: 1) enhancing touch interaction with other modalities; and 2) improving the tactile modality generation in multimodal interaction. Following this approach, I present three devices that provide empirical contributions to multimodal touch interaction: *VisualTouch*, *SansTouch*, and *In-Flat*.

To understand if multimodal stimuli can improve the emotional perception of touch, I present *VisualTouch*, a haptic sleeve that generates congruent visual-tactile stimuli on the forearm. With *VisualTouch*, I quantitatively evaluate the emotional response of multimodal stimuli. The results confirm the cross-modal interaction between visual and tactile modality, which indicates that using an additional visual modality is a promising approach to support affective touch communication.

Inspired by *VisualTouch*, I investigate the use of different modalities in real touch communication. I present the design of *SansTouch*, a multimodal hand sleeve that enables mediated hand-to-hand interactions such as handshakes or holding hands. *SansTouch* provides empirical insights on multimodal interaction of visual, thermal,

and tactile stimuli in the context of face-to-face communication. Furthermore, I explore the possibility of generating human-like touch with pneumatic actuation in *SansTouch*, to improve the tactile modality generation in multimodal interaction.

In-Flat goes one step forward in the use of multimodal stimuli in touch interaction. *In-Flat* is an input/output pressure-sensitive overlay for smartphones. It consists of a transparent inflatable skin-like silicon layer that can be placed on the top or the back of a smartphone. *In-Flat* not only provides further insights on the use of pneumatic actuation in touch generation, but also a better understanding of the role that mediated touch plays in other interaction contexts.

In summary, this dissertation strives to bridge the gap between touch communication and HCI, by contributing to the design and understanding of multimodal stimuli in mediated touch interaction.

Résumé

Comme l'un des plus importants canaux de communication non verbale, le toucher est largement utilisé à des fins différentes, allant de l'expression de sentiments moins intimes comme des salutations (e.g., se serrer la main, s'embrasser, s'embrasser sur les joues) à des interactions plus intimes. (e.g., se tenir la main, se serrer dans ses bras, s'embrasser). C'est une force puissante dans le développement physique et psychologique humain, façonnant les structures sociales et, surtout, communiquant les émotions. Cependant, même si les technologies de l'information et de la communication actuels permettent l'utilisation de divers langages non verbaux, le soutien à la communication par le sens du toucher est encore insuffisant. Il y a donc un grand besoin d'améliorer la communication et l'interaction quotidiennes.

Inspiré par les interactions intermodales dans le système de perception humaine, l'approche que j'adopte dans cette thèse est d'utiliser la multimodalité pour améliorer l'interaction tactile médiée. Cette approche comporte deux directions: 1) améliorer l'interaction tactile avec d'autres modalités; et 2) améliorer la génération de modalités tactiles dans l'interaction multimodale. Suivant cette approche, je présente trois dispositifs qui fournissent des contributions empiriques à l'interaction tactile multimodale: *VisualTouch*, *SansTouch*, et *In-Flat*.

Afin de comprendre si les stimuli multimodaux peuvent améliorer la perception émotionnelle du toucher, je présente *VisualTouch*, une manchette qui génère des stimuli visuels-tactiles congruents sur l'avant-bras. Avec *VisualTouch*, j'évalue quantitativement la réponse émotionnelle des stimuli multimodaux. Les résultats confirment l'interaction intermodale entre la modalité visuelle et la modalité tactile, ce qui indique que l'utilisation d'une modalité visuelle supplémentaire est une approche prometteuse pour soutenir la communication tactile affective.

Inspiré par *VisualTouch*, j'étudie l'utilisation de différentes modalités dans la communication tactile. Je présente *SansTouch*, une pochette multimodale qui permet des interactions main-à-main médiatisées, comme des poignées de main ou des

mains. *SansTouch* fournit des renseignements empiriques sur l'interaction multimodale des stimuli visuels, thermiques et tactiles dans le contexte de la communication en personne. En outre, j'explore la possibilité de générer un contact humain avec l'actionnement pneumatique dans *SansTouch*, pour améliorer la génération de modalité tactile en interaction multimodale.

Enfin, pour aller plus loin dans l'utilisation de stimuli multimodaux en interaction tactile, je présente *In-Flat*. *In-Flat* est une superposition tactile entrée/sortie pour smartphones. Il se compose d'une couche de silicium transparente gonflable à la peau qui peut être placée sur le dessus ou à l'arrière d'un smartphone. *In-Flat* fournit non seulement des informations supplémentaires sur la génération du toucher de la peau, mais aussi une meilleure compréhension du rôle que joue le toucher médié dans des contextes plus généraux.

En résumé, cette thèse vise à combler le fossé entre la communication tactile et l'IHM, en contribuant à la conception et la compréhension des stimuli multimodaux dans l'interaction tactile médiée.

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1

Introduction

A key question that has driven interactive computing for decades is: how can interactive devices better support users' communication?

Back in the early days of human history, the main goal of different communication technologies was to improve the efficiency of communication [248]. The appearance of speech enabled the easier dissemination of ideas and eventually resulted in the creation of new forms of technology. Our communication channels evolved from durable symbol systems like cave paintings or oracle bone script, to more modern postal service. Following that, thanks to advancements in telecommunication systems, users separated by thousands of miles can have interactive conversations as if they were in the same room [248, 247]. Shortly after that, with the birth of computers, internet, and mobile devices, we finally moved into the era of the *Information Age* [249].

With the rapid development of communication technology, the user experience of different communication channels is no longer restricted by the communication medium's speed and accuracy. Our communication devices have progressed from bulky telephone sets to large-screen smartphones or even tiny wearable devices [248]. At an affordable price, we can easily get access to reliable and high-quality telecommunications anywhere, anytime. On the other hand, users' pursuit of a more user-friendly interactive system never ends. They are avidly seeking new communication channels that allow them to better express themselves and facilitate emotional communication. Driven by these needs, our communication channels continue the evolution from traditional phone calls to real-time video and audio calling, audio/pictures/emoji/text messaging, and even AR/VR communication, etc. [247]. Benifiting from these new communication channels, users are able to communicate non-verbally by observing each other's facial expressions and body language through video, listening to the tone and volume of our voices (i.e. paralanguage) [8], and even sharing information about the surrounding environment with people at any moment through video or virtual reality technology. Thus, users are able to complement, regulate, substitute for, or accent a verbal message with these non-verbal channels [171]. So it appears that we now have all the aspects of communication that we needed. But is that really the case?

"One important piece missing from the puzzle: touch."

We may not realize that the use of social touch in everyday life is actually quite frequent: a handshake to greet each other, a hug and kiss to show affection, a child clinging to his father's knee, or a hug to an upset friend. It is the first language we use to communicate with our parents when we are still infants or even fetuses [73]. It is also the last language many people use in palliative care or even at the last moment of their lives while holding their loved one's hand [199]. In our whole lifetime, we use social touch for a variety of purposes, including to communicate support, appreciation, inclusion, sexual interest, affection, playfulness, to gain someone's compliance, to get someone's attention, to announce a response, to greet, etc. [115]. Many of these functions cannot be easily replaced by alternative communication channels. Thus, social touch is a crucial and indispensable piece in our communication, especially for expressing emotions [94].

Despite that the sense of touch is important in early stages of life, and that social contact is important in the formation of connections later in life, the role of touch in social relationships was not structurally researched until the early 1960s [63]. Moreover, even though current communication technology enables the use of a mix of verbal and non-verbal languages in our communication, the support of affective touch in digital communication is still absent, and its importance is still underestimated [230]. Current communication devices, such as smartphones, PCs, or AR/VR headsets, are primarily designed for audio and visual interactions. These devices are typically rigid and static, which provides poor haptic perception. Their major components for generating tactile sensations are vibration motors, which remain limited in generating a variety of touch sensations. As a result, these devices have a limited ability to interpret and convey affective touch in mediated communication. Thus, mediated social touch in communication is still a relatively young field of research that has the potential to substantially enrich human–human and human–system interaction [230].

To this end, the general question I would like to address in this thesis is: **How to improve mediated social touch interaction in our daily communication?** Following the potential research topic suggested by Van Erp et al. in 2015 [230] about social touch in HCI, my approach is to use *multimodality stimulation*, to enrich and broaden mediated touch interaction in communication. More precisely, the approach I take contains two directions: 1) enhance mediated touch interaction with other modalities; and 2) improve the tactile modality actuation in the multimodal interaction. Standing at the crossroads of Human Computer Interaction (HCI) and Emotional Design, mediated social touch involves many elements, such as psychology, neuroscience, sociology, computer science, etc. [230]. Thus, the approach I take here is broad and exploratory, including exploring cross-model interactions within different modalities, improving the actuation approach of the tactile stimulation, and integrating multimodality social touch interaction into daily life. In this introductory chapter, I first define the problem and our research question in Section 1.2, and then present the contribution of my work in Section 1.4. Then, follows a brief overview of the chapters of this thesis.

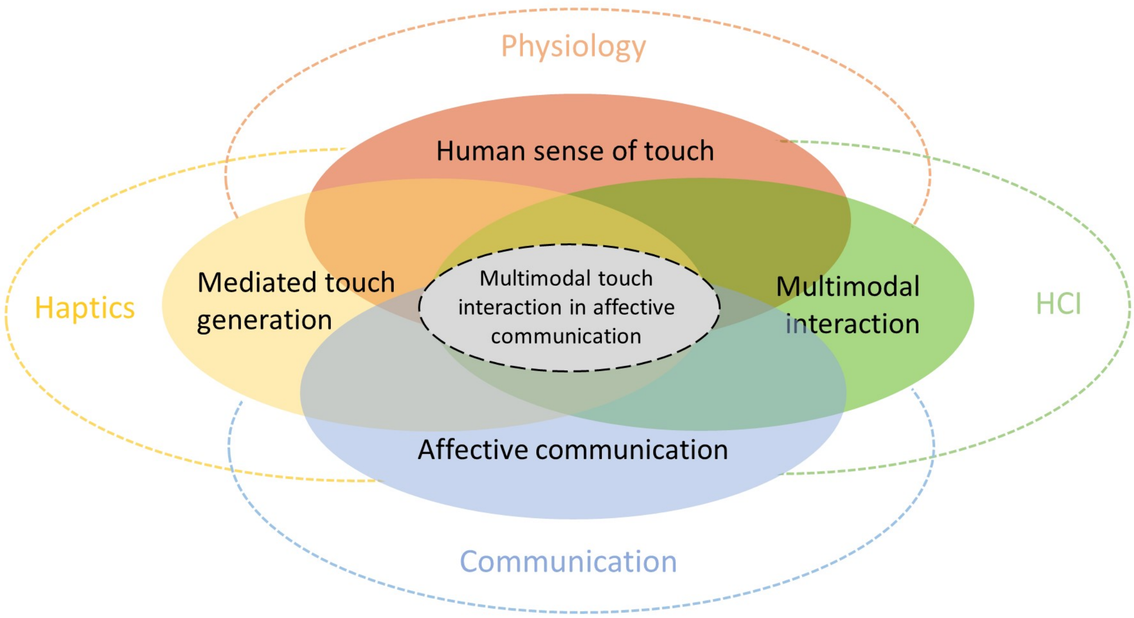

Figure 1.1: Research scope of this thesis.

1.1 Concept definition

To better understand the research question and the contribution of this work, I introduce in this section definitions of some frequently used terms in this dissertation.

- **Mediated communication.** Mediated communication refers to communication carried out by the use of information communication technology (ICT) systems. Typical mediated communication includes telephone conversations, letters, emails, and audio/video chats [247]. This term is often used in contrast to face-to-face communication [247]. In this dissertation, however, these two terms are not opposite to each other. Face-to-face communication can also be mediated by ICT systems, and this concept will be further discussed in Chapter 4.

- **Touch.** Several meanings are associated with the term "touch". Two of these definitions are particularly relevant to this dissertation. The first definition focuses on human perception. In this usage, touch is one of the sensations processed by the human somatosensory system. Thus, the term "touch" here means "touch sensation" or "sense of touch". The second definition focuses on human behavior. Under this definition, the term "touch" refers to the movement or behavior that people communicate and interact with each other via the sense of touch. The main purpose of this dissertation is to explore the use of touch in communication. Unless specified, otherwise, the term "touch" refers to the specific nonverbal communication behavior in this dissertation.

  - **Social touch.** Heslin et al. defined interpersonal touch into five categories: functional touch expresses task-orientation, social touch expresses ritual interaction, friendship touch expresses idiosyncratic relationships, intimacy touch expresses emotional attachment, and sexual touch expresses sexual intent [96]. Unless specified otherwise, the term "social touch" in this dissertation refers to the touch used for social and affective purposes, including ritual interaction, expressing idiosyncratic relationships, and expressing emotional attachment in Heslin's definition. It is worth noting that the intent of a touch is not always exclusive, and touching can evolve into each one of Heslin's categories.
  - **Discriminative touch.** The terms "discriminative touch" or "fine touch" refer to the sensory modality that allows a subject to detect, discriminate,

and identify external stimuli with touch sensation [139].

  - **Affective touch.** Distinguished from discriminative touch, affective touch refers to the sense of touch that serves an interoceptive function, having to do with motivational affective aspects of touch, and giving feedback about the wellbeing of the body [103, 131]. In this dissertation, I use the term "affective touch" to refer to the touch that conveys affective and socially relevant information, i.e. the touch for expressing idiosyncratic relationships and expressing emotional attachment in Heslin's definition [96].
  - **Mediated touch.** Different from the interpersonal touch that we perform directly with our bodies on each other in face-to-face communication, mediated touch refers to the touch generated by ICT systems [78, 230]. In this case, the sense of touch is triggered by the ICT system, instead of by the other interlocutor directly.

- **Multimodal interaction.** According to the definition proposed by Nigay et al. in 1993 [155], *multi* means "more than one" while *modal* covers the notion of *modality* as well as that of *mode*. *Modality* refers to the type of communication channel used to convey information, while *mode* refers to a state that determines the way information is interpreted to extract or convey [155, 233]. And in the context of communication, the modality defines the type of data exchanged, whereas the mode determines the context in which the data is interpreted. From a system-oriented perspective, the term *multimodality* refers to the capacity to communicate with a user along different types of communication channels. From a user-centered perspective, the term *multimodal interaction* also includes the other communication channels apart from mediated touch, such as verbal communication and body language in face-to-face communication.

1.2 Research questions

Touch sensation involves many factors. In our skin, there are multiple distinct receptors that perceive different aspects of tactile stimuli, which makes it challenging to generate precise and vivid touch sensations. Meanwhile, the meanings of touch are inextricably linked to the context of communication, and failure to integrate mediated touch into the context of communication can lead to a number of ambiguities and degrade communication quality. Thus, two issues must be addressed in order to answer the question of how to improve mediated touch interaction in our daily communication: *1) How might the tactile perception of mediated social touch interactions be improved? And 2) how can we integrate mediated touch interaction into our daily communication more effectively?* Combining these two issues with the approach I adopt - combining *multimodality stimulation* with tactile modality, the research questions I would like to answer in this dissertation are:

RESEARCH QUESTION 1: ***Can we use multimodality to improve emotional communication and interaction?***

This research question consists of two sub-questions focusing on social touch and other types of interaction respectively.

- **RESEARCH QUESTION 1(A):** ***Can we use multimodality to improve the emotional perception of current social touch technology?***
  It was the first thought that came to my mind since the first day of my PhD. Despite the fact that numerous technologies and actuators have been investigated and used, the expressiveness of most current social touch devices remains limited. Multimodal interaction, on the other hand, is showing its potential in communication systems [98]. As one of the main sensory modalities, touch influences and is influenced by other sensations. Thus, is it conceivable to use multimodality to improve the emotional communication of current limited touch devices? If so, what are the factors that we need to consider when using multimodality touch in social touch interaction?

- **RESEARCH QUESTION 1(B):** ***Can we use multimodality to improve touch interaction outside social touch context?***
  As a complement to Research Question 1(a), Research Question 1(b) considers other potential applications that multimodality can be used in. Answering this question can not only improve the generalizability of mediated touch devices, but also help us acquire a better understanding of the role mediated touch devices play in daily interaction.

RESEARCH QUESTION 2: ***How can we generate more human-like tactile stimulation to improve multimodal touch interaction?***

The first question considers the possibility of improving current mediated touch communication with the existing actuation approach. Given that human beings have evolved a remarkable system for capturing and interpreting various touch stimuli, generating human-like tactile stimuli still remains challenging in current research. Even though recent research [113] brought up the possibility of improving mediated touch interaction with new forms of touch experience other than mimicing human touch, rendering human-like touch is still considered as a key to successful touch communication [23, 219, 177]. Thus, in the second research question, I would like to investigate the possibility of generating more human-like tactile stimulation, by using appropriate actuation and material technologies. I would also consider key factors to be concerned about when integrating these technologies into multimodal touch interaction.

RESEARCH QUESTION 3: ***How can we incorporate multimodal touch interactions into our everyday communication and interaction?***
The above two questions focus on improving the emotional perception of multimodality touch devices, while the ultimate goal of these mediated touch devices is to improve our daily affective communication. Thus, we are interested in discussing the design factors that we need to take into account, in order to better integrate multimodality touch into our daily communication and interaction.

1.3 Research approach

As shown in Figure 1.2, my work includes the following general approach:

- **Ideation**
  Before starting the design and fabrication process of the touch devices, several rounds of ideation were conducted to define the research question and to generate possible approaches. The ideation work includes literature reviews, sketching the possible approaches, and brainstorming within our research group.

- **Survey**
  In the design process of *SansTouch*, a survey was conducted on social touch habits to identify the social touch breakdowns for different social relationships and the alternatives to replace their touch habits during the COVID-19 pandemic.

- **Interaction design**
  After the ideation and survey, I designed the interaction and functionality of the prototype based on user needs and the context of use. In this stage, I explored the possibility of different approaches generated in the ideation stage. I built low-fidelity (lo-fi) prototypes and conducted pilot testing within the research group. Based on the insights, I identified the desired features and interactions of the design. This method was performed iteratively during the design process.

- **Prototype fabrication**
  Different fabrication methods and tools were used in the prototype building stage, including 3D printing, laser cutting, silicon mode casting, heat sealing, circuit soldering, etc.

- **Controlled experiments**
  To evaluate the usability of the device, controlled experiments were conducted after building the prototypes. This method includes quantitative studies (Chapter 3, 5), scenario-based interaction (Chapter 4), open-ended explorations (Chapter 4, 5) and interviews.

- **Data analyze**
  The data collected from the controlled experiments were analyzed qualitatively and quantitatively. Methods such as ANOVA analysis, MANOVA analysis, REML analysis, and thematic analysis were performed in this dissertation.

1.4 Research contribution

Standing at the crossroad of Human Computer Interaction (HCI) and Emotional Design, this research makes several major contributions in the following aspects according to the HCI research contribution framework by Wobbrock et al. [253]:

CONTRIBUTION 1: Artifact contributions

- ***VisualTouch***: A wearable forearm sleeve that enhances affective communication by combining vibrotactile stimuli with a congruent visual effect.
- ***SansTouch***: A novel inflatable hand sleeve that combines touch, visual, and thermal modalities. This device can support multimodal hand touching interactions in both remote and face-to-face communications.

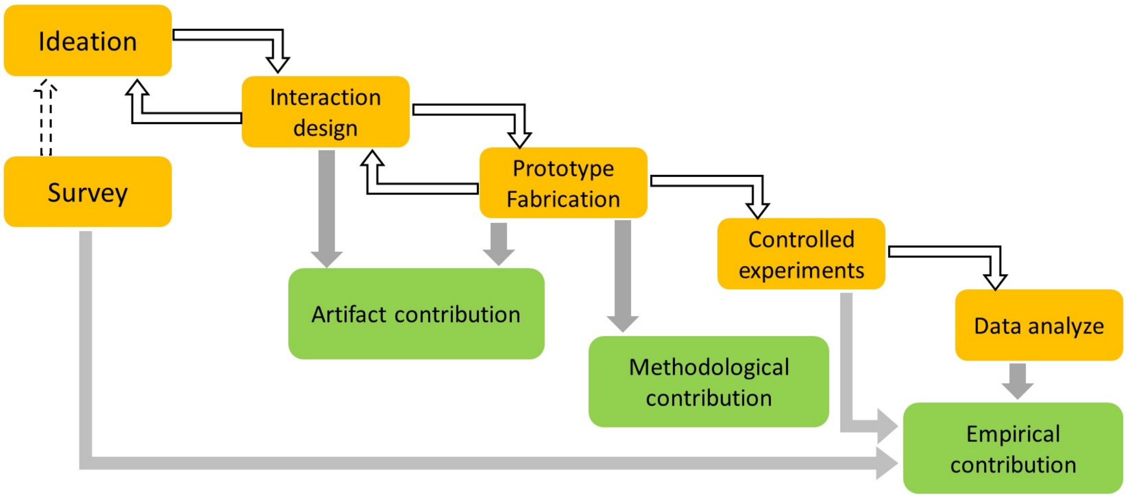

Figure 1.2: Research approach of this dissertation.

- ***In-Flat***: A pressure-sensitive overlay on smartphones that couples pressure-based touch I/O interactions with visual display. *In-Flat* not only allows for skin-like hand touch interaction, but it also provides tangible affordances on visual objects and a variety of novel touch input gestures.

CONTRIBUTION 2: Empirical contributions

- *Multimodal interaction in mediated touch.* I investigated how multimodality improve mediated touch interaction. I explored using additional visual modality to improve emotional perception of tactile stimuli with *VisualTouch*. Based on the insights, I conducted a *scenario-based interaction* with *SansTouch* to evaluate the combination of visual, thermal, and tactile stimuli in touch interaction. These studies showed that multimodality can enhance the emotional perception of mediated touch, and thus improve affective communication. This contribution addresses Research Question 1(a) and 2 of this dissertation.
- *Mediated touch in face-to-face communication.* Previous research rarely investigated mediated touch interaction in a face-to-face communication. I conducted a *scenario-based interaction* with *SansTouch*, from which we provide empirical insights about the design factors that can better support mediated multimodal touch interactions in face-to-face communication. This contribution addresses Research Question 3 of this dissertation.
- *Understanding social touch breakdowns.* Based on the ongoing background of

COVID-19 pandemic, I conducted a survey on social touch habits before and after the lockdown during the pandemic. I identified the social touch breakdowns for different social relationships, and also the alternatives to replace their touch habits. This study contributes empirical insights based on real stories from participants on social touch habit breakdowns, and thus provides insights for the design of *SansTouch* and for future research. This contribution addresses Research Question 3 of this dissertation.

- *Incorporate multimodality touch into mobile interaction.* To discuss the use of multimodal touch devices in more general contexts, I conducted *open-ended exploration sessions* and *semi-structured interviews* with *In-Flat*, providing insights into future design directions and implementations for supporting multimodal touch interaction, as well as the coupling between touch I/O and visual displays on mobile devices. This contribution addresses Research Question 1(b) and 2 of this dissertation.

CONTRIBUTION 3: Methodological contribution

- I proposed a fabrication approach of highly transparent and stretchable overlays for smartphones that enables in-place coupling between visual objects displayed on the smartphone and touch I/O interactions.

1.5 Collaboration works

This thesis is one part of ANR[1] Social Touch research project (ANR-17-CE33-0006 SocialTouch). The goal of this project is to investigate how the sense of touch can be integrated in interactive systems to leverage communicative and emotional channels between humans and machines or between humans via machines. Four partners (LTCI[2], ISIR[3], i3-CNRS[4], Heudiasyc[5]) are collaborating in this ANR project around five tasks: design of test scenarios and analysis methodology, design of human touch recognition device, touch generation device design, development of social touch in human-agent interactions, integration of different tasks and evaluation. As a member of LTCI, my works focused on touch generation device design and evaluation.

[1] Agence nationale de la recherche (ANR): https://anr.fr/

[2] Le Laboratoire de Traitement et Communication de l'Information (LTCI) – Télécom Paris: https://www.telecom-paris.fr/fr/recherche/laboratoires/laboratoire-traitement-et-communication-de-linformation-ltci.

[3] Institue for Intelligent Systems and Robotics(ISIR) – Université Pierre et Marie Curie: http://www.isir.upmc.fr/.

[4] Institut Interdisciplinaire de l'Innovation – Télécom Paris: https://i3.cnrs.fr/

[5] Heuristique et Diagnostic des Systèmes Complexes – Université de Compiègne: https://www.hds.utc.fr/

Working together under the ANR Social Touch project framework, I collaborated closely with Robin Heron, who was doing his thesis during last three years in i3-CNRS department. He was actively involved in the prototype design, evaluation and data analyze process of *VisualTouch* and *SansTouch*. I also collaborated closely with Jessalyn Alvina, a post-doctoral fellow in DIVA. We worked together in the prototype design, evaluation and data analyze process of *SansTouch* and *In-Flat*, as well as writing and publishing the papers. Furthermore, I also worked closely with Mickaël Bouhier, the research engineer in DIVA group. He provided many technical supports during the prototype design and fabrication of *SansTouch* and *In-Flat*, and he also led the design and fabrication process of second version of *VisualTouch*. I also collaborated with Stéphane Safin, an associate professor in i3-CNRS department, in the design and evaluation process of *VisualTouch* and *SansTouch*.

1.6 Thesis overview

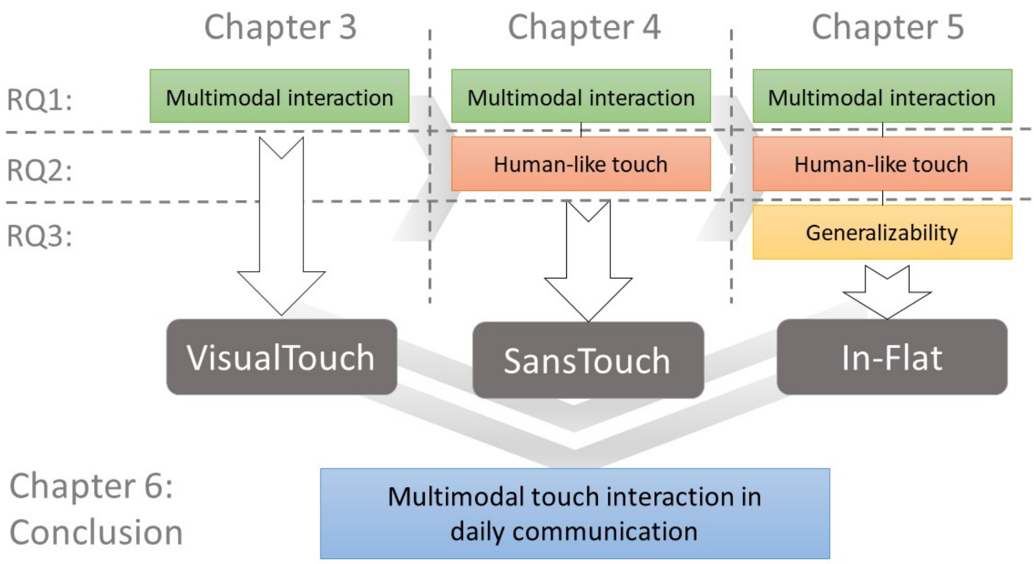

Figure 1.3: Overview of the dissertation

The chapters in this dissertation are outlined as follows:

Chapter 2 first summarizes related work on the physiological and psychological perception of social touch and touch communication. I then address existing research that focuses on multimodal interaction of touch and mediated touch generation.

Chapter 3 investigates the possibility of using multimodality, particularly visual modality, to improve the emotional perception of vibrotactile touch device. I present the design and implementation of *VisualTouch*, as well as a *quantitative user study* about the emotional response of touch feedback with the addition of visual modality.

Chapter 4 describes our approach of using pneumatic actuation and silicone material to generate realistic skin-like touch sensations in multimodal touch interaction. This chapter is split into three subsections. I first highlight previous work on the use of silicone material and pneumatic actuation in mediated touch generation devices. Then I introduce *SansTouch*. First, I introduce our survey about social touch breakdowns during the COVID-19 pandemic for different forms of touch in different relationships. Based on the insights, I present the design and implementation of *SansTouch*. To assess whether a mediated touch device like *SansTouch* can enhance the social experience in face-to-face communication, I conducted a structured observational study with 12 participants. Finally, I discuss the main design factors for building the pneumatic multimodal touch devices based on the insights from the study.

Chapter 5 discusses the use of multimodal touch devices in more general communication and interaction contexts in three conditions. I first present the design and implementation of *In-Flat*, along with the exploration of the fabrication approach. To illustrate how we can incorporate *In-Flat* into our everyday communication and interaction, I present several potential applications and use cases of *In-Flat*. To assess if users can perform pressure input with *In-Flat*, as well as the perception of the dynamic visual+touch output, I designed a controlled experiment and an open-ended exploration with *In-Flat*. Based on the insights from the study, I discuss how we should incorporate multimodal touch interactions into our everyday communication and interaction.

Chapter 6 first presents an overall discussion focusing on how this work expands the boundary of affective touch interactions. I summarize the contributions in terms of scientific understanding and design and give directions for future work.

2

Background of Social Touch

The work presented in this dissertation builds primarily on the fields of touch perception, communication, and human computer interaction (HCI). This chapter reviews the prior research literature related to the physiological and psychological perception of social touch, touch communication, multimodal interaction of touch and mediated touch generation.

2.1 The human sense of touch

In the world of physiology science, the sense of touch is defined as one of the sensory modalities represented by the somatosensory system, which also includes the sense of pain, the sense of temperature, and the proprioception sensation [229]. And what we usually refer to as "the sense of touch" is so called "active" or "haptic" touch, which involves some movement in the touch. This movement can be voluntary, exploratory movements of the hands and other sensory surfaces involved in touch, or it can also refer to experiences generated by objects moving against a stationary body [59]. The term *tactile sensation* is also frequently used to describe this sensation. Thus, the term *touch stimuli* and the term *tactile stimuli* all refer to the external forces that involve physical contact with the skin that give rise to the touch sensation in this work.

Touch plays an essential role in our daily life. We use touch not only to manipulate objects and perceive the surrounding environment, but also to maintain social interactions and convey emotions [94]. The former kind of touch is called *discrim-*

inative touch, with which we detect, discriminate, and identify stimuli in the surrounding world [139, 103]. It allows us to feel the texture of cloth, guides the arm to accurately go through the sleeves, and helps our fingers button up the buttons skillfully even without looking. Our discriminative touch sensation is so well-practiced in this procedure that we can easily wear the clothes even without the involvement of the other sensations.

Beyond the discriminative function of touch, there is another important fact: touch can also be pleasant [131]. For example, when our finger slides smoothly over a piece of fine silk or velvet, our perception is much more pleasant than slipping over a piece of sandpaper. Furthermore, even with the same touch stimuli, such as a caress on the arm, we would feel much more pleasant if the touch was from a loved one instead of a stranger. This function of the sense of touch is referred to as *affective touch* [139, 103], and if the affective touch happens in social interaction, it can also be called *social touch* [131, 139].

To develop mediated touch devices that support social touch interaction, it is important to understand how we perceive the sense of touch and what role touch plays in our social communication. To this end, I start by reviewing the physiological perspective of touch. In addition, I will discuss affective touch in social interaction (i.e., social touch).

2.1.1 Physiology of touch

As the earliest sense that develops in the human embryo, touch is the primary sensation that the fetus and the newborn use to perceive the world and receive stimulation [66], and thus the sense of touch provides us information about the external world continuously from the very early moments of life until the end.

Nerves and receptors

To perceive the sense of touch, human beings have developed a remarkable system to capture, transmit, and process touch stimuli. The organ that is involved most through this procedure is the skin, the largest sensation organ in the human body [131, 183, 103]. There are an enormous number of receptors perceiving the surrounding enviroment everyday in our skin. For example, there are more than 150000 tactile receptors just in one single hand, and over 30000 primary afferent fibers carry signals from these receptors to the central nervous system [64, 114].

This large number of nerves confers fine tactile acuity to our hands, enabling them to read Braille, fabricate and assemble mechanical watches, and do microsurgery on a beating heart.

So what are these receptors under our skin and how do they perceive tactile stimuli? The structure of the skin can answer this question. Our skin is composed of two primary layers: the *epidermis* and the *dermis* [242]. The outermost layer is the epidermis, which is covered with several layers of dead tissue named *stratum corneum* that perform protective functions [241]. Below this protective layer, *cutaneous end organs* can be found within the epidermal-dermal interface and the dermis. *Cutaneous end organs* or so called *cutaneous receptors* are the structures that are responsible for perceiving and transducing chemical, electrical, thermal or more importantly, tactile signals into neural signals [90, 242, 241]. More precisely, the *thermoreceptors* detect the temperature change of the skin, the *nociceptors* detect painful stimuli, and the *mechanoreceptors* detect pressure, friction, tension, and vibration stimuli. Then these neural signals will be transmitted through nerve fibres and processed in our spinal cord or brain. In this way, information regarding temperature, skin deformations, pain, and itching can be perceived and processed by our central nervous system [103, 90, 59].

Mechanoreceptors Specialized to Receive Tactile Information

Among these receptors, there are four major types of mechanoreceptors that are specialized to provide tactile stimuli: Meissner's corpuscles, Pacinian corpuscles, Merkel's disks, and Ruffini's corpuscles (Figure 2.1 [79]).

The Meissner's corpuscles and the Pacinian corpuscles both provide information primarily about the dynamic qualities of mechanical stimuli [79, 59, 90]. The Meissner's corpuscles are more sensitive to light touch with low-frequency vibrations (30–50 Hz). This type of stimuli often occur when textured objects are moved across the skin. Meanwhile, the Pacinian corpuscles adapt more rapidly than Meissner's corpuscles. They are more efficient in transducing information about stimuli that produce high-frequency vibrations of the skin.

Meanwhile, the Merkel's disks and Ruffini's corpuscles are considered as slowly adapting cutaneous mechanoreceptors. The Merkel's disks play a major role in the static discrimination of shapes, edges, and rough textures. They are particularly dense in the epidermis of sensitive areas like the fingertips and lips. Although the

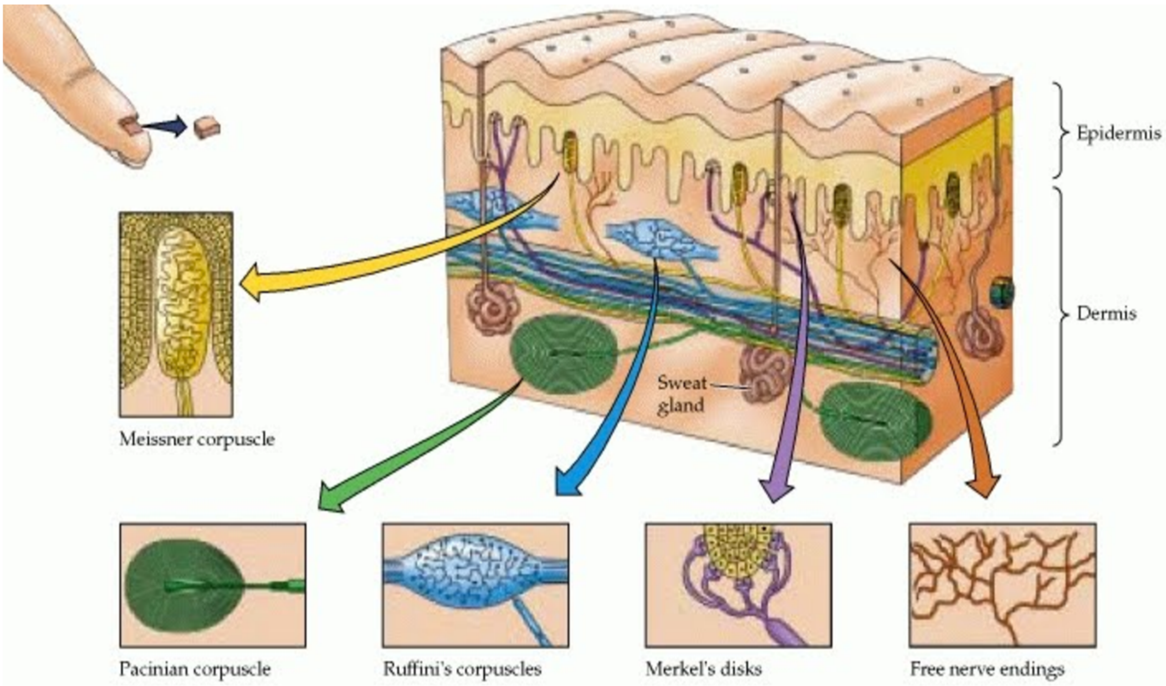

Figure 2.1: The skin harbors a variety of morphologically distinct mechanoreceptors. This diagram represents the smooth, hairless skin of the fingertip (by Purves et al. [178]).

functionality of Ruffini's corpuscles is still not well understood, it is generally accepted that they are particularly sensitive to the cutaneous stretching produced by digit or limb movements, so they probably respond primarily to internally generated stimuli [79, 59, 90].

Mechanosensory Discrimination across the Body Surface

Other than the functionality of the receptors, the distribution of the mechanoreceptors can also influence the accuracy and sensitivity of tactile sensation. Even though the mechanoreceptors can be found in every inch of our skin, they are not equally distributed over the body surface. One method to measure the tactile spatial acuity across the body surface is to measure the *2 point discrimination (2PD)* thresholds for different skin regions. This method measures the minimal interstimulus distance required to perceive two objects touching the skin as two distinct points instead of one [79, 90, 137]. The smaller the 2PD threshold is, the higher the tactile spatial acuity the skin can reach. For example, our fingertips or lips can perceive two points separated by 2mm, while on our back or calf, we may not easily recognize two point stimuli until the distance increases to around 40mm. Different 2PD discrimination thresholds of different body parts can be seen in Figure 2.2 [137].

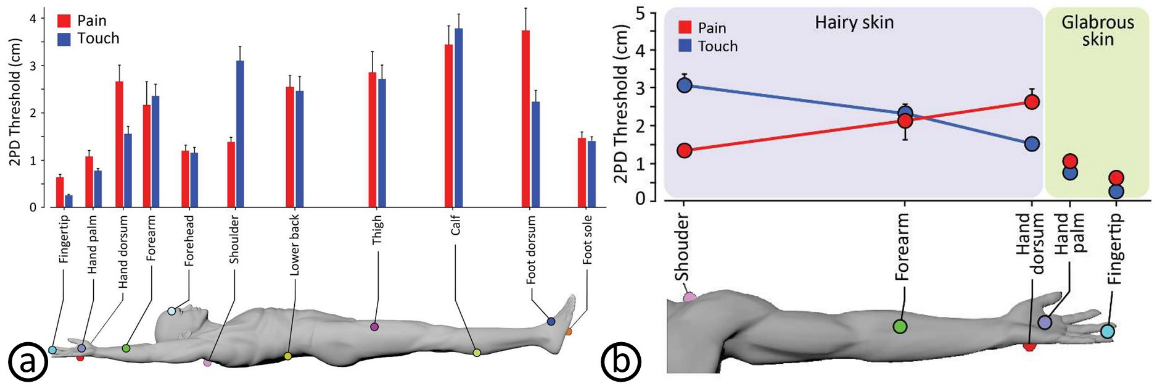

Figure 2.2: (a) Mean two-point discrimination (2PD) thresholds for pain and touch across the body surface. (b) Gradients of 2PD thresholds on the hairy and glabrous skin of the upper limbs, for pain and touch [137].

More than discriminitive touch: pathways of affective touch

After the mechanoreceptors catch the tactile stimuli, the tactile signals need to be transduced to our central nervous system through nerve fibers. There are two groups of nerve fibers involved in conducting tactile signals: myelinated group A nerve fibers and unmyelinated group C nerve fibers. The myelinated group A nerve fibers are usually thicker and faster (conduction velocity up to 120m/s), thus they usually carry urgent information such as proprioception, touch, fast or acute pain. On the contrary, the unmyelinated group C nerve fibers are thinner and slower (conduction velocity lower than 2m/s)than the group A nerve fibers, and they usually transmit innocuous tactile stimulation related to slow pain, itch, temperature, and light touch.

However, recent research has discovered some new roles some C group nerve fibers play in affective touch. This slow-conducting, unmyelinated peripheral C-tactile afferent (CT afferent) helps our nervous system code slow, gentle touch in an affective and hedonic manner rather than just discriminatively [131, 79, 139]. In a controlled study with a patient who suffered from losing myelinated nerve fibers, investigators performed the same stroke on the forearm of the patient as well as healthy participants, and let them describe the stimuli they perceived. Unlike the healthy participants, the patient could not feel vibration stimuli on the lower arm and she could not detect the direction of the stroke as healthy subjects did. However, she could clearly describe the stroking touches as pleasant [159]. Investigators analysing the functional Magnetic Resonance Imaging (fMRI) results during the experiment. They found that even though the somatosensory cortices, which were involved in the processing of sensory-discriminative stimuli, were not activated in the patient's brain during the study, the insular cortex which were involved in processing affective stimuli were still activated, just as in the other healthy participants' brains.

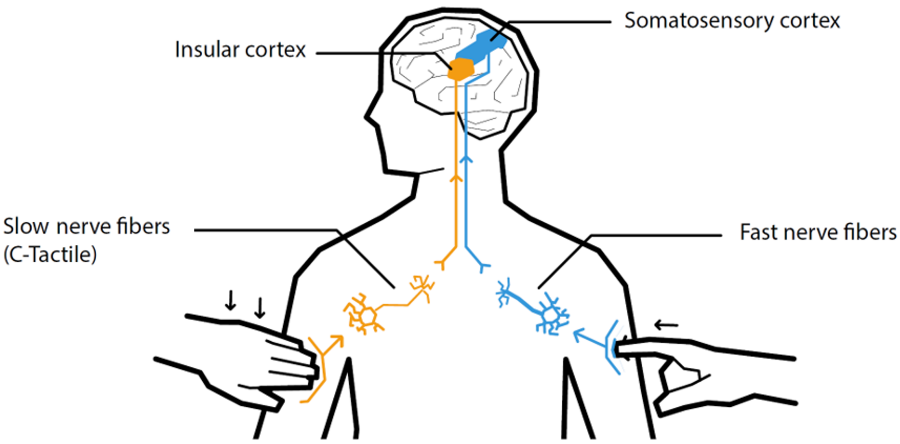

Figure 2.3: The slow-conducting, unmyelinated peripheral C-tactile afferent helps our nervous system code slow, gentle touch in an affective and hedonic manner [215].

These findings suggest that the CT afferent system is involved in processing affective touch and also generating emotional, hormonal, and behavioral responses to tactile stimuli [159]. Combined with some more recent studies [160, 140], we can see that there is a biological foundation in our body to process and react to affective touch or social touch, and we are just starting to understand the complexity of the affective-motivational aspects of touch.

2.1.2 Cross modal interaction of touch

One interesting phenomenon in touch sensation is the cross-modal interaction between touch and other sensations. We experience a mix of information from different sensation channels every day, and we build a model of the surrounding world in our mind by combining and processing information from all these channels. These modalities are not always equal: due to selective attention [1], our mind tries to focus on some attended sensory modality while ignoring the information from the unat-

[1]Selective attention refers to the processes that allow an individual to select and focus on particular input for further processing while simultaneously suppressing irrelevant or distracting information.

tended modalities [138]. However, our perception system still receives information from unattended sensory modalities even though less attention is paid to these modalities. For example, while eating a delicious meal and chatting with a friend, we may ignore the surrounding environment, such as the color, lighting, temperature, or noises. But these environmental factors can influence our perception of food as well as the eating behaviors [204]. Another example of the cross-modal interaction between modalities can be found in the experiment presented by DuBose et al., in which they found that our perception of the flavor of beverages or cakes can be significantly manipulated by applying different colors to the food [49]. This cross-modal interaction was also observed from the perspective of electrophysiological and neuroimaging data. Evidence points out that when one attention (e.g., touch) is directed to a particular spatial location or body site, it will result in a concomitant shift of attention in the other modalities, such as audition or vision to the same spatial location [190]. All of these examples indicate that our perception channels never act alone.

Similarly, as one of the main sensory modalities, touch always influences and is influenced by other modalities. Among these sense perceptions, researchers investigated the possible relationship between vision and touch and found a strong cross-model interaction [62]. In the famous "Rubber Hand Illustion" experiment, researchers found that watching a rubber hand being stroked synchronously with one's own unseen hand causes the rubber hand to be attributed to one's own body [224] (Figure 2.4). This experiment reveals the multisensory integration between vision and touch, as well as the dominant role vision plays over touch and proprioception. Other research goes one step forward on how the visual and touch modalities interact with each other. Several studies have shown that visual cues, even non-informative ones, can improve haptic spatial perception and enhance tactile acuity [154, 53]. Both the perception speed and accuracy of touch are increased by giving extra visual cues, and this effect is increased when more informative cues are given. Moreover, the competition between neural representations and the recruitment of attentional resources results in a visual dominance effect [84], so that users generally do not perceive small conflicts between visual and tactile cues [180]. Finally, researchers also found that spatially congruent visual cues can affect tactile perception [135]. They noted that visuo-tactile cross-modal links dominate the representation of near-body space, and passive viewing of the body can influence the perception of somatosensory stimuli. Taken together, these studies support the notion that there is a strong cross-modal interaction between vision and touch, and using multi-modality stimuli in touch interaction could be a potential approach to overcome the inherently ambiguity of touch [230, 237].

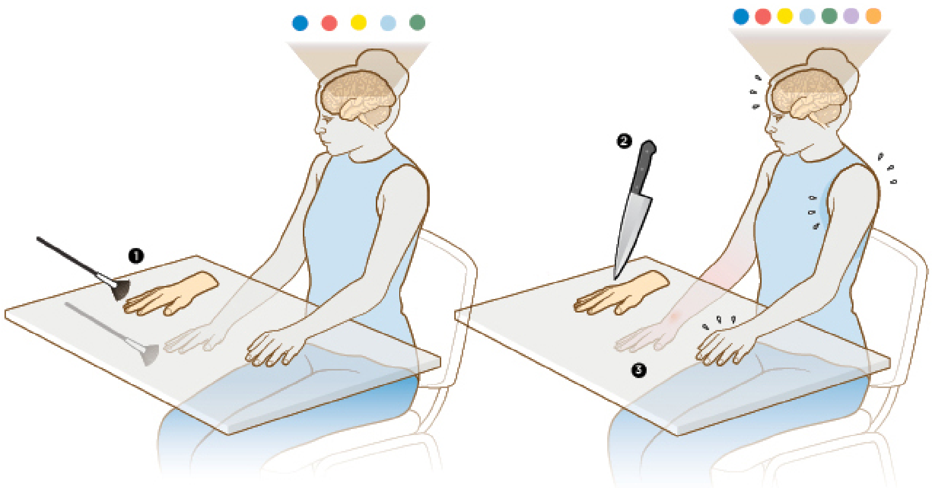

Figure 2.4: Rubber hand illusion illustrates how the tactile perception can be influenced by visual input. Participants watch a rubber hand being stroked, while their actual hand, hidden from their view, is also stroked synchronously. Most participants reported tactile feeling on the rubber hand, and pain perception was also reported when the rubber hand was simultaneously pricked with a knife [224].

2.2 Social touch

As mentioned, our neural system constitutes a physiological platform for affective touch. If the intention of the affective touch is communication, then it can also be called ”social touch”. This section introduces the concept of social touch, including the definition of social touch, why social touch is important for us, and the forms of touch that are used in affective communication.

2.2.1 Social touch in social communication

It is human nature to communicate one’s own emotional state with groups, individuals, and even animals or objects. Many different non-verbal communication channels are used to perceive and express emotional information. Visually, humans rely on facial expressions, body motion, and posture to convey emotion [43, 168]; Auditorily, the prosody (pitch, intensity, speaking rate) can also influence the emotional communication [127, 168]. Except for these, social touch - touch can effectively communicate or evoke emotion during communication [257] - has received much less attention in either psychology or in HCI field.

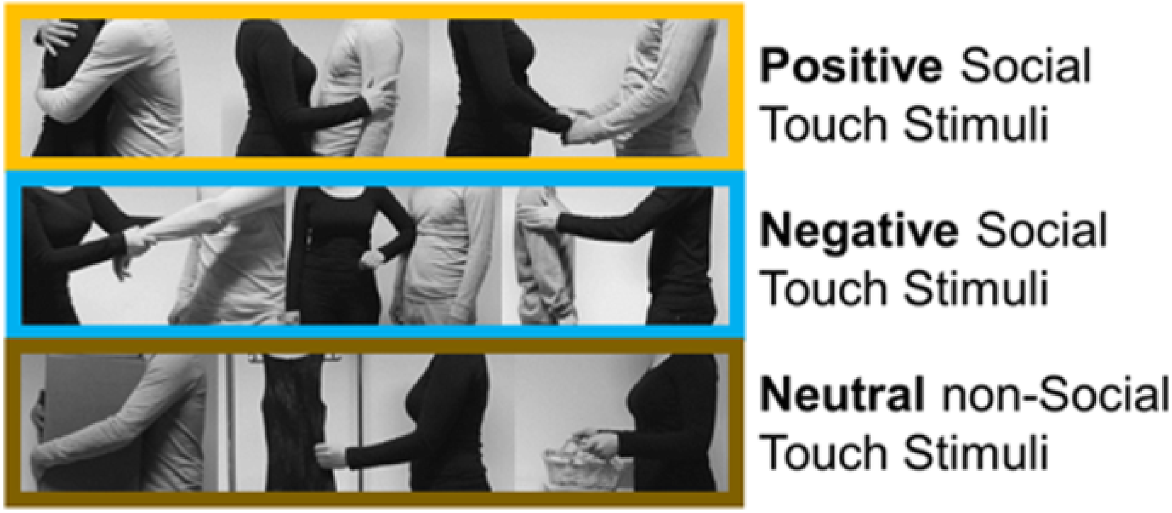

Figure 2.5: Types of stimuli. The figure shows still frames of exemplary stimuli, showing different types of touch events. Positive, negative, and neutral stimuli are in the first, the second, and the third rows respectively [126]).

To reveal the role of social touch in communication, we have to understand what social touch is. Morrison et al. define social touch as ”tactile processing with a hedonic or emotional component” [146], and Huisman defines social touch as ”touch occurring between two or more individuals in co-located space” [104]. From these definitions, we can see that 1) the social touch is always interpersonal, which means the touch is shared between the *sender* and *receiver* who have some social relations with one another; and 2) social touch is often used for hedonic or emotional purposes. Since social touch is an interpersonal behavior used for certain communication purpose, many factors such as context, relationship and social conventions can all have an impact on social touch communication [230].

A clear criteria for social touch is that it is interpersonal [25], which means there has to be a *sender* who performs the touch and a *receiver* who perceives and interprets the touch. So the relationship between the *sender* and *receiver* of social touch gestures is crucial, whether it is an intimate, long-term relationship or a more superficial, short-term one. It is not difficult to understand that the majority of social touch practices happen in close or intimate relationships [109]. In whole life span, affective touches such as hand-in-hand, a soft caress or an embrace are common and customary in the development and maintenance of intimate relationships [72, 109].

People generally dislike having strangers touch them anywhere on their bodies, yet a romantic partner will have access to most of these body areas [116, 208]. And previous research also found that people could perform and identify a wider range of emotions with touch within intimate relationships [220].

2.2.2 The function of social touch

Touch is a powerful force in human development, shaping social reward, attachment, cognitive, communication, and emotional regulation from infancy and throughout life [25]. Moreover, the effects of social touch during interpersonal communication are not only limited to the communication of emotions, but also include more diverse functions [131]. In this section, I introduce the function of social touch in the following aspects:

Impact the physical and psychological state

In the well-known baby monkey experiment conducted by Harlow et al. in 1958 [81], they created two kinds of artificial mothers for the monkey infants: a wire-frame surrogate mother that provided food, and a soft surrogate flannelette mother without food. From the wire-frame surrogate mother, the monkey infants can get sufficient food, but the touch feeling has a very low similarity with real touch. From the soft surrogate flannelette mother, they can perceive the warmth of the cloth and furry touch perception. In the experiment, the baby monkeys showed a strong preference for the soft surrogate flannelette mother (Figure 2.6(a)). They consistently ran towards the soft flannelette surrogate mother, touching her and clinging to her. They even kept the skin contact with the soft flannelette surrogate mother while drinking the milk on the wire-frame surrogate mother (Figure 2.6(b)). In their latter study, in which the monkey infants suffered from touch deprivation, they also observed "severe deficits in virtually every aspect of social behavior" [82]. Even though these experiments are ethically debatable, they reveal a fact that the need for touch is not just a social phenomenon; it belongs to the biological fundamental needs that can influence physical, emotional, and cognitive behavior.

Similarly, physical contact also has a significant impact on the early development of human. Several studies have shown that touch deprivation has a significant impact on children's cognitive, emotional, and social development, and that this impact can last for years [24, 31, 51]. On the other hand, experimental evidence supports the notion that sufficient physical contact between the mother and the in-

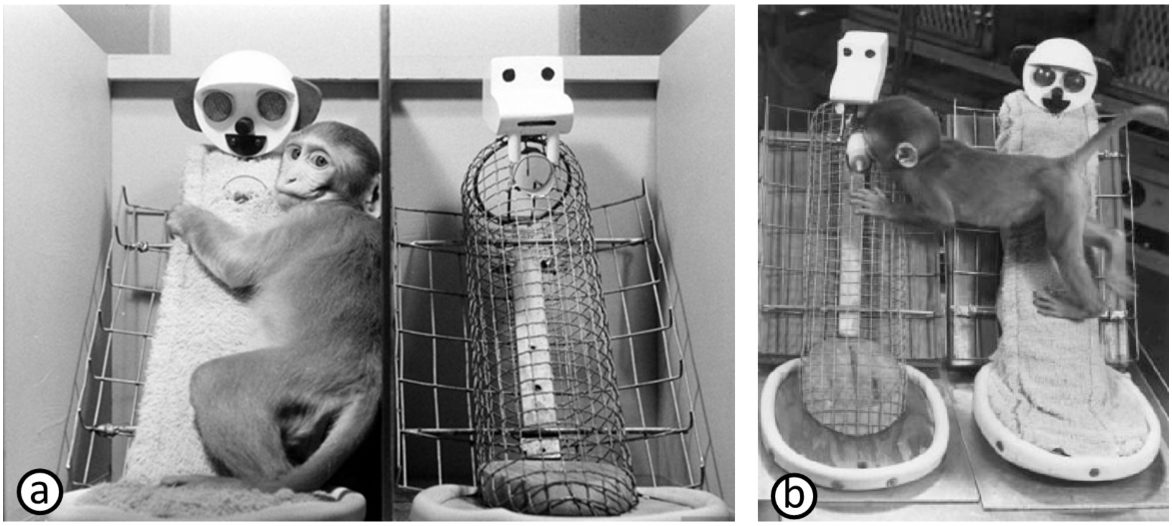

Figure 2.6: The well-known baby monkey experiment conducted by Harlow et al. in 1958 [81]). (a) Two kinds of artificial mothers were provided to the monkey infants: a wire-frame surrogate mother that provided food, and a soft surrogate flannelette mother without food. In the experiment, the baby monkeys showed a strong preference for the soft surrogate flannelette mother. (b) The baby monkeys kept the skin contact with the soft flannelette surrogate mother while drinking the milk on the wire-frame surrogate mother.

fants could positively affect the development of infants. For example, the neurological development of low birth-weight infants is relatively low, but the infants who receive more frequent maternal touch from their mother show better neurological development [203, 55]. Recent work has found evidence that touch during infancy resulted in a decrease in corticosteroids, a steroid hormone involved in stress, as well as several biochemical processes that play an important role in the development of the brain [194].

Moreover, the impact of social touch on a person's physical and psychological state is not just on infant development. Maintaining a physical contact with others is a important part of well-being during the whole life. In the baby monkey example above, the maternal touch between the mother and child not only improved the neurological development of the baby, but also the mental state of the mother [55]. Evidence proves that proper interpersonal physical contact decreases blood pressure, heart rate, and pressure level [47], and this effect of touch on stress is more significant when the touch is applied within an intimate relationship rather than to a stranger [35]. But no matter what relationship it is, appropriate interpersonal physical contact can positively impact our physical and psychological state, and these "healing touches" can potentially be used in therapies [125] or psychological health care [101].

Improve attachment and reduce social exclusion

One of the most important function of interpersonal touch is that physical contact can improve interpersonal attachment and reduce the feeling of social exclusion. Back to the baby monkey experiment, even though the soft flannelette surrogate mother could not provide the baby monkey with a sufficient food supply as the wire-frame surrogate mother did, the baby monkey still spent most of the time attaching to the soft surrogate mother [81]. Similar behaviors are also observed in human beings, such that young children often become attached to certain objects such as blankets or dolls, especially when the physical contact between the mother and child is not sufficient [144]. When a child experiences distress or is afraid, the physical contact from the mother could provide a feeling of safety and security to the child, and thus decrease the anxiety level and increase the ability to deal with social situations [18]. Thus, physical contact plays a very important role in developing a secure attachment between the mother and the child.

The impact of social touch on social attachment is not just limited to the parent-child relationship, but also in other intimate relationships. When we feel alone or anxious, a warm hug or hand held in a warm hand by the partner can positively impact our mental state, and create an affective connection between couples [75]. Recent research has shown that the social touch performed between couples could lead to the release of oxytocin in our brains, which helps lower stress levels and blood pressure, provide trust and security, and further help form a lasting social relationship [76].

Furthermore, social touch can reduce the feeling of social exclusion in a group. We may see from the documentary that in the animal world, grooming[2] is a widespread activity throughout the animal kingdom. Monkeys spend a lot of time sitting together grooming each other, even if the frequency is already much larger than their hygienic need [14]. Thus, social touch has been proven to reinforce social structure and build relationships within the group, and leads to a specific decrease in feelings of social exclusion [234].

[2]Social grooming, or allogrooming, is a behavior in which social animals, including humans, clean or maintain one another's body or appearance within a social group. Social grooming involves gentle touches as well as stroking, scratching, and massaging.

Midas Touch effect

A very famous term related to social touch is *Midas Touch*. In Greek myth, King Midas owes the power of turning everything he touched to gold, which later turned his daughter into a golden statue. Nowadays, studies have shown that certain types of social touch really have the ability to turn this social behavior into ”gold”. In the famous restaurant study performed by Crusco et al., the brief touch that waitresses performed on customers, such as a touch on the hand or shoulder, significantly increased customer’s willing of paying tips. The effect of touch only impact the attitude of paying the tips to the waitresses, and has no impact on the attitude towards the restaurant [38]. They conclude that social touch effects can occur without awareness. More recent studies with similar settings on *Midas Touch* effect have shown that the interpersonal physical contacts positively influence their attitude towards the touch sender, and that their behavior can also be influenced [38, 100].

Many possible explanations for the *Midas Touch* effect have been proposed. One explanation is that interpersonal physical contact is interpreted as a friendly or trust signal, which then turns into pro-social behavior [185]. But it does not explain why unconscious touch can also have positive effects on social behavior. More recent research relates the *Midas Touch* effect to the bonding theory I discussed above. Similar to parent-child touch or touch between partners, these casual interpersonal touches can also result in the release of oxytocin in our brains. It then triggers the link between the touch and the positive feelings that we develop in our infancy, resulting in a positive social response to the touch [62, 48]. No matter which explanation, proper touch can have a positive effect on a person’s attitude or behavior and thus reinforce interpersonal communication.

Communicate affection

One of the most important functions of touch that I want to address in this thesis is supporting affective communication. As social animals, it is human nature to decode feelings of others and also express our own feelings. This ability is crucial for our ancestors to avoid risk, solve conflicts, and support each other [8]. A large portion of this emotional communication happens through non-verbal communication, as the development of this ability is even earlier than the evolution of verbal abilities [165, 8]. Even though we don’t need to decode the potential danger of predators from other’s emotions now, conveying emotion with non-verbal communication still works as a crucial part in building interpersonal relationships.

The commonly used non-verbal languages to express emotion include the facial expression (e.g., smile, tears etc.), vocal expression (e.g., tone and speed of the speech, laughing etc.), body language (e.g., postures, gestures etc.), and social touch.

Working together with other non-verbal languages, touch plays an essential role in affective communication and can be used to express various detailed emotions. As Field describes, ″touch is ten times stronger than verbal or emotional contact, and it affects damned near everything we do. No other sense can arouse you like touch...We forget that touch is not only basic to our species, but the key to it.″ A strong handshake, a firm hug, an encouraging pat on the back, or a tender kiss, these physical contact can immediately and effectively convey strong emotion at times more powerful than other language [115]. Previous research shows that various emotions such as love, anger, fear etc. can be effectively expressed just by touching the forearm alone [94], and the recognition accuracy of the expressed emotion through touch is similar to the recognition accuracy of emotional facial expressions [54]. Furthermore, touch might be preferred over other non-verbal languages when conveying emotions for intimate purposes, such as showing love and sympathy [8]. In the meantime, compared to other non-verbal languages, touch is also more effective and accurate for conveying intimate emotions [8].

2.3 Mediated touch interaction

In the previous chapter, I introduce how our communication approach has revolted in past centuries. Nowadays, a large proportion of our social communication happens through mediated channels. We can communicate information, convey emotions, and influence each other's behavior even when we are physically and temporally separated. With the development of mediated communication technology, the form of communication is gradually shifting from verbal communication, such as phone calls or emails, towards a mix of verbal and a variety of non-verbal communication. However, even though increasing evidence indicates the importance of touch in affective communication, communicating through the sense of touch, as in co-located communication, still remains challenging in today's mediated communication systems.

In this section, I review previous works on supporting mediated touch communication from the standpoint of HCI. The goal of this section is to present the existing evidence about whether mediated touch can reliably support affective communication, along with the technology and approach current research takes to achieve this goal. Furthermore, as my approach is to enhance mediated touch stimulation with multi-modality stimulation, I will introduce cross-modal interaction in touch and how to use multi-modality stimuli in mediated touch interaction.

2.3.1 Mediated touch generation

It has been decades since researchers started the exploration of technologies that can create an experience of touch by applying forces, vibrations, or motions to the user. In this part, I review a few frequently used technologies that have been used into these touch generation systems.

Vibrotactile actuators

Vibrotactile actuators, also known as vibration motors, have been widely used in touch generation devices due to their small size and low energy consumption [176]. Two types of vibration motors are mostly used: eccentric rotating mass (ERM) vibration motors (Figure 2.7(a)) and solenoid vibration motors (Figure 2.7(b)). The ERM vibration motor is a DC motor with an offset (i.e. non-symmetric) mass attached to the shaft. As the ERM rotates, the centripetal force of the offset mass is asymmetric, resulting in a displacement of the motor. With a high number of revolutions per minute, the motor is constantly being displaced and moved by these asymmetric forces. It is this repeated displacement that is perceived as a vibration [175]. On the other hand, solenoid vibration motors are driven by magnetic fields. Switching currency stimulates the coils, and generates a magnetic field to cooperate with the ring magnet incorporated into the stator to switch the pairs of polarity. The fast-switching magnetic field generates a force that causes the weight to move repeatedly, thus generating vibration [175]. Besides, linear resonant actuators (LRAs) that have been used in recent smartphones also belong to the category of solenoid vibration motors.

Typical vibration motors that are used in touch generation systems usually have a very compact size and light weight. For example, the ERM vibration motor used in TaSSt (Figure 2.8(a)) [105] is only 2.7mm in height and 12mm in diameter, with only a few grams of weight and quite a low cost [105]. These properties ensure high mobility and make it possible to use the vibration motors in wearable devices [128, 29, 231] or mobile devices (Figure 2.8(b)) [251, 19, 191] without bringing too much burden, and also open up the possibility of using multiple motors [128, 231] or

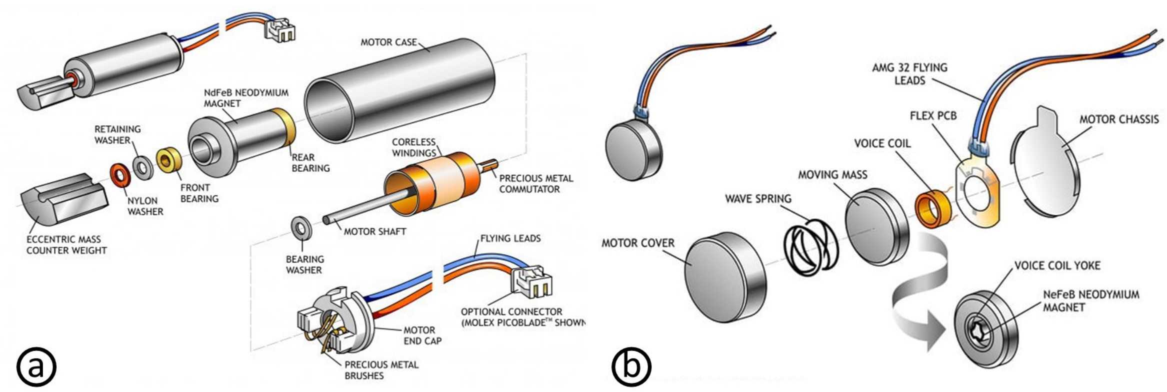

Figure 2.7: (a) Eccentric rotating mass (ERM) vibration motors. (b) Solenoid vibration motors

even an array [105, 157] to increase the expressiveness of the device. Furthermore, when maintaining firm contact with the skin, the vibrotactile stimuli generated by the motors can be clearly and accurately perceived [108, 222, 105]. Thus, different touch patterns can be simulated and we can even create different types of haptic illusions [184, 206]. However, despite these advantages in mobility and availability, vibration motors can hardly generate human-like touch for affective communication. As we discussed in the previous section, there are four major types of mechanoreceptors that are specialized to provide tactile stimuli (Figure 2.1). Our daily touch interaction involves the activation of these different receptors. Using a vibration motor which mainly triggers the Pacinian corpuscles in our skin, cannot effectively simulate complex human-like touch [124].

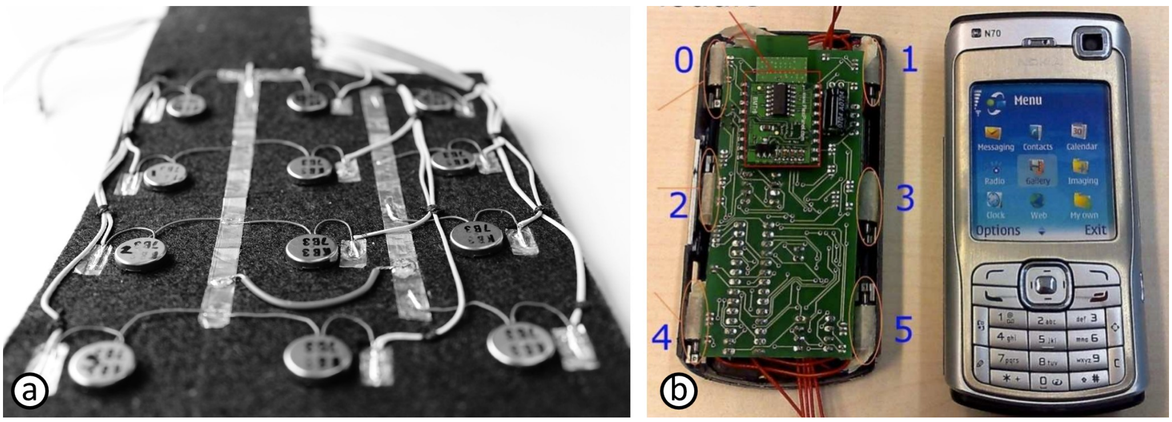

Figure 2.8: Touch generation systems that used vibration motors. (a) Solenoid vibration motors in TaSSt device [105]. (b) ERM vibration motors in a mobile-based tactile device [191].

Pneumatic actuation

Pneumatic actuators are components that convert the energy of compressed air or gas into mechanical motion. Due to its powerful mechanism, it has been widely used in many different industrial applications, including automatic control, vehicles, and manufacturing. More recent research has started to investigate pneumatic actuation in soft robotics as well as in the HCI field. When combined with soft and stretchable material, the pneumatic actuators can provide high-strength yet stable actuation with any shape needed [179].

Several features make the pneumatic actuator a promising approach to soft actuation. First is the high flexibility of the pneumatic actuator. Typical fabrication approaches of the pneumatic actuator, such as heat-sealing or mold casting, make it easy to implement a complex and personalized design for the actuator [162]. And the stiffness or the strength of the inflatable part can also be controlled by choosing different materials (e.g.,silicon [254], latex [83], fabrics [162]), using different inflation medium (e.g., air [162], gas-liquid fluid [2], liquid [129]), or changing the parameters of the actuator (Figure 2.9). Furthermore, the cost of producing pneumatic actuators is relatively low, while the reliability of deployment is still sufficient for soft actuation [26].

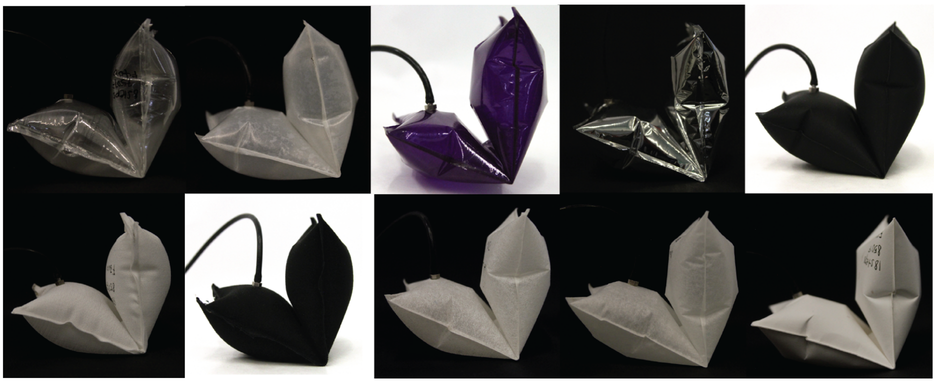

Figure 2.9: A wide variety of materials can be used for pneumatic actuators [162].

In HCI research, the soft actuation approach enables a wide range of applications in supporting tactile experience [44, 263, 258], enabling tangible interaction [83, 68], and generating a sense of touch [164, 148]. For supporting tactile experience, Delazio et al. created a pneumatically-actuated jacket (Figure 2.10(a)) to generate an embodied haptic experience on upper body [44]. They produced multiple haptic illusions on the upper body by inflating the different airbags with variable strengths, frequencies, and speeds, which provide immersive experiences by engaging the entire body. It's worth noting that the researchers addressed the pneumatic actuator's ability to generate static pressure stimuli, which the other techniques can hardly reproduce [44]. They also proposed and tested the application of creating interpersonal touch, such as a hug, a punch, or a hand tap with the jacket [44]. Similarly, Park et al. also used pneumatic actuator to generate interpersonal touch while calling (Figure 2.14). They attached an inflatable surface named POKE to the back of a smartphone, which enables multiple cheek-touch gestures during a phone call [164]. They showed that pneumatic tactile stimuli could enhance interpersonal phone communication by support various forms of non-verbal communication and facilitate the understanding and expression of emotion. Moreover, pneumatic actuation also opens up the possibility of integrating in-place touch input and output, and thus enables various forms of tangible I/O interaction. This feature will be further discussed in Chapter 5.

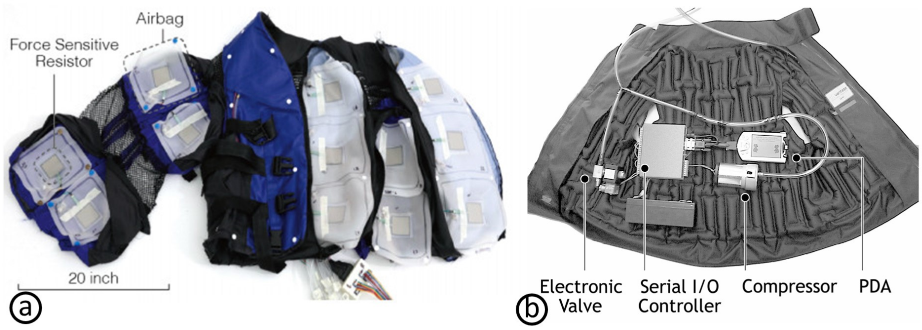

Figure 2.10: Two pneumatically-actuated jacket designs. (a) Delazio et al. created a pneumatically-actuated jacket to generate an embodied haptic experience on upper body [44]. (b) Mueller et al. created Hug Over a Distance vest to simulate touch sensation [148].

Shape-memory alloy (SMA)

Shape-memory alloys (SMA) are a unique class of alloys that can be deformed when cold but return to their pre-deformed shape when heated. Typical commercially available SMAs transform between 40°C and 150°C and cycle on the order of 30-60 seconds. The transform temperature and speed are settled during the fabrication depending on the specific alloy chosen, the post-processing steps implemented, the magnitude of power applied, and the specific system architecture [255, 99]. This ability has contributed to the extensive popularity of this material for a wide range of applications, including automotive, mini actuators and micro-electromechanical systems, robotics, and HCI [111].

SMA actuators are actuated by the change of temperature. Without mechanical actuation, the size of the actuator can be quite compact, lightweight, and silent, which fits well in on-body applications [111, 255]. For instance, Duvall et al. used SMA wires in a jacket (Figure 2.11(a)), which can let parents and therapists give a comforting ”hug” to a child who suffers from Autism Spectrum Disorder (ASD) anywhere anytime [52]. Yarosh et al. also used the similar on-body compression approach and created an armband with SMA actuators (Figure 2.11(b)). They showed that the compression stimuli generated by SMA actuators could be used in interpersonal communication and remote collaboration, and they found that they were particularly appropriate for easing mental and physical demand in high-emotion tasks [255]. In more recent works, Simons et al. took a similar approach and created pinching, squeezing, and twisting gesture for social touch purposes using different SMA layouts [198]. They found the SMA actuation approach performed well in simulating positive affective touch sensations, particularly in comparison to vibrotactile stimuli [198] .

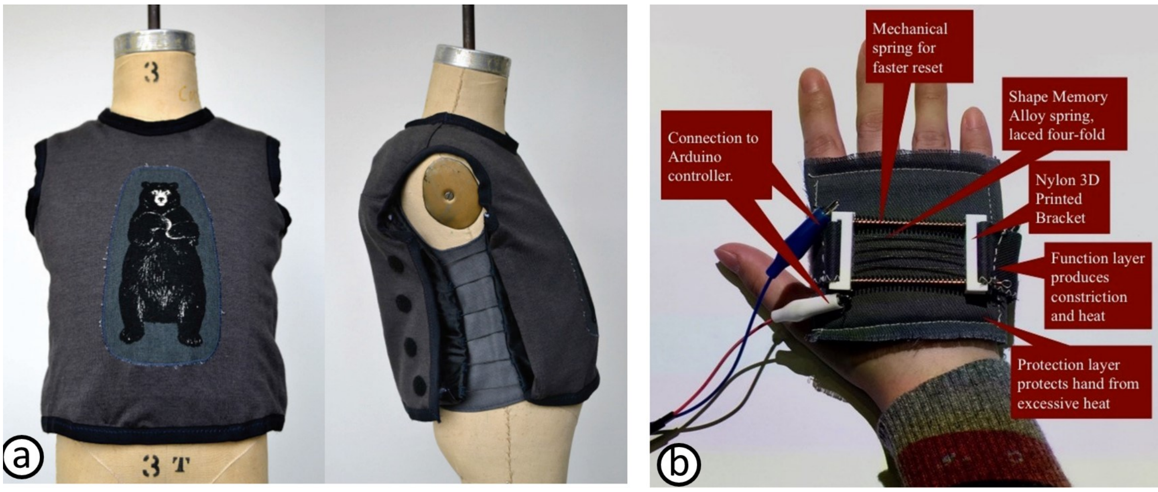

Figure 2.11: Two mediated touch devices using SMA actuators. (a) Duvall et al. used the SMA wires into a jacket, which could let parents and therapists give a comforting ”hug” to a child who suffered from Autism Spectrum Disorder (ASD) [52]. (b) Yarosh et al. created Squeezeband to generate squeeze gesture in interpersonal communication and remote collaboration [255]

.

Despite the high expressivity and mobility of SMA actuators, there are some clear flaws in using the SMA actuation method in mediated social touch. First, the reaction time of SMA actuators (usually around 30-60 seconds [111, 255]) remains long compare to other types of actuators. Even though efforts such as adding an extra mechanical tension coil spring to speed up the reset speed [255] are made to reduce the reaction time, it is still not sufficient for real-time touch communication. Second, the typical transform temperature of SMA can reach hundreds of degrees [111]. Thus, an additional protective heat-resistance layer is needed to protect the users, which however diminishes the tactile perception and introduces the potential risk of overheating [111, 255].

Electrical muscle stimulation (EMS)

Electrical muscle stimulation (EMS) is a technique that applies electrical impulses to the user's muscles, which causes an involuntarily contract of the muscle. It delivers impulses through electrode pairs formed by an anode and a cathode. When the EMS device is activated, the electric current travels between the electrode pairs and passes through nerves and motor neurons. When the internal voltage of the neuron reaches a certain threshold, the motor neurons activate and pass the signal to the muscle, causing it to involuntarily contract [130, 4, 132]. The typical electric currents required for EMS stimulation are below the safety level of human (less than 100mA), and the muscle can react rapidly (less than 100ms interval) after the stimuli are delivered [130, 4, 132]. EMS stimulation has already been widely used in the medical field, on replacing/supporting human motor functions in the field of rehabilitation medicine and in sports recovery [130].

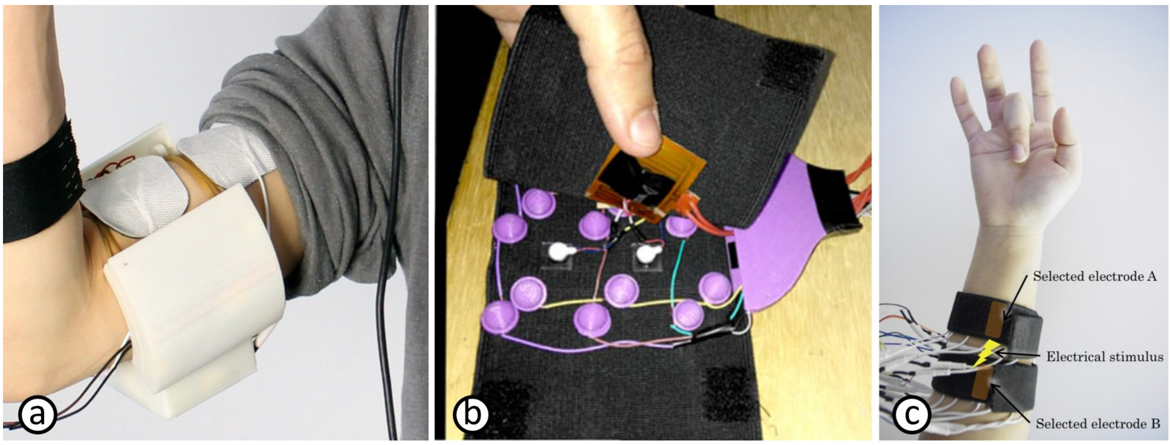

Figure 2.12: Three examples using EMS actuators. (a) Lopes et al. used the EMS force feedback into the VR game and simulate the sensation of being punched [133]. (b) Gomes et al. used a combination of electrical muscle stimulation, thermal, and mechanical stimulation to simulate interpersonal touch between couples [69]. (c) Tamaki et al. created a forearm belt to control and guide the user's finger movement for learning a new instrument [210].

Benefiting from its compact size and unique ability to trigger muscle movement, EMS stimulation has also been explored in HCI research. For example, Tamaki et al. presented PossessedHand (Figure 2.12(c)), a forearm belt to control and guide the user's finger movement for learning a new instrument [210]. They showed how precise and powerful EMS stimulation can be in controlling muscles. Except for controlling the muscles, EMS devices were also used to generate sensations and enhance the immersion experience. For instance, Lopes et al. used EMS force feedback into VR games and simulated the sensation of being punched or hitting a ball with the foot [133] (Figure 2.12(a)). Furthermore, these EMS-driven physical sensations have also been used to simulate interpersonal touch. In the design of the TouchYou device, Gomes et al. used a combination of electrical muscle stimulation, thermal, and mechanical stimulation to simulate interpersonal touch between couples [69] (Figure 2.12(b)). However, there are still some limitations to the use of EMS actuation in social touch. First, while EMS can be effective at controlling muscle movement and triggering proprioception sensations, it is less effective at creating a sensation of being touched, such as a caress or being held. Second, it can cause muscle fatigue as the muscle is involved in the interaction [132]. Third, in some cases, the feeling that the muscle is being controlled is reported as unpleasant or scary by some users [210].

2.3.2 Mediated touch devices

As discussed, supporting affective touch communication is an important yet underexplored topic in current HCI research. Due to the complexity of human perception system and the diversified communication approach, it is difficult to create a universal device that supports vivid touch communication in all kinds of contexts. Thus, facing different types of communication and interpersonal touch interaction, different approaches have been purposed to improve mediated touch interaction experience in communication. In previous works, Wanger et al. classified the body-centric interfaces according to the body restriction in the environment [235]. Similarly, Pedersen et al. classified the body-centric devices according to the relationship between human body and the interaction interface [166]. Following the similar classification approach, I summarize previous works on generating mediated affective touch in three categories: fixed devices, handheld devices, and wearable devices.

Fixed social touch devices

Previous research has explored using fixed devices to create touch stimulation for communication. As the devices are fixed, the mobility and power-consumption of the actuation can be ignored, which leads to more powerful and more flexible actuation to generate touch. For example, Chen et al. explored the use of a robot nurse (Figure 2.13(b)) to generate a comforting touch on a patient's arm in a healthcare situation. They discussed the role of social factors in this human-machine touch interaction and proposed applications for robot-initiated touch in healthcare [30]. Similarly, Teyssier et al. explored the design space of device-initiated touch for conveying emotions with a robotic arm (Figure 2.13(a)). By performing the touch to the forearm of participants with different force, velocity and amplitude characteristics, they discussed how these characteristics are associated with the emotion perception of touch stimuli [219].

Furthermore, the robotic arm is also used in interpersonal touch interaction. Nakanishi et al. used a human-like robot arm (Figure 2.13(d)) to analyze the handshaking interaction during a video-conference [152]. They found that the mutual touch mediated by the robotic hand could enhance the feeling of being close to the partner, even though a few unpleasant experiences were reported due to the uncanny valley issue [3].

In addition to robots, other types of fixed devices have also been designed and evaluated. Hauser et al. created an interactive bed (Figure 2.13(c)) named Calmer that can simulate maternal skin-to-skin holding for premature infants. Calmer is an actuated platform placed in an infant incubator, administering breathing motion, heartbeat sounds, and skin-like tactility to an infant lying on it. By iteratively designing and testing the device in the long term, they showed how infant health development benefits from such touch interaction [87].

Handheld social touch devices

Even though fixed social touch devices could generate powerful and flexible stimuli without the limitation of mobility, their range of application remains limited for the same reason. Considering that a large portion of mediated communication happens in a mobile context, the mobility of the touch device plays a crucial part in supporting affective touch communication. Thus, researchers explored the design

[3] Uncanny valley is when the emotional response to a device abruptly shifts from empathy to revulsion as it approaches, but fails to attain, a lifelike appearance [145].

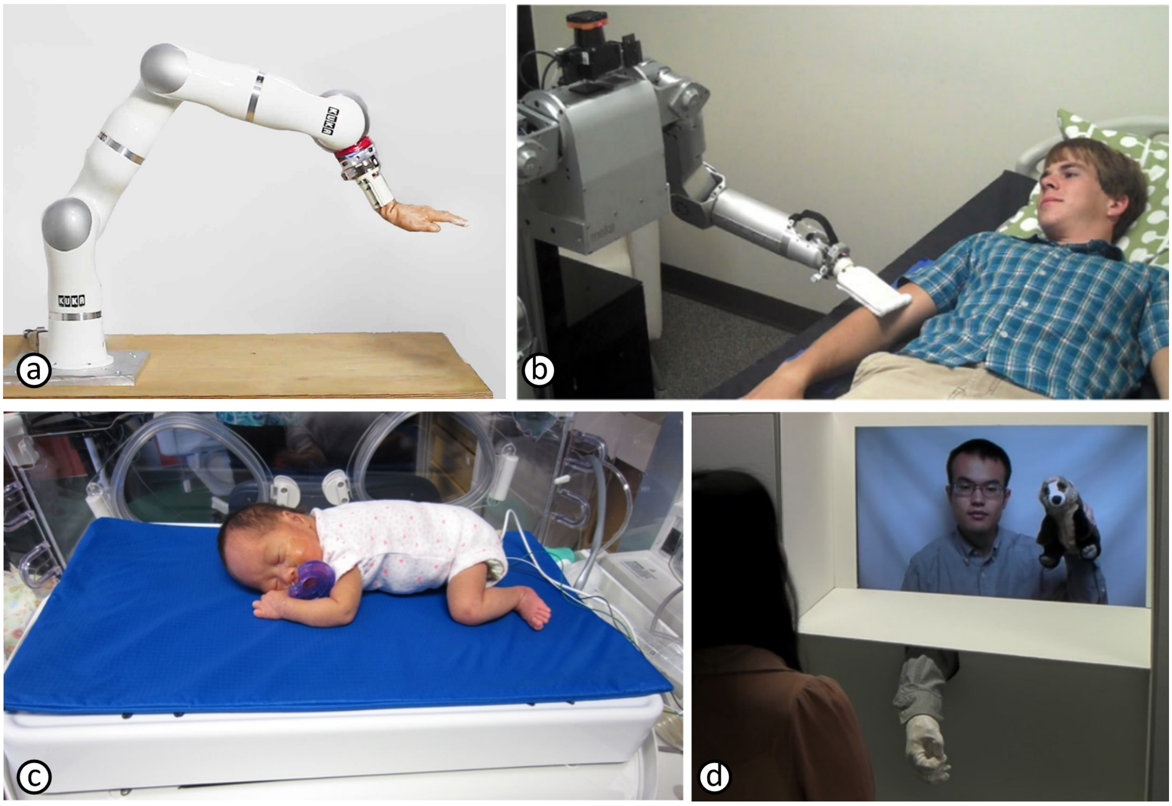

Figure 2.13: The fixed devices can have powerful and flexible actuation to generate touch. (a) Teyssier et al. explored the design space of device-initiated touch for conveying emotions with a robotic arm [219]. (b) Chen et al. explored the use of a robot nurse to generate a comforting touch on a patient's arm in a healthcare situation [30]. (c) Hauser et al. created an interactive bed named Calmer that can simulate maternal skin-to-skin holding for premature infants [87]. (d) Nakanishi et al. used a human-like robot arm to analyze the handshaking interaction during a videoconference [152].

space of generating affective touch with mobilized touch devices, such as handheld devices.

One of the most researched directions is to integrate mediated touch actuation into smartphones. As the main device used for mediated communication, smartphones are also naturally becoming a promising medium for mediated touch communication. The built-in sensors, batteries, actuators, and various applications of smartphones open up a lot of possibilities either for tactile interaction or for social touch. For instance, Rehman et al. created a mobile-based tactile device called iFeeling to evaluate how personalized vibration patterns can be used to convey emotional information to visually impaired users [227]. Similarly, more research on emotional perception of vibrotactile stimuli on smartphones have been conducted, such as SemFeel [256] or Multi-Moji [251] (Figure 2.20).

Except for vibration motors, other types of actuators are also used in smartphone-based touch interaction. Park et al. explored the use of POKE (Figure 2.14), a pneumatic actuator on the phone, to enable cheek-touching interaction during the phone call [164, 163]. POKE delivers these touches through an inflatable surface on the front of the device that receives index finger pressure inputs on the back of another device, while allowing the callers to maintain a conventional phone-calling posture. They indicated that mediated social touch in distant communication could support the roles that touch plays in face-to-face communication [164].

Figure 2.14: Park et al. used POKE device to enable cheek-touching interaction during the phone call [164]. During a phone call, one user (left) touch the silicon button as input, while another user (right) perceives the touch output on his/her cheek.

Other types of handheld devices have also been used to simulate interpersonal touch. DiSalvo et al. proposed a hug design sketch that facilitates intimate communication across distances. They discussed the main design factors involved in the design of robotic touch devices with this concept [46]. Furthermore, O'Brien et al. [158] compared several doll-like handheld touch devices to represent the other person's hand in remote touch communications. However, their participants showed unwillingness to use doll-like touch devices while they were in public, sometimes even hiding them in their bags or leaving them at home. This result suggests the importance of social acceptance level when using mediated touch devices in daily communication.

Wearable social touch devices

The most commonly chosen form of mediated touch device is wearable devices. First of all, to maximize the tactile perception of mediated touch devices, it is important to keep good contact between the skin and the actuator. By attaching to our bodies directly, wearable social touch devices could enable stable and clear tactile stimulation under different conditions. Second, like handheld devices, the mobility of wearable social touch devices is relatively high, which supports communication in a mobile setting, and thus enables a large range of applications in different contexts. Third, by combining with the clothes or wearable accessories, wearable touch device can have higher social acceptability and comfortableness [67]. According to different types of touch interaction on different body parts, various wearable social touch devices were purposed, and they were mainly focused on the upper part of the body considering social acceptance (see Figure 2.15 [208]). Typical devices include gloves or rings for hands, bracelets or sleeves for arms, and clothes or belts for the upper body.

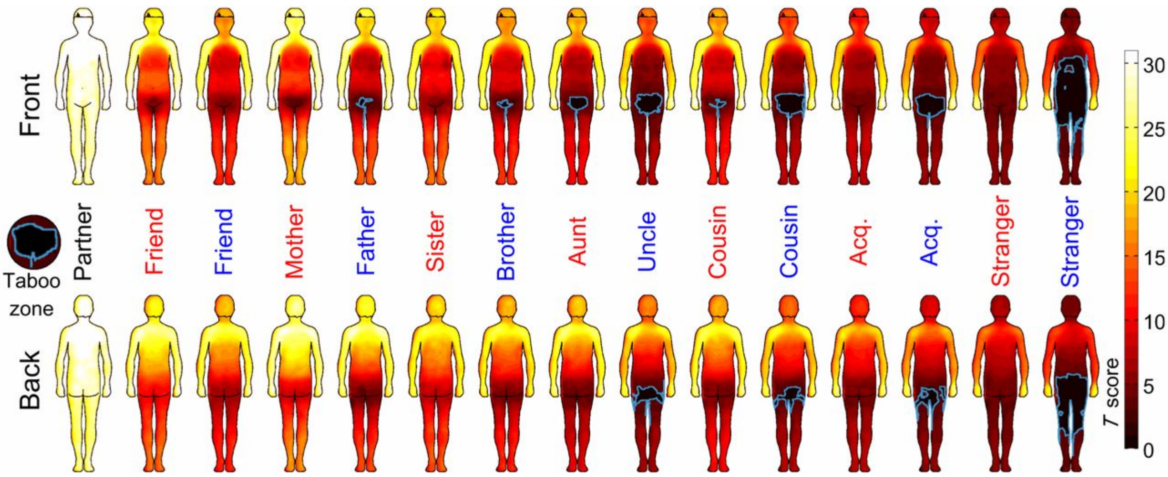

Figure 2.15: Relationship-specific touch-area maps. The blue-outlined black areas highlight taboo zones, where a person with that relationship is not allowed to touch. Blue and red labels signify male and female subjects, respectively [208]).

Touch interaction on hands. Creating touch on the hand received the most attention in HCI research because it is the most frequently used body part in interpersonal interaction [103]. The most typical design for hand-based mediated touch interaction is tactile gloves. For instance, Singhal et al. created a pair of gloves (Figure 2.16(a)) that allow distance-separated couples to feel the flexing of their remote partners' fingers through vibrotactile sensations on their skin [200]. Similarly, vibrotactile glove design was also used in the VibroGlove design. The VibroGlove generates vibrotactile stimuli on the back of the hand, and it can convey haptic emoticons that represent the six basic human emotions as well as a neutral expression [123].

Other types of actuators are also used in tactile gloves. For instance, Ahmed et al.

proposed using pneumatic actuators in tactile gloves to generate affective touch in virtual reality applications (Figure 2.16(b)), and they used this design to investigate how mediated touch device improves multimodal affective communication and increases the sense of social connectedness between users [1]. And as mentioned, Yarosh et al. used the SMA actuator in the SqueezeBands design and showed its effectiveness in emotional communication during collaboration tasks [255].

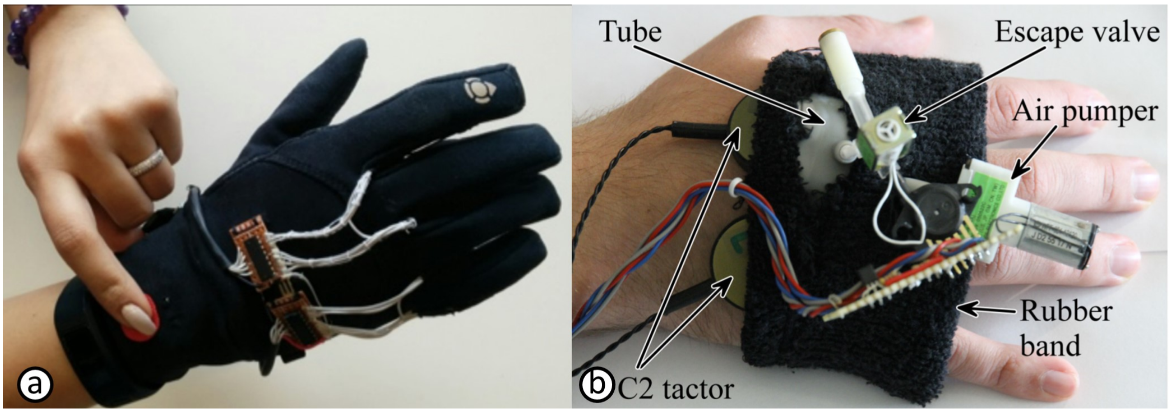

Figure 2.16: Two examples of tactile glove in interpersonal interaction. (a) Singhal et al. created Flex-N-Feel glove that allow distance-separated couples to feel the flexing of their remote partners' fingers. (b) Ahmed et al. used pneumatic actuators in tactile gloves to generate affective touch in virtual reality applications [1].

Touch interaction on arm. Arm is also a popular location for having both skin-to-skin touch interaction and mediated touch interaction. It has a large surface, sufficient sensitivity to interact with (Figure 2.2(b)), and relatively high social acceptance (Figure 2.15) for having interpersonal touch interaction [235, 208].

Typical devices for generating mediated touch stimuli on the arm include sleeves and bracelets. Huisman et al. developed a tactile device named TaSSt [105] (Figure 2.17(b)), a forearm sleeve that can generate vibrotactile stimuli and sense touch input at the same time. By activating different parts of the vibration motor array with different intensities and durations, the TaSSt device could simulate the touch gestures that we use in daily life to convey different emotions, such as stroke, poke, or hit. Similarly, Tang et al. also designed and developed a tactile sleeve with a vibration motor array. But instead of targeting supporting touch communication, this device was designed to simulate different types of social touch to treat ASD [211] (Figure 2.17(a)). Other types of actuation are also used in the tactile sleeve designs, such as pneumatic actuation [263] or motors [12].

Except for sleeves, a large portion of the research focuses on generating mediated

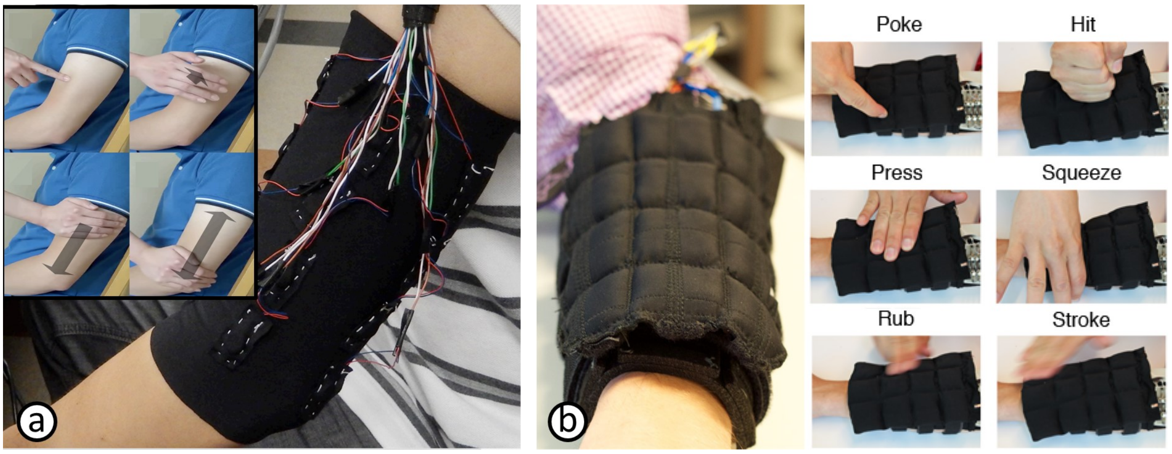

Figure 2.17: Two examples of tactile sleeves in interpersonal interaction. (a) Tang et al. developed and tested a tactile sleeve for the treatment of ASD. (b) Huisman et al. developed TaSSt that can generate vibrotactile stimuli and sense touch input at the same time. they also created and tested a set of touch gestures for the TaSSt device [1].

touch with bracelets or watch-like devices. For example, Pezent et al. designed and fabricated a wristband named Tasbi (Tactile And Squeeze Bracelet Interface) [169] (Figure 2.18(a)). By combining vibrotactile stimuli and squeeze force generated by a tensioning cord, the Tasbi could simulate squeeze gesture as well as various of tactile hand interactions. Similarly, the Bellowband design by Young et al. also focuses on generating touch stimulation with vibrotactile and the squeeze mechanism. Eight independent airbags are distributed around the wrist and deliver various haptic cues to the wrist [258]. In addition to these devices, the bracelet design can also be seen in the Squeezeback design by Pohl et al. [173] (Figure 2.18(b)) or ThermalBracelet by Peiris et al. [167].

Touch interaction on body. Previous research also explored generating touch stimuli on a larger area of the user's body, which led to the design of touch jackets. By placing actuators on different parts of the jacket, touch gestures such as a pat, a hug, or a hit can be simulated on the upper body. For instance, in the HugMe design, Cha et al. used a vibration motor array in a jacket to enable hug interaction during video chatting [29]. Similar attempts at hug jackets can also be seen in works such as [226] (Figure 2.19(a)) or [102] (Figure 2.19(b)). Furthermore, the touch jacket could potentially be used in a wider range of applications than just hugging. In the design of the Force Jacket, Delazio et al. used 26 airbags on the upper-body that cover the arms as well as the front, back, and sides of the body. By precisely controlling the movement of these airbags, they could simulate not only touch gestures

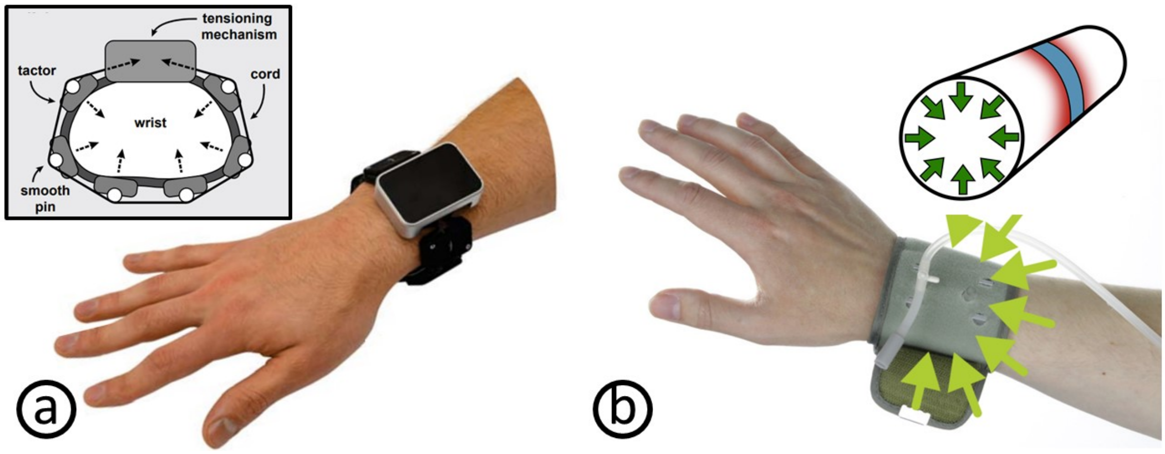

Figure 2.18: Two examples of tactile bracelets. (a) Pezent et al. designed Tasbi that supported tactile hand interactions with vibrotactile stimuli and squeeze force [169]. (b) Pohl et al. used pneumatic actuators in the Squeezeback design to generate a uniform squeeze pressure on the wrist [173].

such as punch, hug and pat, but also haptic illusions such as snakes moving across the body, snowball hits, or even motorcycle vibration [44].

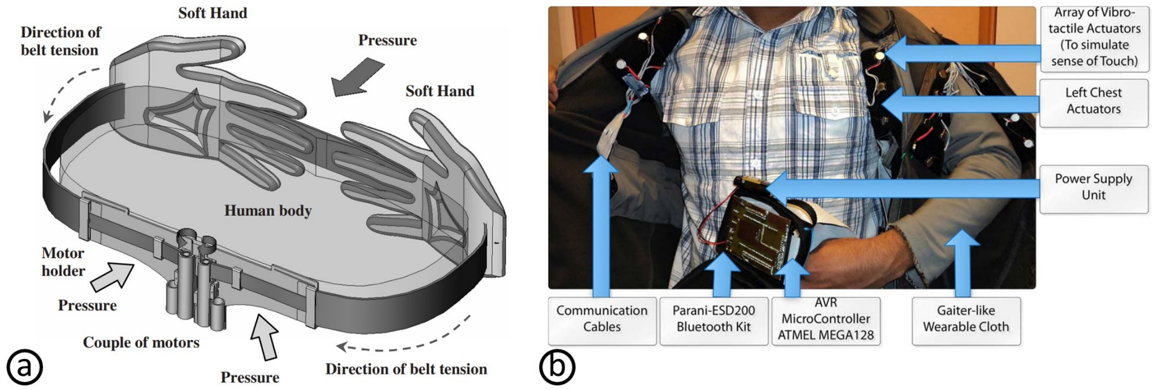

Figure 2.19: Two examples of hug devices. (a) Tsetserukou et al. designed HaptiHug that supported interpersonal hug interaction over a distance [226]. (b) Hossain et al. designed a haptic-jacket to support emotional communication in a virtual reality environment [102].

2.3.3 Multimodal interaction in mediated touch communication

In the previous section, I introduced the cross-modal interaction of touch modality and other modalities. It is not just an important topic in psychological research, there has been an increasing interest in HCI research about how to use cross-modal interaction to better support touch interaction.

The visual modality receives the most attention in multimodal touch interaction.

The majority of research in multimodal touch interaction has focused on how tactile feedback improves visual perception and how to support tangible interaction with tactile stimuli, with less emphasis on multimodal touch interaction in emotional communication. Early studies such as [3] or [80] investigate how the visual and touch modalities interact with each other. For example, Akshita et al. tested the emotional responses of visual stimuli, haptic stimuli, and visual-haptic stimuli, and explained how visual-haptic interaction could be used in the design of multimodal affective feedback [3].

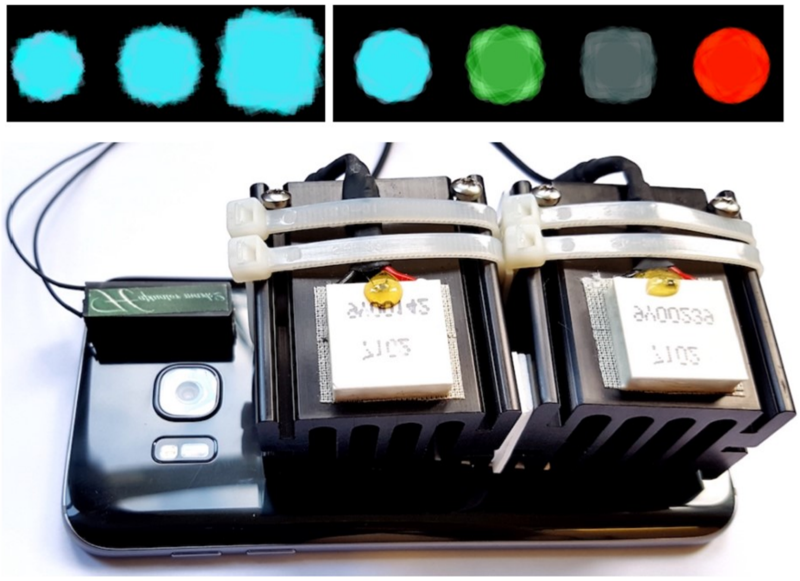

Figure 2.20: Wilson et al. investigated the emotional response of different combinations of modalities (temperature, vibration, and abstract visual displays) with Multi-Moji device.

More recent research expands the exploration of cross-modal interaction to affective interpersonal communication. For instance, Wilson et al. explored the combination of multiple concurrent modalities (temperature, vibration, and abstract visual displays) for conveying emotional information with the Multi-Moji device [251] (Figure 2.20). They found that even though each modality works differently on emotion expression, the combination of modalities increased the available range of emotional states. Except for abstract visual stimuli, Teyssier et al. [219] found that more concrete visual cues such as facial expression could also open up a wider range of emotional expression for touch stimuli.

2.4 Conclusion

This chapter first introduces the working mechanism of human touch perception and the role touch plays in human communication. Then I highlight different technologies and research approaches for mediated touch generation. However, even though efforts are made on mediated touch interaction, current communication systems' ability to support affective communication through the sense of touch still remains limited. As Van Erp et al. remarked, mediated social touch is a relatively young field of research that has the potential to substantially enrich human–human and human–system interaction [230].

Due to the complex human-perception system, existing technologies still lack the capability to simulate all the properties of human touch. Inspired by works on cross-modal interaction [3, 251, 80], we argue that combining multi-modality stimuli with current touch generation technology would potentially improve the emotional perception of touch. Even though some studies have begun to investigate the cross-modal interaction between vibrotactile and other modalities [251], there is still a lack of research into how multi-modality stimuli improve mediated touch communication. Moreover, how these modalities impact each other in communication and how these modalities can be used outside of social touch context is still not clear. To provide insights on these questions, I described our exploration on the cross-modal interaction between visual modality and touch in **Chapter 3**. As a complement to works in visual-tactile interaction [219, 3] and thermal-tactile [167, 69] interaction, I further discussed the multimodal interaction between visual, thermal, and tactile stimuli in communication in **Chapter 4**. More importantly, I explored multimodal touch interaction in the face-to-face communication context, which has seldom been explored in previous research. In **Chapter 5**, I discussed the use of multimodal touch interaction outside of the social touch context.

To overcome the mentioned constraints of existing touch generation methods such as vibration motors [128, 29, 231, 251] or SMA [111, 255, 99], we also explored generating more human-like touch with pneumatic actuation. Previous research suggested that inflatable actuators offer more possibilities for generating realistic skin-like touch sensations, as they feature a smaller difference in the mechanical impedance between the device and human [263, 89]. Complementary but distinct from the pneumatic devices I introduced in this chapter, the approach described in **Chapter 4** focused on the combination of different modalities and mediated touch interaction that mimics real-life touch gestures. Furthermore, previous research respectively discussed the input and output capability of pneumatic devices. Inspired by these explorations, in **Chapter 5**, we expanded the usability of pneumatic touch device with highly transparent material and the combination of touch input/output interactions. This part will be further discussed in **Chapter 5**.

3

Touch Is Not Alone: Enhancing Social Touch with Multimodality Stimulation

Psychological studies have explored the importance of touch and how people use touch to communicate distinct emotions [94, 230]. However, as discussed in Chapter 2, the expressiveness of most current social touch devices remains limited. This results in difficulties in precisely interpreting touch signals and their associated meaning. Moreover, touch is, by essence, ambiguous because similar touch signals can have very different meanings depending on the context [119]. Thus, additional information may help to disambiguate touch signals and make them more expressive. More specifically, I would like to explore if using multimodality stimuli can improve the emotional perception of the touch stimuli.

In this chapter, I start my exploration with the enhancement of visual modality. To this end, I present *VisualTouch*, a haptic sleeve consisting of a haptic layer and a visual layer. I first introduce the design rationale of *VisualTouch* with the main human factors we considered for building the device. I then present the design and implementation of *VisualTouch*. Finally, to explore the effect of dynamic visual cues on the emotional perception of vibrotactile signals, I present our two studies with *VisualTouch*, and discuss the insights with RESEARCH QUESTION 1(A) of this thesis: **Can we use multimodality stimuli to improve the emotional perception of**

current social touch technology?

3.1 Motivation

As mentioned in Chapter 2, vision is the most important sensory channel for perceiving the outside world. Moreover, there is a strong interaction between vision and touch, especially when visual and touch signals are congruent [135]. And this interaction can be leveraged to improve the perception of touch [122, 154]. In particular, we [1] consider color as it has been shown to have a strong impact on affective communication.

Furthermore, studies have shown a strong interaction between color and emotion. Back in 1954, Wexner et al. investigated the association between colors and mood-tones [239]. More recent studies, such as Suk et al. [207] or Wilms et al. [250] evaluated the effect of colored light using LEDs. Similarly, Simner et al. discovered a touch–color correspondencs which influences our perception of tactile qualities [197].

Considering the potential of using color to enhance the perception of emotions, we designed a prototype that combines tactile output with colored visual signals. More specifically, our hypothesis is that congruent visual cues can help counterbalance the imprecision of tactile perception (either due to inherent ambiguity or technological limitations), and thus enhance the expressiveness of affective touch.

3.2 *VisualTouch*

Based on the motivations outlined above, we designed the *VisualTouch* prototype (see Figure 3.1). *VisualTouch* is a wearable device that is placed on the forearm of the user by wearing a polyester sleeve strapped with elastic bands and velcro. There are two modality layers: the *visual layer* which consists of an array of LEDs, and the *vibrotactile layer* which consists of an array of micro vibration motors. The visual layer covers the whole surface of the device, and the vibrotactile layer makes contact against the skin of forearm.

Meanwhile, a web-based user interface is developed to generate touch stimuli and transmit them to the wearer of *VisualTouch* sleeve (Figure 3.5). In normal usage,

[1] Main part of this chapter was published in 2019 ACM International Conference on Multimodal Interaction (ICMI'19). Thus, any use of "we" in this chapter refers to the authors of this work: Zhuoming Zhang, Robin Héron, Eric Lecolinet, Françoise Détienne and Stéphane Safin.

Figure 3.1: *VisualTouch*

the sender of mediated touch generates and sends the touch signal in real-time by touching the interface on a touch-sensitive device like a smartphone or a tablet. The intensity, location, and duration of the sent touch stimuli can be controlled by the sender by implementing different touches on the screen. When a touch signal is sent by another person, the receiver can feel the vibration on the forearm along with a congruent visual movement.

When the *VisualTouch* sleeve receives the touch signal from the sender, both the visual layer and the vibrotactile layer are activated. In normal usage, the array of vibration motors will vibrate following the sequence of the touch gesture that the sender performed. Meanwhile, the visual pattern follows the vibration pattern at the same speed and the same intensity, with a color that is preset by the sender. It is aimed at raising the tactile attention of the receiver and to enhance the emotional perception of the tactile cue. By offering more degrees of freedom (e.g. by using color), it can also provide additional information.

3.3 Implementation

3.3.1 Visual layer

The visual layer is the top layer. This layer displays the movement of the touch on the forearm. The visual cues are displayed by a 10cm*17cm LED array consisting

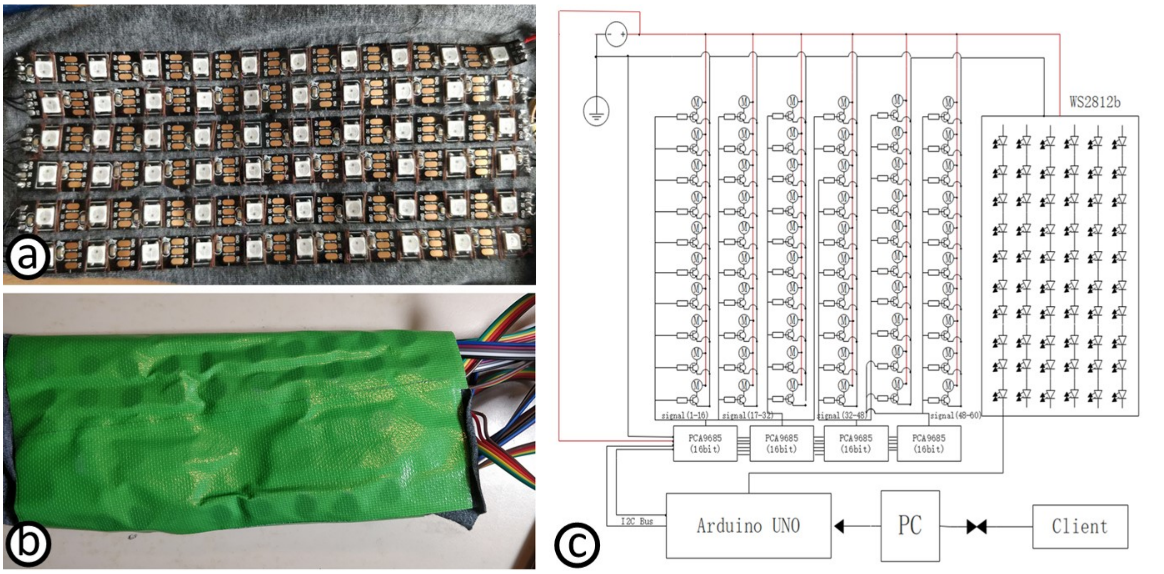

Figure 3.2: Structure of *VisualTouch*. (a) The visual layer of *VisualTouch*, it consists of sixty (10*6) RGB LEDs. (b) The tactile layer of *VisualTouch*. Sixty '1027' micro-vibration motors are wrapped in the sleeve with insulation tape. (c)the circuit of *VisualTouch*

of sixty (10*6) RGB LEDs (Figure 3.2). This array consists of individually addressable RGB LED strips (*ref. WS2812B*) which incorporate intelligent digital port data latches and signal to reshape amplification drive circuits.

Because of working memory in tactile sensation, the sense of touch can be perceived for a few milliseconds when we are touched by others [11]. Hence, we decided to make the trace fade away gradually over one second to simulate the persistence of touch. Although our device provides an unusually large number of LEDs, this number is still insufficient to deliver a very accurate pattern. Moreover, shape of corners and other gesture discontinuities can affect the fluency of the resulting effect. We thus implemented an anti-aliasing effect, using two complementary techniques. First, an anti-aliasing algorithm decreases the intensity of LED light and blurs sharp corners. Second, we added a physical cover (made of cotton cloth, paper sheets, and cotton wool) to the LED display to obtain an unpixelated rendering effect (Figure 3.3).

3.3.2 Vibrotactile layer

In previous sections, we reviewed possible ways of generating tactile feedback using vibration motors, solenoids, air jets, ultrasounds, etc. As our main purpose was to evaluate how vision and color could enhance touch perception, we used common

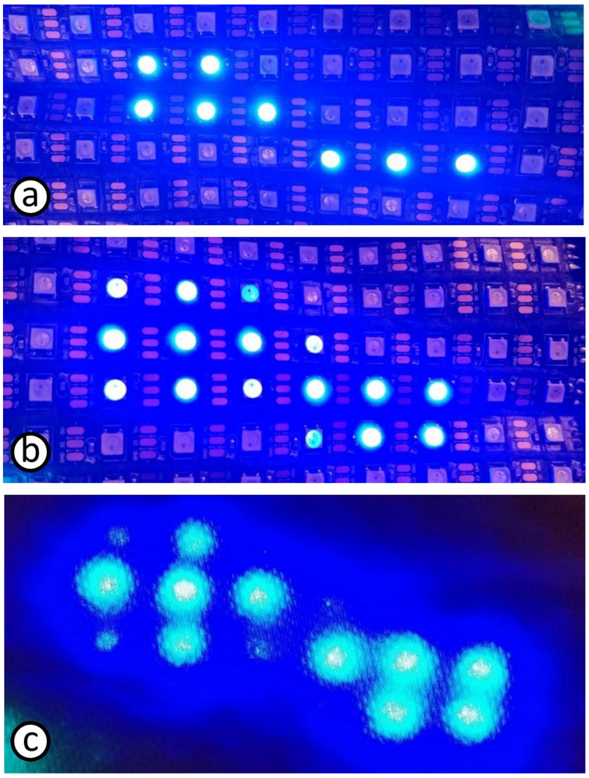

Figure 3.3: The anti-aliasing effect of *VisualTouch*. (a)Without anti-aliasing. (b)With anti-aliasing algorithm. (c)With anti-aliasing cover sheet.

technology to generate tactile feedback. Located beneath the previous layer, the vibrotactile layer consists of sixty '1027' micro-vibration motors. Both layers have the same spatial arrangement so that the motors are aligned with the LEDs of the visual layer. These motors are driven by PWM (Pulse Width Modulation) waves, to generate tactile signals with proper intensity and location. Thus the frequency of the vibration can be controlled to change the perceived intensity of touch stimuli accordingly.

All motors are attached on a polyester sleeve and covered with insulation tape to stabilize them. When a touch signal is detected, the motors corresponding to the target area vibrate 300ms (including the time to shade away). According to the results of the 2PD test [137], touch resolution on the forearm is around 2 cm. So considering the limited resolution of the sense of touch, the anti-aliasing effect is not been used on the vibrotactile layer.

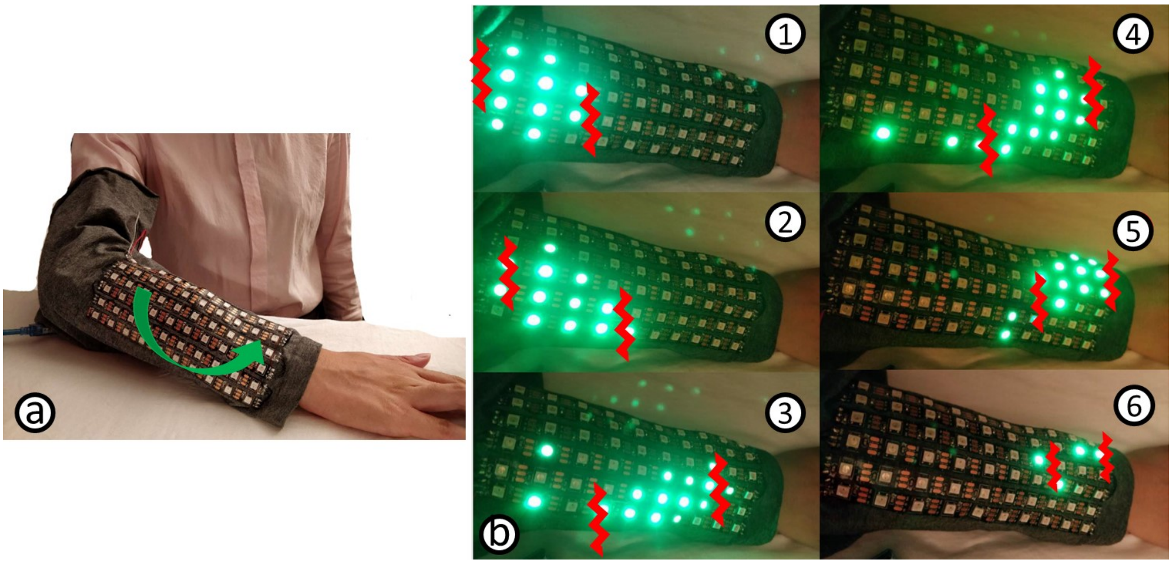

Figure 3.4: One example touch gesture. (a) The shape of the gesture. (b) Step 1 6 shows the movement of the viusal cue as well as the vibration.

3.3.3 Input and control

Touch patterns can be produced computationally or by using a user interface that was developed for this purpose. The interface captures the movement and the pressure of a movement on a touch-sensitive surface such as a touchscreen. The larger the force implemented to the screen, the stronger the vibrotactile will be generated on the sleeve, and this intensity can be changed dynamically during one touch pattern. This feature makes it possible to create realistic touch patterns as it can capture the characteristics of actual human touch gestures. Gestures are encoded as a sequence of points with their corresponding location, timestamp and pressure values. In addition, a color can be attributed to the whole gesture. In the current setting, the touch stimuli are generated through a touch-sensitive smartphone. However, the *VisualTouch* prototype can also work with any sort of compatible data, obtained for instance through pressure-sensitive fabrics [85], a tactile suit [108], etc.

Lastly, a JavaScript robotics and IoT platform called Johnny-Five [15] controls the *VisualTouch* prototype in real-time. The received data is transferred to Arduino with *Firmata* format under the *StandardFirmata* protocol. The vision layer receives the data from a digital port and the vibrotactile layer through the I2C bus. Four PCA9685 16 channel PWM driver chips are used to control the 60 motors. A simple amplifying circuit, consisting of a 220 Ohm resistance and a BC547B transistor, is attached to each motor. The PWM frequency is 980Hz. The duty cycle is 90% for

Intense touch, 60% for Mild touch and 30% for Soft touch.

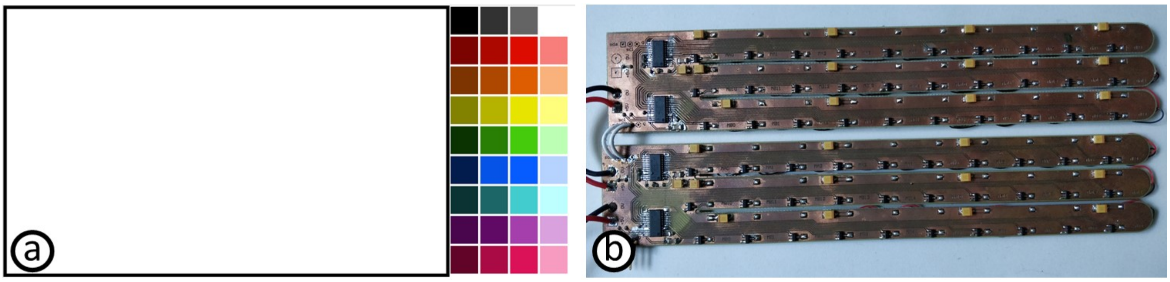

Figure 3.5: First round iteration of *VisualTouch*. (a) Interface for the first round of iteration. (b) PCB board for the vibration layer.

3.3.4 *VisualTouch* - iteration

From our observation and participants' feedback, we found that: 1) the complexity of the circuit makes the whole device quite fragile and hard to repair; 2) the size of the actuation part affects the experience of wearing the device; 3) the use of Arduino Uno and the external power supply increases the difficulty of using it in communication as the plenty of cables limits the mobility of the device; 4) the perception of the vibrotactile stimuli. Thus, we [2] iterated the *VisualTouch* design to improve the mobility, robustness and generating more realistic touch stimuli.

In the iteration, we 1) simplified the circuit by changing the wire connection of the actuation into printed circuit board (PCB), and 2) using battery and Wi-Fi microchip (ref. ESP8266) as power supply and controller to reduce the cable connection. These procedure makes the device much more rigid and all the interactions can be done remotely in a wireless way. Furthermore, we also explored an alternative solution to replace the 60 (10 * 6) vibration motors into 10 (5 * 2) servo motors. Although there is a little sacrifice in the precision of the touch gesture, the strong tactile feedback from the servo motor and rigid structure make it much more possible to be used in real touch communication.

The second version of prototype was being used and tested in another study in the ANR Social Touch research project framework.

[2] The revision of *VisualTouch* is a collaboration work with Mickaël Bouhier, Karim Benkalaia and Robin Heron.

Figure 3.6: Second round iteration of *VisualTouch*. (a) The two layers are placed into the 3D printed case to ensure stability. (b) Alternative tactile actuation with 5 * 2 servo motors. (c) Final user interface of *VisualTouch*.

3.4 Tactile emotional response

As previously explained, our goal is to investigate whether colored visual cues improve the perception of tactile cues. Our hypothesis is that congruent visual cues can help counterbalance the imprecision of tactile perception (either due to inherent ambiguity or technological limitations), and thus enhance the expressiveness of affective touch. We conducted two studies with the first version of *VisualTouch* prototype for this purpose. The first study, which is presented in this section, was conducted to select appropriate tactile stimuli for the second study (i.e. stimuli that produce sufficiently different emotional responses). The second study, which will be presented in the next section, compared the emotional response when visual stimuli were present or not.

3.4.1 Stimuli

Taking previous research into consideration [251, 105], we used three dimensions, and two values on each dimension, to generate the vibrotactile stimuli: *Duration* (L: Long or S: Short), *Intensity* (I: Intense or M: Mild), and *Dynamism* (S: Static or

D: Dynamic). Eight different stimuli were thus obtained by crossing these dimensions: LIS, LID, LMS, LMD, SIS, SID, SMS, and SMD. The duration was, respectively, 2500ms and 1000ms for Long and Short touch stimuli. The Intensity of the stimuli was controlled through PWM wave. The PWM frequency is 980Hz. The duty cycle is 90% for Intense touch and 60% for Mild touch. The last factor, Dynamism, depends on whether the stimulus involves movement (Dynamic) or not (Static). The stimuli captured through the smartphone were manually modified to match the previously described parameters. The parameters of the stimuli are selected and tested during the pilot test within our colleagues.

3.4.2 Emotion assessment

Emotions can be assessed through not only physiological or behavioral data but also verbally. A first particularly used method for assessing emotions consists in asking the participant to select affect words from a list [94, 95, 205]. Another method ask participants to rate their feeling over two scales (Valence and Arousal) ratings which can later be represented on the circumplex model of emotions developed by Russell et al. [187, 251]. In our experiments, we used the Self-Assesment Manikin (SAM), which provides visual clues (cartoon-like images) to help participants to rate Valence and Arousal on a scale [17, 250, 207]. Thus, a sheet with two SAM scales (one for Valence and one for Arousal) and affect words representing each pole was provided to participants before each experiment [17] (Figure 3.7). To answer, participants were asked to circle one number on each scale.

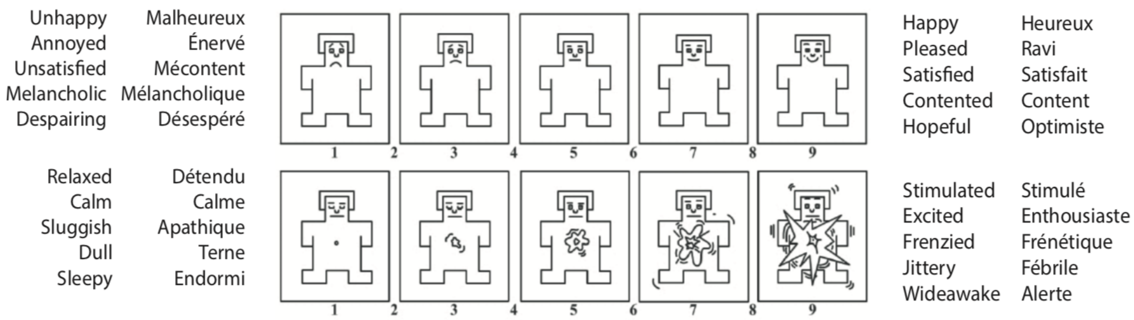

Figure 3.7: SAM presentation sheet

3.4.3 Participants

16 participants (22-45 years old; mean: 26.4) involved in our study. No participant reported sensorimotor impairments or color vision deficiency.

3.4.4 Procedure

The participants were asked to sit in front of a desk and the experiment was explained to them. They were then asked to read and sign an informed consent form, and the *VisualTouch* prototype was strapped on their non-dominant arm. The objective of the study was to explore the general emotional interpretation of visuo-tactile signals and whether multimodality channels can enhance the emotional perception of tactile signals. Following previous research in emotional haptic communication studies [251, 95], we told the participants 1) that the stimuli had been recorded by another person who intended to convey certain emotions through these stimuli, 2) that their task was to assess the intended emotion of each stimulus. In other words, the task was to evaluate the interpretation of the emotion expressed by a sender.

After clarifying the procedure, four training stimuli were displayed to familiarize participants with the device, as well as SAM scales. The eight previously described stimuli were then presented twice to the participants, in a random order. The participants were asked to rate the Valence and Arousal after each stimulus, using the SAM scale. A short interview was conducted at the end of the experiment. Throughout the experiment, participants wore headphones playing white noise, at a comfortable volume so they would not hear motor noise. The visual layer of the *VisualTouch* prototype was not activated in this experiment.

3.4.5 Results

The mean score for each touch stimulus on Valence and Arousal are presented in Table 3.1. As shown in the table, larger differences were obtained for Arousal than for Valence. The results of a MANOVA for Valence and Arousal show a significant effect (Pillai's Trace = .54, $F_{14,496}$= 12.9, p $<$.001)). A repeated-measures ANOVA on both Valence and Arousal scores showed no significant effect on Valence, but a significant main effect on Arousal ($F_{7,8}$= 78.49, p $<$.001).

As the goal of this first study was to find a few stimuli producing a substantially different response, we mainly took Arousal into consideration to select them. First, we selected the LID and SMS stimuli because they have the highest and lowest

Arousal scores. Then we added the LMD stimulus, which had the highest Valence score and a medium Arousal score. Finally, we selected a fourth stimulus, SIS, to balance stimuli in terms of Duration, Intensity, and Dynamism. This choice resulted in having two stimuli for each value of the (Duration, Intensity, Dynamism) dimensions: two with a Short Duration, two with a Long Duration, two with a Mild Intensity, etc.

Table 3.1: Mean and standard deviation for Valence and Arousal of the eight touch stimuli

Valence			Arousal		
touch	m	sd	touch	m	sd
LMD	**5.62**	**2.20**	**LID**	**7.78**	**1.48**
LMS	5.03	2.02	LIS	7.56	1.44
SMS	4.97	2.07	SID	7.12	1.48
SID	4.94	2.45	SIS	5.31	1.57
SMD	4.87	1.79	LMD	4.91	1.65
SIS	**4.59**	**1.86**	LMS	4.91	2.02
LIS	4.53	2.77	SMD	4.41	1.48
LID	4.31	2.84	**SMS**	**2.81**	**1.60**

Another advantage of selecting these specific stimuli is that they correspond to well-known touch gestures: LID (Long, Intense, Dynamic) corresponds to a Rub, LMD (Long, Mild, Dynamic) to a Stroke, SIS (Short, Intense, Static) to a Hit, and SMS (Short, Mild, Static) to a Pat gesture (for the sake of clarity, we will use these naming in the rest of the paper). As this selection provided a reasonable coverage of common touch gestures, we did not retain more stimuli to avoid making the next experiment too long.

3.5 Visuotactile emotional response

The objective of this second study was to investigate the interaction between visual and tactile cues. For this purpose, we considered and combined three factors: Tactile Output, Color, and Visuo-Tactile Congruence. We considered two factors for the visual modality: 1) Color because of its impact on emotional response, and 2) Congruence between tactile and visual signals, as this factor may reinforce the perception of tactile stimuli.

3.5.1 Stimuli

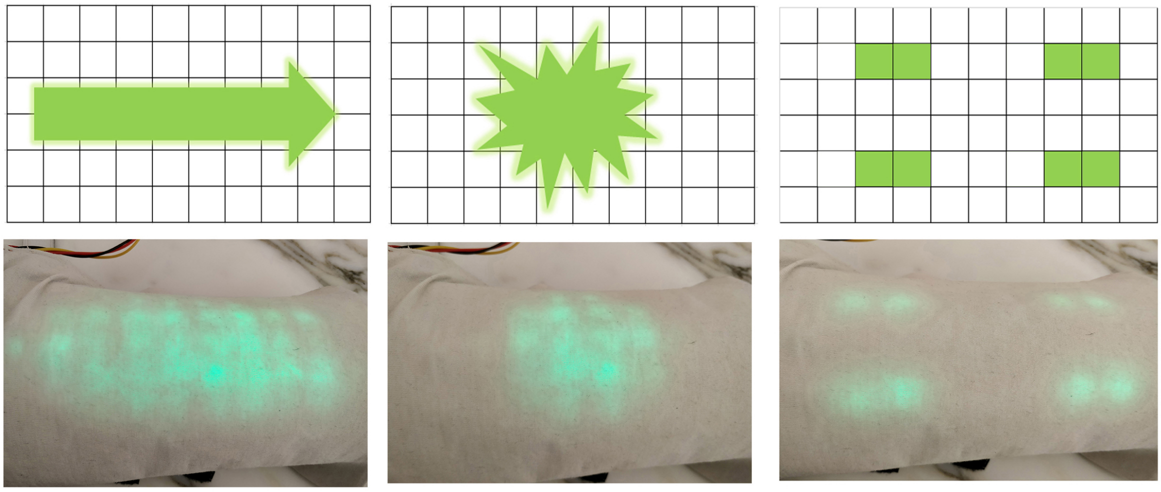

Figure 3.8: Three visual conditions (congruent dynamic or static visual and non-congruent visual)

Tactile Output: We used the four stimuli which were selected in the previous study, i.e., Rub, Stroke, Hit, and Pat, using the same (Duration, Intensity, Dynamism) characteristics.
Color: We chose to use the Red, Green, Blue and White colors because these colors have been widely considered in previous literature and have been shown to significantly impact Valence and Arousal [207, 239].
Congruence: Congruence here means that the tactile and the visual signal follow the same movement on the two layers of the *VisualTouch* prototype (Figure 3.8, left and middle). In the non-congruent condition (Figure 3.8, right), eight LEDs were displayed at a fixed position that is not related to the tactile signal. This visual signal was sufficiently large to be easily noticed. It was never similar to the tactile signal, even for static tactile stimuli, because the LEDs were not at the same locations than the motors that were vibrating. In both conditions (either congruent or non-congruent), the duration and the intensity of the LEDs followed the duration and the intensity of the tactile stimuli, so that the only difference was whether the movement of the two signals was the same or not.

Combining of these three factors led to three types of multimodality stimuli: *Touch Only* (4 tactile stimuli without visual feedback), *Congruent Visual Movement* (4 tactile stimuli x 4 colors = 16 stimuli), *Non-Congruent Visual Movement* (4 tactile stimuli x 4 colors = 16 stimuli). This study thus involved a total of 36 stimuli (4 +

4x4 + 4x4).

3.5.2 Participants

The study featured 12 participants (22-36 years old; mean: 26.4). No participants were color-blind or reported sensorimotor impairments. None of them participated to the previous experiment.

3.5.3 Procedure

This study was conducted under the same conditions as the previous one, except that the visual layer was used. After four training stimuli, the 36 stimuli were presented twice in random order. After each stimulus, the participant was asked to rate Valence and Arousal with the SAM scale. A short interview was conducted at the end of the experiment.

3.5.4 Results

First, we obtained similar results as in the first study (see section 5) for *Touch Only* stimuli by conducted a one-way repeated-measures ANOVA only on this data. We then conducted a MANOVA on the whole data set. The results show significant effect for *Touch* ($F_{6,1656}$=121.08, Pillai's Trace = .61, p <.001), *Color* ($F_{8,1656}$=20.36, Pillai's Trace = 0.18, p <.001), *Congruence* ($F_{2,827}$=11.62, Pillai's Trace = .03, p <.001) as well as for the interaction *Touch*Congruence* ($F_{2,827}$= 4.26, Pillai's Trace = .03, p <.001). In order to assess the effect of our three factors on Valence and Arousal more precisely, we divided our statistical analysis into two parts:

Table 3.2: Factors effects on Valence

Factors	Effect on Valence	Comments
Touch	p <.001	the higher the intensity the lower the Valence, the higher the duration the higher the Valence
Color	p <.001	red and blue are perceived as negative while green and white as positive
V-T Congruence	p = .002	congruent stimuli are perceived as more positive
V-T Congruence x Touch	p = .005	effect only present with dynamic stimuli

Touch and Color: Congruent stimuli are not included in this analysis so that the results only depend on tactile stimuli and color (LEDs at a fixed position, no visual movement). *Touch Only* signals (thus not involving color) were taken into account in this analysis. A 4 x 5 repeated-measures ANOVA was performed on both Valence and Arousal scores, then Post-hoc t-tests for pairwise comparisons, with Bonferroni correction. The within-subject factors were Touch and Color.

Congruence and interactions: This second part analyzes the effect of Visuo-Tactile Congruence and the interactions between all the factors. As they do not involve visual feedback, *Touch Only* signals are irrelevant for evaluating congruence and were thus discarded in this analysis. We performed, a 4 x 4 x 2 (Touch x Color x Congruence) repeated-measures ANOVAs on Valence and Arousal, then Post-hoc t-tests for pairwise comparisons with Bonferroni correction. The within-subject factors were Touch, Color and Visuo-Tactile Congruence. Table 3.2 and table 3.3 summarizes the significant effects of the factors on Valence and Arousal.

Table 3.3: Factors effects on Arousal

Factors	Effect on Arousal	Comments
Touch	$p < .001$	the higher the intensity and the duration the higher the Arousal
Color	$p = .002$	the addition of color increases the Arousal
V-T Congruence	$p = .001$	congruent stimuli are perceived as less aroused
V-T Congruence x Touch	$p < .001$	effect only present with static stimuli

Touch and Color

There is a significant main effect of *Touch* on *Valence* ($F_{3,33}$= 9.53, $p < .001$). Stroke is perceived as significantly more positive than Rub or Hit (<.001). Pat is perceived as significantly more positive than Rub or Hit ($p < .02$). There is also a significant main effect of *Touch* on *Arousal* ($F_{3,33}$= 278.65, $p < .001$) with significant differences between every stimuli ($p < .001$) except between Hit and Stroke.

Concerning *Color*, there is a significant main effect on *Valence* ($F_{3,33}$= 33.20, $p < .001$) with Red (m = 3.66, sd = 2.01), Blue (m = 4.14, sd = 1.66), *Touch Only* (m = 4.53, sd = 1.86), White (m = 5.21, sd = 1.58) and Green (m = 5.81, sd = 1.91). The Red and Blue colors are perceived significantly more negative than the White and

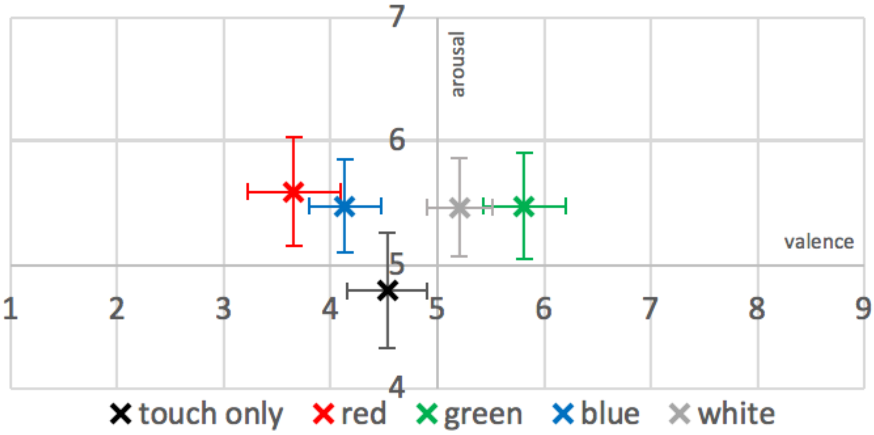

Figure 3.9: Distributions of Colors split by Visual-Tactile Congruence on the Circumplex model of emotion

Green colors (p <.001). *Touch Only* stimuli are perceived significantly more positive than stimuli with Red color (p = .001) and significantly more negative than stimuli with Green color (p<.001).

There is also a significant main effect of *Color* on *Arousal* ($F_{3,33}$= 4.89, p = .002) with *Touch Only* (m = 4.79, sd = 2.30), White (m = 5.47, sd = 1.94), Green and Blue (m = 5.48, sd = 2.11 and 1.87) and Red (m = 5.59, sd = 2.16). Colored stimuli are perceived significantly more intense than *Touch Only* stimuli (p<.05).

In short, *Color* impacts Valence progressively, with the *Touch Only* condition having a neutral value. *Color* also impacts Arousal, but the *Touch Only* condition then has the lowest effect. This suggests that *Color* can be used as an effective means for improving the emotional response, especially for Arousal, as shown in Figure 3.9.

Visuo-Tactile Congruence

We observed a main effect of *Congruence* on Valence ($F_{1,11}$= 15.65, p = .002), with Non-Congruent (m = 4.70, sd = 1.98) and Congruent (m = 5.26, sd = 2.08). There is also a main effect of Congruence on Arousal ($F_{1,11}$= 17.06, p = .001), with Congruent (m = 5.23, sd = 2.25) and Non-Congruent (m = 5.53, sd = 2.02). Congruent stimuli appear to increase Valence, but to decrease Arousal.

A more in-depth analysis clarified this effect. As shown in Figure 3.10, there are interaction effects on Valence and Arousal between Touch and Congruence. First, there is an interaction effect on Valence ($F_{3,33}$= 4.97, p = .005), but significant differences between Congruent and Non-Congruent stimuli only for Rub (p = .02) and Stroke (p = .002), as can be seen on Figure 3.10. Second, there is also an interaction

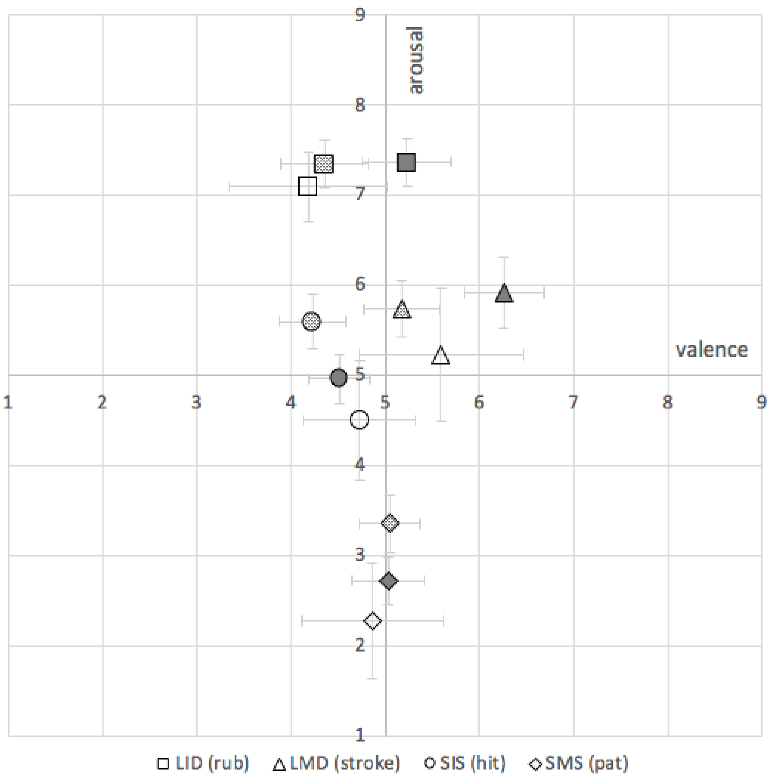

Figure 3.10: Visuo-Tactile Congruence effect on the touch distribution on the Circumplex model of emotion (grey - congruent, hashed - non-congruent, white - *Touch Only*)

effect on Arousal ($F_{3,33}$= 6.77, p <.001), but significant differences for tactile stimuli Hit (p = .005) and Pat (p = .007).

Hence, it seems that congruent *dynamic* stimuli (Rub, Stroke) increase Valence, but congruent *static* stimuli (Hit, Pat) decrease Arousal. This result is interesting as it opens a way to widen the spectrum of emotions.

Evaluating emotions

We also got some interesting feedback from the interviews. First, most of participants tended to associate Valence with Color (7/12 participants): the Red color being mostly seen as negative (10/12), and the Green color as positive (8/12). White was rather seen as neutral positive (5/12), and Blue as neutral negative (5/12). In contrast, Arousal was more often associated with Touch (9/12), and was also influenced by the intensity of the Color and the length of the pattern (6/12), with longer patterns were perceived as more aroused (4/12). Interestingly, two participants also associated non-congruent color movement with eyes movement (jovial or frightening).

3.6 Discussion

Our observations tend to confirm our main hypothesis that the visual layer enhances the communication of emotion in mediated social touch. In the first study, we observed that the type of tactile stimuli has only a significant effect on Arousal. This means that different types of Touch stimuli succeed in conveying only a partial emotional information: the intensity of the perceived emotion, but not the Valence.

Adding a visual layer strengthens the variety and the amplitude of the emotional feelings of the participants. There is a significant effect of color on Valence scores, with Red and Blue (lowering), Green and White (increasing) significantly modifying the Valence of the interpreted emotion. The interviews confirm that Red and Blue are associated with more negative emotions (anger, sadness), and White and Green with more positive emotions (happiness, enthusiasm). This can be linked with the cultural background as these results are similar to those of previous researches on color and emotion [251, 207, 250].

Although we also observe an effect of color on Arousal, it is only the presence of the visual display of a color that increases the perceived Arousal of the stimulus, no matter which color it is. This would mean that in the *VisualTouch* setting, the tactile stimuli can determine the Arousal, and the Color the Valence. Moreover, Visuo-Tactile Congruence increases the expressive capabilities of the device. The interaction effect between Touch and Visuo-Tactile Congruence shows that Congruent stimuli allow a widening of the distribution of the scores on the Circumplex model.

These results support the idea that adding a congruent visual layer can help express more subtle stimuli, thus allowing greater variations in the emotional response of the receiver. More importantly, these results respond to RESEARCH QUESTION 1(A) of this thesis: *Can we use multimodality stimuli to improve the emotional perception of current social touch technology?* Although the vibration motors are still limited to generating expressive emotional touch stimuli, the addition of congruent visual effects to the touch modality still expands the spectrum of emotion perception, thus opening new opportunities to support emotional communication in social touch.

There are still some limitations to this work. In the *VisualTouch* prototype, we used vibration motors as the actuator to generate tactile stimuli, which can trigger Pacinian corpuscles in our skin. This limitation has also been noted by the participants. They mentioned that even though the vibrotactile perception was comfortable and very interactive, it was not similar to any type of touch in real life. Thus, in order to support affective touch communication, generating more human-like tactile stimulation using appropriate actuation and material technologies is necessary. Thus, except for my next step is to answer RESEARCH QUESTION 2 of this thesis in the next chapter: *How can we generate more human-like tactile stimulation to improve multimodal touch interaction?*

Meanwhile, our evaluation and discussion of *VisualTouch* just concerned the perception of multimodality stimuli, while our goal is to use multimodal touch interaction into our daily communication and interaction. Thus, to understand the role multimodal touch plays in communication, further discussion (in CHAPTER 6 of this dissertation) of the *VisualTouch* and different modalities in the context of communication and interaction is necessary. And the further discussion will also respond to RESEARCH QUESTION 3 of this thesis: *How can we incorporate multimodal touch interactions into our everyday communication and interaction?*

4

Generating Human-like Touch: Improving Mediated Social Touch Sensation Using Pneumatic Actuation

In the previous chapter, I explored how the use of the visual modality improves emotional perception of tactile stimuli. Meanwhile, the vibration motor used in *VisualTouch* prototype has been shown to be insufficient to generate expressive and realistic social touch [60]. From the evaluation of *VisualTouch*, participants also made similar remarks about the sensation of vibrotactile stimuli, such as "*[the touch stimuli] is comfortable and interesting but doesn't feel like a real touch*". Thus, in order to improve our daily touch communication and interaction with multimodal stimulation, generating more realistic touch sensations is necessary.

In Chapter 2, we reviewed different technologies that have been used in touch generation devices. Typical actuators include shape memory alloys (SMA), electrical muscle stimulation (EMS), air-jet, pneumatic etc.. SMA can generate high loads with a small device size, and it has been used to generate the sense of squeeze [255, 77] or skin-stretch [150]. But the response speed to either activating or resetting the actuator is slow compare to other types of actuators. For example, the response time of SMA actuator in SqueezeBands prototype was over 10s [255], while the response time of vibration motors in *VisualTouch* was less than 100ms. This feature of limited SMA's usage in communication. Air-jets devices are used to generate pressure on skin, but the actuation parts are usually large and fixed [209, 225], and it is hard to balance the size of the device and the strength of the generated touch stimuli. EMS devices are usually compact and suitable for mobile and wearable applications, but the accuracy is limited and some users perceive temporary discomfort caused by the electrical stimuli on muscles [132].

Meanwhile, pneumatic actuators offer more possibilities of generating realistic skin-like touch sensation. They feature a smaller difference in mechanical impedance between the device and human [263]. In this chapter, I present the *SansTouch*, a multimodal pneumatic hand sleeve used along with a smartphone, to enable mediated hand-to hand interactions such as handshakes or holding hands. I first present the survey study about social touch breakdown based on the background of the COVID-19 crisis, which motivated our design of *SansTouch*. Then I introduce the design and implementation of *SansTouch*. To assess whether a mediated touch device like *SansTouch* can enhance social experiences between users with semi-intimate relationships during face-to-face communication while social distancing, I conducted a qualitative usability test with 12 participants. Finally, I discuss the main design factors for building pneumatic multimodal touch devices based on insights from the study.

4.1 Background: Social touch breakdown

In Chapter 2, I discussed the importance of social touch to our physical and social well-being. However, social touch communications can be highly restricted under certain circumstances, for instance due to social distancing during a pandemic like COVID-19 [34] or for people with medical conditions [189, 86]. Moreover, social touch breakdowns may not only have direct consequences on intimate relationships such as families or close friends, but also on semi-intimate relationships such as casual friends or colleagues. Research highlighted that long-term touch deprivations may severely impact health and well beings [57, 78]. As such, it is important to overcome these social touch breakdowns with mediated touch devices, especially under circumstances in which people might have to practice social distancing for a long time [34].

To this end, our work aims to complement and expand the design space of computer-mediated touch, to better support interpersonal touch communications that are: 1) not only for users with intimate but also semi-intimate relationships, and 2) not only used in remote but also face-to-face communications.

To better inquire into the potential use case scenarios of touch devices in face-to-face communications, we [1] first conducted a survey with 136 participants (followed by in-depth interviews with 6 participants) to investigate social touch breakdowns due to social distancing during the COVID-19 pandemic (Due to social distancing measures, people around the world have been forced to restrict and/or change their social touch habits even when they are co-located with others, especially after COVID-19 pandemic lockdowns were imposed in their countries [22].).

To better understand potential challenges and use case scenarios of mediated touch devices in face-to-face communication, we were interested to investigate the forms of social touch that were highly restricted with social distancing, the relationships that suffered from social touch breakdowns, and the challenges of re-establishing the alternative ways of touching others while social distancing.

4.2 Study: survey on social touch with social distancing

4.2.1 Recruitment and participants

We recruited 136 participants (46% women, 52% men, 2% preferred not to say) who were at least 18 years old in different countries. More than half of them are adults below 30 years old (56%). The rest are between 30-40 years old (31%), 40-49 years old (4%), and 50-59 years old (8%). The effect of cultural backgrounds on social touch breakdowns was not our focus, so we did not specifically control the country of residence nor the cultural background as an independent variable in the participant pool. That said, to diversify our participant pool, we tried to include participants from different cultural backgrounds. Our participants were currently living in different continents: Europe (59% of participants), Asia (36%), America (4%), and Australia (1%). Although the majority of them lived in Europe, the participant pool included diverse cultural backgrounds: 58% Asian, 37% Europeans, 4% Americans (i.e., north and south Americans), and 1% Africans. Around one third of them (33%) currently lived outside of their country of origins. When filling in the survey, the lockdown had ended for more than a month where the majority of the participants

[1] Main portions of this section was published in 2021 ACM Conference on Human Factors in Computing Systems (CHI'21). Thus, any use of "we" in this section refers to the authors of this work: Zhuoming Zhang, Jessalyn Alvina, Robin Héron, Stéphane Safin, Françoise Détienne and Eric Lecolinet.

(70%) lived.

4.2.2 Method

The participants completed the online survey in 15 minutes on average. The survey consisted of five parts. Part 1 collected demographic data including countries of origin and residency. Part 2 asked participants about their social touch habits before the lockdown started, while Part 3 about their new social touch habits after the lockdown ended. In these two parts, we asked about 1) the frequency of social touch (Likert-scale 1="*Never*" to 5="*Always*"); and 2) the forms of social touch (e.g., handshake, holding hands, hugs, kissing cheeks, etc.) for different relationship categories (Figure 4.1). We chose the relationship categories considering different intimacy levels and our pilot study with three participants. Specific to Part 3, we asked two additional questions: 1) the forms of social touch that the participants wished to do but did not after the lockdown; and 2) frustration levels for their current social touch habits (Likert-scale -2="*Extremely frustrated*" to 2="*Extremely happy*"). In Part 4, we asked the participants to share *social touch breakdown stories*: a past event in which, during a face-to-face communication, they wanted to touch someone but could not due to social distancing (if any). For each story, the survey asked: 1) with whom; 2) the context (e.g., why they did not touch); 3) the form of social touch they wanted to do; 4) the purpose of social touch; and 5) what they did instead. Part 5 was optional: we gave a touch breakdown scenario to the participants, and asked them to imagine solutions to touch but without touching skin-to-skin. We told the participants that they could build any imaginative device to mediate the touch, but we did not restrict the solutions to technology-mediated touch only.

We also conducted follow-up interviews: we first went through the social touch breakdown stories from the survey, then contacted 8 participants with the richest stories, i.e., included concrete details related to social context and/or how they dealt with it (6 participants responded). This helped us to understand the nuances in the issues and the rationale behind their social touch decisions. These interviews lasted 20-45 minutes.

4.2.3 Data Analysis

We started the data analysis by performing statistics on the quantitative data (i.e., Likert-scale data) related to the evolution of the frequency and the forms of social touch before and after the social distancing. Although sharing social touch break-

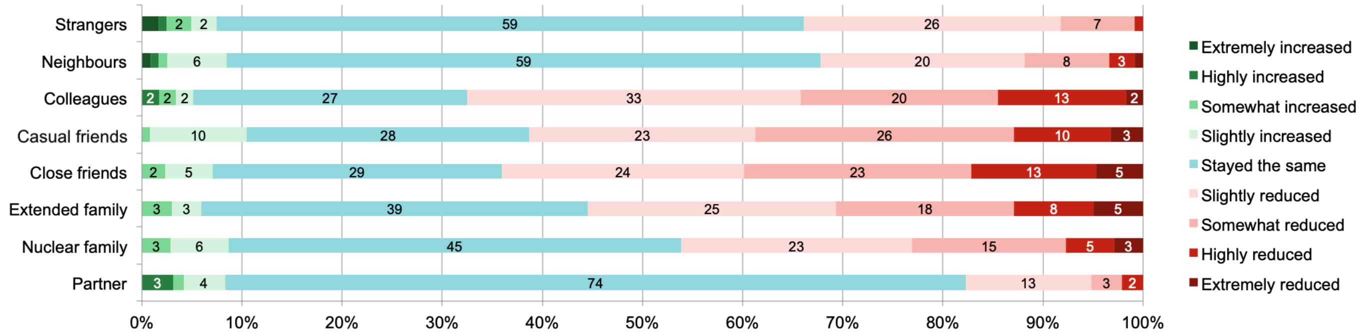

Figure 4.1: The percentage of participants who increased (green bars) or reduced (red bars) the frequency of social touch when they met after the lockdown ended. '*Extremely reduced*' was when the participants reported '*always*' touching before the lockdown but '*never*' touching after the lockdown ended. The highest reduced frequency was with colleagues, while the frequency mostly remained the same for partners.

down stories was optional, our survey collected a total of 84 stories reported by 72 participants (53%). 82 stories were analyzed (we discarded 2 irrelevant stories e.g., due to long distance relationships). We analyzed the data inductively and deductively with several iterations using Braun and Clark's thematic analysis approach [33]. Altogether, the recurring themes highlighted different levels of social touch breakdowns for different social relationships, and the specific challenges that the participants faced as they re-established their new social touch habits.

4.2.4 Key results

Social touch breakdowns affected social relationships differently

Not surprisingly, some participants avoided seeing people in their circles even after the lockdown ended. Of those who met others after the lockdown ended, the participants reduced the frequency of touch with their colleagues the most (68%), followed by close friends (64%) and casual friends (61%) (Figure 4.1). In particular, they were the most frustrated that they could not share social touches with close friends. The social touch breakdown stories were also dominated by wanting to touch casual friends (27%) and close friends (17%) but could not. The new social touch habits with colleagues (i.e., after the lockdown ended), despite its highly reduced frequencies(68%), was not perceived as frustrating as with friends by the participants.

Around one third of the participants reported frustrations related to their new social touch habits with extended families (35%) and nuclear families (31%). Of particular interest, the extended family category had the highest number of participants reporting extremely frustrated (14% of participants). This might be related to health concerns, as extended families most likely included the elderly who were more vulnerable to viral infections [34], as expressed by P93, *"I have extended family members with health issues, and therefore avoid giving them hugs as much as possible when greeting them, even avoid touching them all together. It's depressing."*

"I still touch my partner and I would like to keep it that way"

On the other hand, the social touch frequencies with partners, neighbours, and strangers in general remained the same. 74% of participants reported the same frequency before and after the lockdown, and only 18% of participants reported reduced frequencies for partners (the lowest). Interestingly, 33% of participants did not meet/have partners before the lockdown, but they reported increased frequencies after the lockdown. This may be due to the fact that 7% of the participants moved in with their partner after the lockdown, and some participants might also get into a new relationship during this period. No social touch breakdown stories specifically mentioned wanting to touch their partners but could not.

Around 60% of participants reported that they kept the social touch frequencies with neighbours and strangers, while around 34% of them reduced the frequencies. The participants were in general happy with the new social touch habits with neighbours and strangers.

Hence, we might conclude that the social distancing significantly affected social touch among semi-intimate relationships such as casual friends and colleagues, but not intimate relationships (e.g., partners) nor strangers.

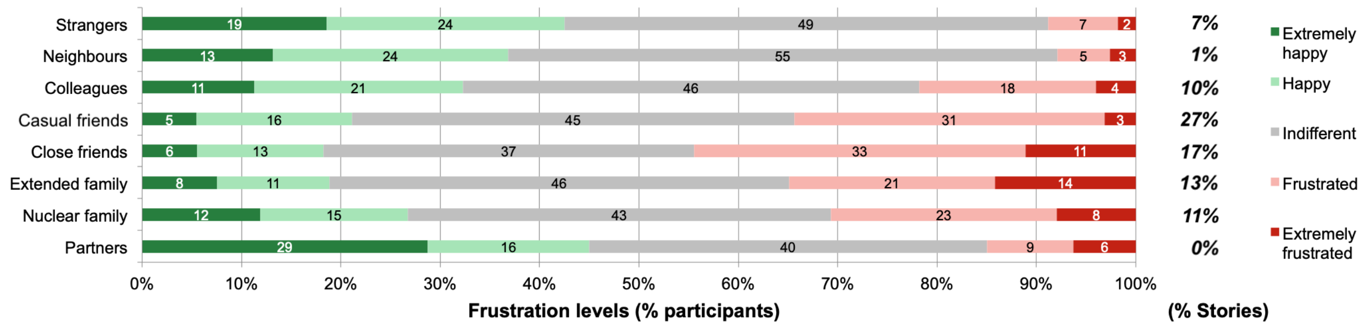

Figure 4.2: The perceived frustration levels of the new social touch habits and the percentage of social touch breakdown stories per relationship category reported by participants. Only 86% of the stories specifically mentioned with whom the social touch breakdown happened. High frustrations were reported for close and casual friends.

Handshakes, kissing cheeks, and hugs were highly reduced

Before the lockdown started, we found that the most frequent forms of social touch that the participants had had were handshakes, kissing cheeks, and hugs. Notably, both handshakes and kissing cheeks are commonly used as greetings. A high number of participants reported handshaking with all social relationships. Hugs were more likely shared among intimate relationships, as reported by the participants hugging partners, families, and close friends.

That said, we observed a significant decrease of the number of participants handshaking after the lockdown ended, especially with neighbours (from 57% to only 13% of participants), casual friends (51% to 19%), close friends (43% to 24%), extended families (35% to 20%), and colleagues (26% to 8%). Despite these decreases, they actually wished they could handshake other people, notably neighbours (43%), friends (40%), close friends (36%), and colleagues (31%). We also observed a similar trend of wanting to do it but could not for kissing cheeks and hugs. These results were in line with the social touch breakdown stories reported by the participants, with the majority of them expressing greetings (39% of the stories), affections (24%), and missing the other person (24%). The forms of social touch that they wanted to have but could not included hugs (37% of the stories), kissing cheeks (25%), handshakes (18%), touching hands (6%), and touching face (1%) (the rest was unspecified).

Social touch breakdowns forced the participants to re-establish touch communication habits

In more than half of the social touch breakdown stories, the participants ended up not touching the other person at all. In 6% of the stories, the participants mentioned that they even specifically avoided any face-to-face interactions to minimize the chance that they would have to touch the other person. In 37% of the stories, the participants substituted their old habits with other forms of social touch, such as mid-air gestures (e.g., waving, namaste, kiss bye). 19% of the stories reported "inventing" new forms like bumping fists, knees, feet, elbows, and arms.

Given these different new social touch habits, some participants reported confusions and frustrations as they were not sure what forms of social touch were acceptable anymore and having to learn the new forms of social touch. 11% of the social touch breakdown stories specifically described this confusion. For example, P101 shared a story: "*Shortly after the end of the lockdown, I went back to the pizzeria in my* *neighbourhood, where I have a good relationship with the owner. On arrival, he welcomed me, extended his hand, then made a ridiculous arm gesture with a little joke on the fact that he didn't know what to do now. So I extended a hand and we shook hands."* P51 explained that he had to observe the body gestures of the person he was talking to, in order to guess which form of social touch the other person would use for greetings. P87 also felt that this now-necessary observation was frustrating, especially if the other person was not familiar with the new form: *"It is annoying now I have to read the signs of what each person wants to do. One time, I was like, heyyy, and lifted my elbow [to do an elbow bump] and then yeaahhh, she didn't understand [what I was doing], so I had to turn it into something else. It was super awkward."*

To avoid this confusion, some participants had to explicitly negotiate on the forms of social touch they were going to share, as described in 24% of the stories. For example, P92 explained, *"Sometimes I am unsure whether or not people are okay with touch or what level of touch they are comfortable with. For example, before the lock-down [my friend and I] would often hug. There was just a bit of an awkward exchange in which we both weren't sure what the other person was comfortable with, so we just briefly joked/talked about it and went for a fist bump instead."* This negotiation process sometimes also happened after one party initiated a form of social touch, but rejected by the other.

However, this situation was often perceived as uncomfortable by the participants. For example, P42 had to reject a handshake but was worried that the other person would misunderstand: *"I said, 'I'm sorry but no handshakes, let's do this instead', like namaste, or fist bumps. I was trying not to hurt their feelings. It was very hard to say something like that to my colleagues or close friends."*

4.2.5 Insights from the study

Reflecting back on our goal to design a novel touch device that supports face-to-face communications, we highlighted three of the survey findings that served as challenges and opportunities for design: First, social touch practices were the most reduced between people with semi-intimate relationships like casual friends and colleagues. This finding emphasized the need to design and evaluate mediated touch communication tools for semi-intimate relationships, which are currently under-explored in the literature. Second, handshakes, kissing cheeks, and hugs were highly reduced after the lockdown – the forms of social touch commonly used for greetings. This ritualistic touch is an important part of our daily touch behaviour

[115], and failing to greet another person appropriately may have consequences for the embodied relationships [118]. This result highlighted the opportunities to design mediated touch devices for handshakes, complementing the past research on mediated touch devices for hugs [7, 46, 117] and for cheeks [163, 164]. Finally, the participants reported struggles and frustrations, not only because their social touch habits no longer worked (i.e., social touch breakdown), but also they had to establish new social touch habits with extra learning efforts. Establishing communication between two people requires a common understanding (i.e., a common ground) on the purpose and the medium of the communication [32]. Hence, when the participants tried to replace the touch with mid-air gestures (e.g., waving hands) or "inventing" new form of greetings (e.g., fist or elbow bump), they faced some challenges updating and negotiating their common ground with the other person, which they perceived as frustrating. These results motivated us to explore the possibilities of using mediated touch device to re-enable some common forms of greetings, such as handshakes, that can be used in face-to-face communications.

4.3 *SansTouch*: enabling hand-to-hand interaction in face-to-face communication

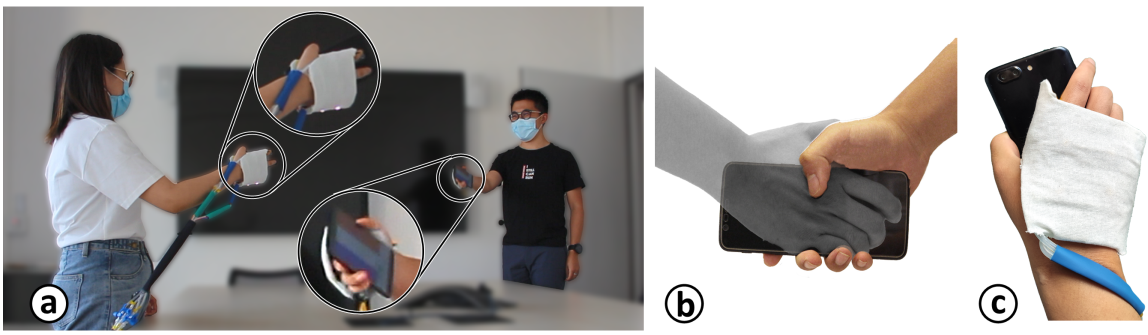

Figure 4.3: (a) Two users exchanging a mediated handshake with SansTouch at 2-meter distance. (b) To trigger the handshake stimuli, both users synchronously mimic the hand movement of a handshake as in real life. (c) Each user wears the multimodal hand device while holding a smartphone.

4.3.1 Design rationale

Based on the insights from the study, our goals were to build a novel touch device that 1) enables users to exchange bi-directional touch for greetings without physical contacts in face-to-face communications; 2) minimizes the efforts to learn new touch interactions; and 3) can generate realistic touch sensations (i.e., similar to real touch). The design process included two steps: designing the touch communication medium and designing the user-to-user interactions. We considered that interpersonal touch communication should be bi-directional: users feel the sensation of touching and being touched at the same time. This bi-directional interaction is quite usual in our daily touch interaction. For example, when we are holding another person's hand, we feel the sensation of squeezing the other person's hand and, at the same time, the pressure on the areas that are squeezed.

In Chapter 2, I reviewed touch devices designed for intimate relationships such as couples (e.g., touching cheeks [163], kissing [193]) and close friends or families (e.g., hugging [7, 13, 86], tickling [60]). But generating mediate interpersonal touch within semi-intimate relationships like colleagues still remains challenging. Nakanishi et al. proposed robot arms to enable remote handshaking for colleagues [152], while Teyssier et al. designed a finger-like robotic manipulator attached to a mobile device to enable touch on the hand [216]. However, these robot-mediated touch devices often suffer from uncanny valley issues[2], especially when the appearance of the actuator looks like human parts [152, 216].

Considering these aspects as well as previous research, we proposed *SansTouch*, a mediated touch communication tool that combines a wearable hand sleeve and a smartphone (Figure 4.8). The wearable device of *SansTouch* is a hand sleeve wrapping on the hand of user (Figure 4.3, further described in Section 4.3.3). Considering the social acceptability aspect [158], we opted for smartphones to represent the other person's hand as they have a high social acceptance, high accessibility, built-in sensors, as well as connectivity features. Since they are handheld devices, usually users can comfortably grip their smartphones as well.

With *SansTouch*, we can emulate handshakes and other hand-to-hand interactions such as holding hands, high-fives, or patting hands (Figure 4.7). The interactions happen mid air, with both the sender and the receiver wearing the wearable hand device while holding the smartphone. The touch stimulus is triggered as soon as both users synchronously mimic the hand position as in real life. We specifically let users mimic the real hand interaction to minimize the efforts to learn the mediated interactions and to establish the communication ground with *SansTouch*.

[2]Uncanny valley is when the emotional response to a device would abruptly shift from empathy to revulsion as it approached, but failed to attain, a lifelike appearance [145].

4.3.2 Exploration of generating human-like touch with pneumatic actuation

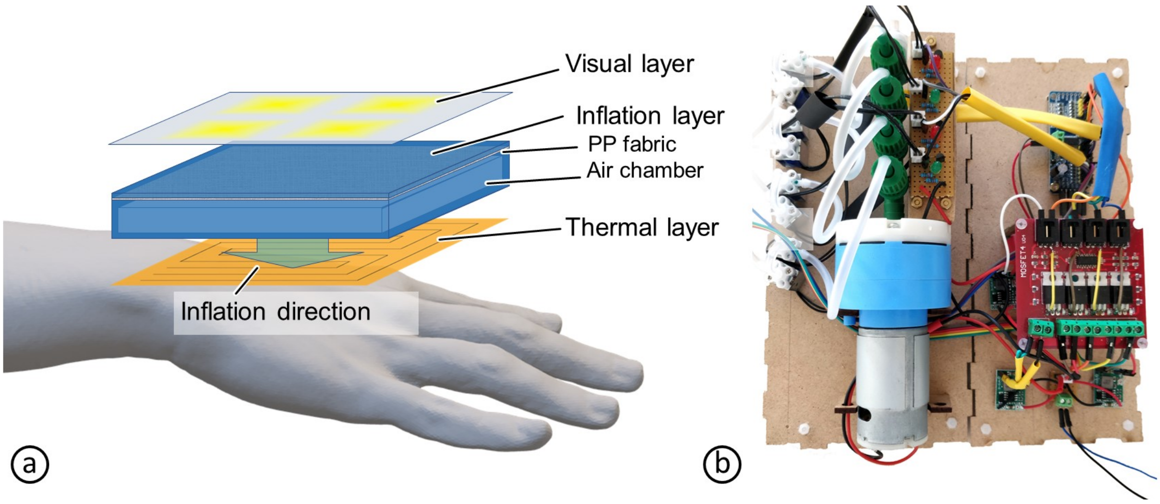

Figure 4.4: (a) Each *SansTouch*'s patch consists of three layers: visual, inflation, and thermal. (b) Circuit and actuators of *SansTouch*.

As discussed in Chapter 2, compared to ”hard” haptic interaction devices such as robot arms or vibration motors, ”soft” touch interaction actuators such as pneumatic actuation features a smaller difference in mechanical impedance between human and device, which lead to a more efficient sensing and transmission of the touch stimuli. Thus, using pneumatic actuation generate human-like touch stimuli can be a promising way to support mediated touch communication. Thus, using pneumatic actuation generate human-like touch stimuli can be a promising way to support mediated touch communication.

In this section, we present our exploration regarding to the material and actuation of the pneumatic device, in order to effectively generate touch stimuli with pneumatic actuation.

Material

As a touch generation device, the material of the device should have the following features: easy-to-get, soft, skin-contact friendly, strechable, robust, and easy-to-fabricate. There are two approaches of fabricating inflatable devices: 1) heat-sealing polymer sheet such as thermoplastic polyurethane (TPU) or polyethylene (PE) to create airtight chambers, or 2) using latex or silicone rubber to cast the air chamber.

We first explored fabricating air chamber with polymer sheet. The polymer sheet is widely been used in pneumatic devices such as in aeroMorph [162] or in Bellowband [258]. These materials are easy-to-get, and can be fabricated manually with a heat sealer or digitally with a CNC-sealing machine. We tested TPU-coated Nylon (210 den), PE sheet as the material, and tested soldering iron and hear-pressing machine as the tool to heat-sealing the polymer sheet. The sealing process is done by moving the heated iron (400°C) over two layers of stacked material with 400mm/min speed [162]. As previous research indicated [162], the fabrication approach is rather convenient and fast, and the sealed hinge can keep airtight after been sealed, especially with the multi-layered material such as TPU-coated Nylon. However, there are still large differences between the touch perception of the polymer sheets and real touch. The TPU-coated Nylon provokes fabric sensation to the skin, and the PE sheet induces "plastic" perception when touching the skin. Furthermore, the stretchablility of these fabrics is quite limited, which makes the air chamber rigid when fully inflated or when been pressed.

Then we explored the use of silicon rubber to build the air chamber. In HCI, silicon rubbers often been used to reproduce the properties of skin [39, 218] or make skin-contact soft devices such as Strechy [238] or in PneuHaptic [89]. With different composition, silicone rubber offers a great range of physical property such as hardness, strechability, color, texture etc. and thus provides large range of application. Thanks to these properties, using silicon rubber in touch devices can better simulate skin-contact compared to polymer fabrics. In our exploration, we tested silicon rubber with three different hardness: Shore A 10 [3](*ref. Ecoflex 00-10*), Shore A 20 (*ref. Ecoflex 00-10*) and Shore A 40 (*ref. Ecoflex 00-10*).

When the air chamber is inflated, the whole inner surfaces of the silicon airbag suffer the same air pressure, thus the expansion would happened in all directions. However, only one side of the airbag is contacting our skin when the device is working, and the expansion on the opposite side of the air chamber could decrease the pressure induced to the skin. Thus we designed a composite structure (Figure 4.4(a)) to limit the strechablity of the non-contacting surface of the silicon airbag. We tested inserting different types of textiles into the silicone, including paper, cotton fabric and non-woven polypropylene fabric. We found that paper cannot form stable adhesion with the silicone rubber, and cotton fabric would largely increase the thickness of the silicone layer after absorbing the gel into the cotton

[3] The Shore A Hardness Scale measures the hardness of flexible mold rubbers that range in hardness from very soft and flexible, to medium and somewhat flexible, to hard with almost no flexibility at all.

thread. Meanwhile, the thin (0.08mm) non-woven polypropylene (PP) fabric that frequently used in the medical masks perform well as the insert, as it can bonding to the silicone rubber stably with its meshing structure. The insert of the PP fabric can largely limit the expansion of the free side of silicone airbag thus providing stronger touch perception on the skin-contacting side.

The steps of the silicone air chamber fabrication are:

- Mix thoroughly the two ingredients of the silicone rubber with the correct portion (1A:1B by weight with the Eco-Flex series).
- Vacuum the mixed material for 2-3 minutes to eliminate any entrapped air. This step is optional for low viscosity silicone gels such as Ecoflex 00-10 or 00-20 as the air bubbles can be self-eliminated during the curing.
- Pour the degassed silicon gel into the 3D printed mold.
- Pour the silicon gel on a leveling surface, spread the material and placing the non-woven PP fabric into the silicon.
- After the silicone gel is cured, demold and agglutinate different parts as well as the air tubes with the newly mixed silicone gel.

Actuation

From the ideal gas law [4], we know that in order to inflate the airbag to generate touch stimuli without heating it, we need to increase the amount of gas in the airtight silicon chamber to increase the volume. There are two frequently used methods of increasing the amount of gas. The first way is to use actuators such as air pump to transfer the gas from the outside to inside of the airbag. The airflow is distributed and controlled by valves. Even though this method involves many external actuators and tubes to control each airbag individually, the flow rate and amount of air can be controlled accurately and rapidly. Thus this actuation is widely used in inflatable devices which require large airflow and high reaction speed. The second way is using the principle of liquid-to-gas phase change, to turn the liquid inside a sealed airbag into gas by heating the liquid, thus increase the volume of the airbag. The actuation part in this method is integrated into the airbag with

[4]The ideal gas law is the equation of state of a hypothetical ideal gas.The ideal gas law is often written in an empirical form: $PV = nRT$,where P, V and T are the pressure, volume and temperature; n is the amount of substance; and R is the ideal gas constant.

only few wire connections. This tubeless method has been used in shape changing interfaces [153, 228] and soft robotics [151, 16]. However, the reaction time of the phase change actuator is quite slow compared to the motors, and it takes even much longer time to deflate the airbag [2, 151, 16].

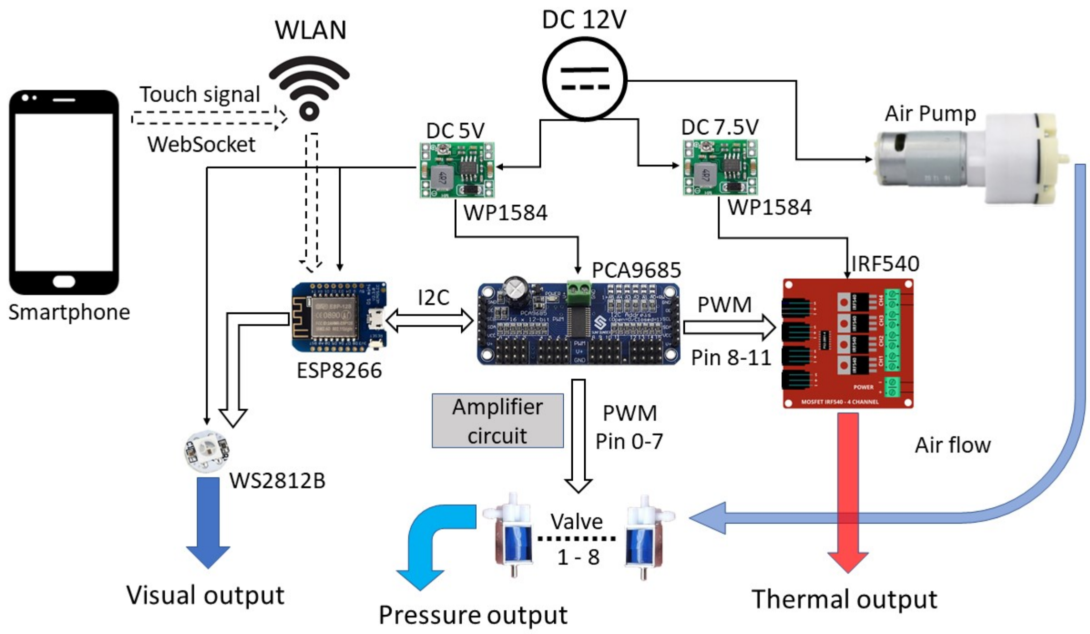

Figure 4.5: Structure of the circuit and actuators.

In our design, the touch stimuli need to stay synchronized with the communication which happens real-time, no matter at distance or face-to-face. Thus, the slow reaction speed of phase change actuator cannot support real-time touch communication. To this end, we use traditional air pump as the source of the pressure and control the airflow using solenoid valves. These actuators are connected to the airbag with silicone tubes. In this way, we can generate touch stimuli in a wide strength range with a high speed, thus provide real-time affective touch in our communication.

4.3.3 Generating touch stimuli with *SansTouch*

The output channel of *SansTouch* is a wearable sleeve wrapped on the user's hand that can generate a warm touch along with visual feedback. *SansTouch* has four different patches (Figure 4.6a and b): one patch on the palm, one patch on the back of the hand (Figure 4.6a (1),(3)), and two patches on the sides of the hand (Figure

4.6a (2),(4)). Each patch consists of three layers: thermal, inflation, and visual (see Figure 4.4c).

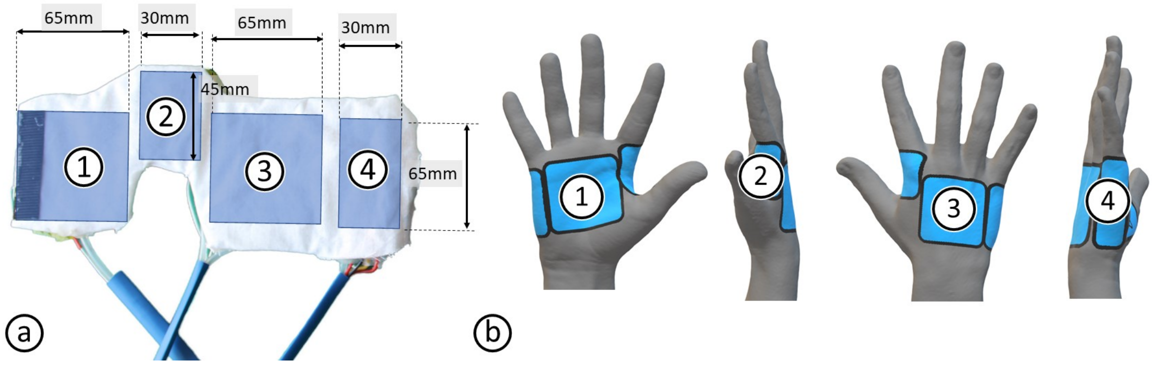

Figure 4.6: (a) *SansTouch*'s output channel is a wearable hand sleeve. (b) It consists of four patches located on the palm, the back of the hand, and the two sides of the hand.

Skin-like grip force

Our goal is to reproduce skin-like touch sensations that can be perceived as more realistic than those generated with vibration motors. As in [152, 163, 218], we opted for skin-safe and highly stretchable silicon rubbers (*ref. Ecoflex 00-20*) to make inflatable airbags that generate a grip force on the user's hand. The walls of the silicon airbags are 1.5mm thick, while the surfaces are 3mm thick, with a layer of polypropylene (PP) fabric inserted to limit its stretchability. With this setting, the airbag mainly inflates towards the skin, increasing the generated touch pressures. The inflation and deflation of each airbag is controlled by 2 two-way DC solenoid valve (*ref. ZHV0519*) through a 16 channel PWM servo driver (*ref. PCA9685*). A 12V DC vacuum pump (*ref. WP36C*) as the air source to inflate airbags.

Body temperature

Past research highlighted the importance of conditioning a touch device to body temperature to generate a more natural and realistic touch sensation [152, 70]. To this end, we built a thermal layer with 0.1mm Cr20Ni80 Nichrome wire and polyimide tapes. By adjusting the length of the Nichrome, we harmonized the resistances of these four thermal patches into 11±0.2Ω. These four thermal patches are powered with 7.5V DC through a MOSFET switch module (*ref. IRF540*) and controlled through the PWM servo driver. The temperature of the thermal patch can

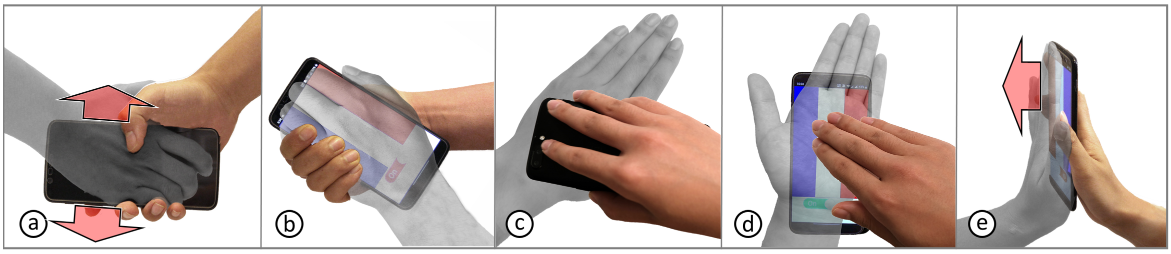

Figure 4.7: Hand-to-hand interactions with *SansTouch*. (a) Handshake. (b) Holding hands. (c) Tapping the back of the hand. (d) Touching the palm. (e) High-five.

change from room temperatures to $45\,°\mathrm{C}$, which is within the heat pain threshold [40].

Visual feedback

In last chapter, I mentioned that adding visual modality on remote touch devices can effectively enhance tactile perception [259, 251]. Hence, we added one layer of addressable RGB LED (*ref. WS2812b*) to generate visual effects with different colors on top of the inflation layer. On the palm patch and the back patch, 4 LEDs are evenly distributed on the surface, while we included 2 LEDs on each of two side patches.

4.3.4 Capturing input parameters with smartphones

We developed a web interface that manages the communications between the smartphone and the wearable hand sleeve of *SansTouch* and controls all the parameters. We developed an Android application to detect the phone movement (with the accelerometer sensor and the device's orientation) and the touch events. By combining these input channels, we can generate a variety of hand-to-hand interactions (as described in Section 4.3.5). To increase the mobility of *SansTouch*, we used an ESP8266 micro controller (*ref. Wemos D1 Mini*) to control the actuators and to communicate with the android application or the web application via Wireless Local Area Network (WLAN) (Figure 4.5). Thanks to the low latency of the WLAN, there is no significant delay between the input and the output, which largely ensures a fluid, synchronous touch interaction.

4.3.5 Application: Mid-air hand-to-hand interactions

We designed five simple hand-to-hand interaction samples to explore the possibilities of using *SansTouch* to mediate touch communications, including handshakes and holding hands that are commonly used yet reduced in the survey's participants' current touch habits, as well as touching palms, tapping the back of the hand, and high-fives (Figure 4.7). After the connection between the smartphone and the controller is established, the touch stimuli can be triggered just by mimicking the hand movement as in real life, only now it is performed mid air while wearing the hand sleeve and holding the smartphone. We considered the Google developer guideline [71] to use the interactions with *SansTouch*: the device coordinate frame, described by the values x, y, and z, is aligned based on the center of the device. The parameters are chosen as suggested in the literature [70, 152] as well as based our preliminary tests. The detailed parameters of these hand interactions as well as the output of each modality are listed in Table 4.1 and Table 4.2.

Table 4.1: The *input* parameters of the five pre-defined hand interactions. We set the parameters for the participants in the study to try them out. Users can easily adjust the parameters through the *SansTouch*'s web interface.

Input hand interaction	Orientation of the phone	Activate movement
Handshake (Figure 4.7a)	y, z axis: horizontally positioned (±15°)	$\lvert a_x \rvert \geq 3.5ms^{-2}$
Holding hand (Figure 4.7b)	Any	3 fingers touching on the left/right side of the screen
Tapping the back of the hand (Figure 4.7c)	z axis: vertically positioned (±15°)	$\lvert a_z \rvert \geq 3.5ms^{-2}$
Touching palm (Figure 4.7d)	Any	Tapping the middle side of the screen
High-five (Figure 4.7e)	y axis: vertically positioned (±15°)	$\lvert a_z \rvert \geq 3.5ms^{-2}$

Table 4.2: The *output* parameters of the five pre-defined hand interactions. We set the parameters for the participants in the study to try them out. Users can easily adjust the parameters through the *SansTouch*'s web interface.

Hand interaction	Activated area(s)	Activated duration (ms)	Intensity of inflation and light	Temperature increase (°C)
Handshake	Palm and two side: (Figure 4.6: (1)(2)(4))	2500	60%	10
Holding hand	Palm and two side: (Figure 4.6: (1)(2)(4))	4000	50%	10
Tapping the back of the hand	Back of the hand: (Figure 4.6: (3))	1000	50%	10
Touching palm	Palm: (Figure 4.6: (1))	1000	50%	10
High-five	Palm: (Figure 4.6: (1))	1000	100%	10

4.4 Study 2: Qualitative usability testing on social touch with *SansTouch*

Our next goal was to examine whether a mediated touch device like *SansTouch* can enhance social experience between users with semi-intimate relationships during a face-to-face communication while social distancing. This goal is complementary to the evaluations of touch devices in the literature that mainly focused on remote communications between users with intimate relationships. Our primary focuses were 1) to assess *qualitatively* how the participants experienced the unique condition of exchanging mediated touch for greetings during a face-to-face communication in an ecologically-valid setting; 2) to evaluate user perceptions of *SansTouch*'s touch stimuli; and 3) to elicit user feedback regarding the generalizability aspects of *SansTouch*, including the use of *SansTouch* for other types of relationships and for remote communications. In order to do so, we conducted a qualitative usability test in which the participants experienced exchanging greetings with and without *SansTouch*.

4.4.1 Participants & Setups

Twelve participants took part in our study (3 women, 9 men, aged 20-37 years old, median age 28.3 years old), all worked/studied in the university. We followed the health protocol advised by WHO [161]. The participants sat in a wide meeting room with opened windows to ensure air circulation. We maintained a two-meter distance with an exception when the interviewer was setting up the *SansTouch* prototype on the participant's hand. We disinfected the surface of *SansTouch*, the table, and the smartphone before starting each study session. Everyone involved in the study cleaned their hands and wore a mask upon entering the room.

4.4.2 Method

A study session consisted of three parts: an introductory interview; a scenario-based interaction; and an open-ended self exploration. We audio recorded the whole session, and video-recorded the hand interactions during the scenario-based interaction and the self exploration parts.

Introductory interview

We asked the participants to describe 1) their social touch habits before and after the lockdown; 2) the forms of social touch they reduced; and 3) social touch breakdown stories. The goal was to remind them of their experience related to social touch breakdowns with social distancing. We finished this part by setting up the *SansTouch* prototype on the participant's right hand and introducing how to exchange a mediated handshake with *SansTouch*. We let them familiarize with it for a few minutes, prompting them to think aloud. This part took around 15 minutes to complete.

Scenario-based interaction

Our goal was to compare the participant's experience when having a conversation in which the touch was 1) *mediated* (i.e., handshakes with *SansTouch*); and 2) *substituted* with other forms (i.e., waving hands, without *SansTouch*). Note that the context of the conversations is key in building a more concrete perception and experience. Therefore, we carefully chose a use case scenario that involved exchanging greetings with colleagues face to face, because 1) the interaction among colleagues in a meeting room was ecologically valid; and 2) our survey revealed more social

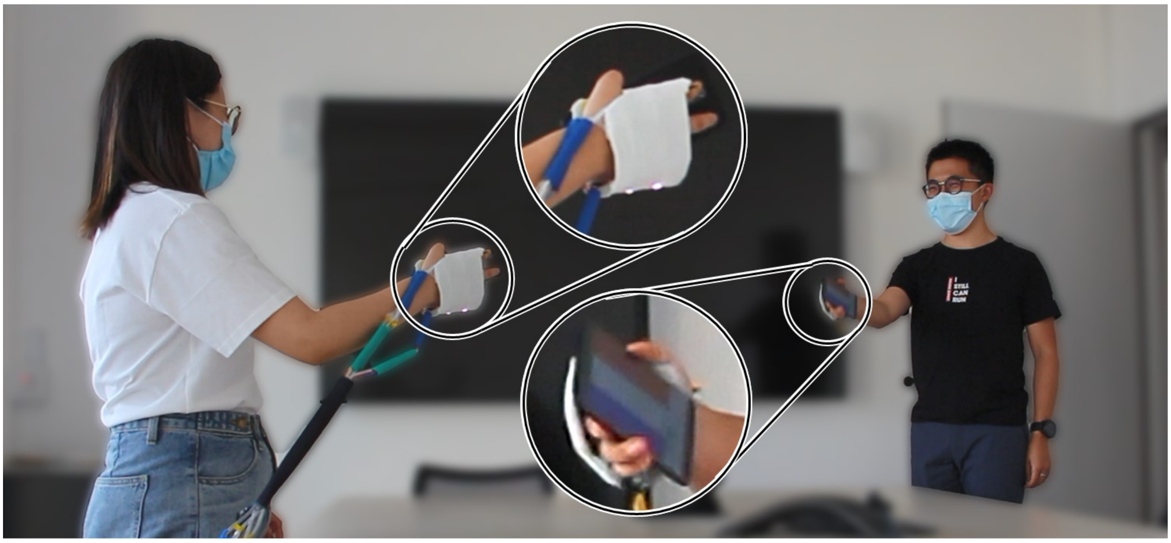

Figure 4.8: Scenario-based interaction with *SansTouch*. The goal was to compare the participant's experience when having a conversation in which the touch was 1) *mediated* (i.e., handshakes with *SansTouch*); and 2) *substituted* with other forms (i.e., waving hands, without *SansTouch*).

touch breakdowns for semi-intimate relationships like colleagues, with handshakes being the most reduced. We substituted handshakes with waving hands since it was frequently mentioned in our survey results. We excluded other substitutions that still involved physical touch (e.g., bumping elbows) since we wanted to maintain the two-meter distance between people.

The use case scenario we introduced to the participants was: "*You are attending the first group meeting after the summer holiday. Two of your colleagues, [*colleague-1*] and [*colleague-2*], are also attending the meeting. You have not met for a few months due to the summer holiday, so they would be happy to see you in person. They will enter the room and say hi. One of them also has the device as you do.*" To increase the ecological validity, we ran the study during the first two weeks after the university's official summer holiday. Three experimenters were involved: an interviewer leading the whole study session, and two (one man, one woman) posing as *colleague-1* and *colleague-2*.

We used two *SansTouch*s, one for the participant, one for the experimenter[5]. During the experiment, one colleague (experimenter) performed mediated handshake with *SansTouch* to greet the participants, the other opted for waving hands. A OnePlus 5T smartphone was provided to the participants as the input device. The order of the two conditions was counter balanced along with the male and female experimenters, in order to avoid gender bias. We did not specifically brief the participants

[5]The *SansTouch*'s sleeve worn by the experimenters was not inflated – they wore it only to make the participants believed that the experimenters felt the touch sensation.

which condition would start first. The experimenters and the participants mainly had casual conversations such as *"How are you?"*, *"How was your holiday?"*, or *"How do you feel getting back to work/school after some time?"*. The conversations lasted for 5 minutes in total.

After the conversations, the two experimenters left the room, and the participants were asked to compare their experience, specifically related to which condition made them feel 1) the social interaction was better; 2) it was easier to establish social connections with the colleagues. We also asked their perceptions of each modality of *SansTouch*. The interview took around 15 minutes.

Open-ended self exploration

Finally, we introduced all the five interaction samples we designed with *SansTouch*. We let the participants play around by themselves, prompting them to think aloud. The goal was to encourage them sharing how they would use it in their daily touch communication. We also asked about their perception of each interaction in terms of how realistic it was to the real touch, to probe on the generalizability of the *SansTouch*'s interactions for other types of relationships and communications. For each interaction, we asked them to fill in a short Likert-scale question on how similar it was to the real touch (1="Completely different" to 5="Identical"). This part took around 15 minutes.

4.4.3 Data analysis

After transcribing the audio recording, we used thematic analysis to identify recurring themes [33]. We started with a round of open coding, where two authors tagged interesting and meaningful elements, built the codebook, then grouped the codes into categories. Finally, all authors iterated on the key themes during multiple meetings.

4.5 Key results from the study

4.5.1 *SansTouch* enhanced interpersonal connections in face-to-face communication

The participants reported social touch breakdowns that were largely consistent with those in the survey, including changes in their social touch habits and frustrations on having to re-establish their social touch habits. As such, almost all participants (11/12) preferred the mediated condition (i.e., greeting with *SansTouch*) during the face-to-face conversation, as they felt more positive interpersonal connections. Only one participant (P1) claimed no preference between the two conditions. Half of the participants (6/12) specifically mentioned that they felt a stronger connection with the person they were talking to after the handshake using *SansTouch*.

SansTouch encouraged behaviour transfer from physical to mediated touch

Like during a real handshake, the majority of the participants (9/12) reported that they maintained eye contacts during the handshake with *SansTouch*, which led them feel that the mediated handshake was real and more engaging than just waving. P9 explained why: "*The waving is friendly. But to establish the connection, the [touch] contact is also important, it makes people look at you, and you look at the people.*" Although some participants (3/12) felt that the physical distance made handshaking with *SansTouch* felt different from a real handshake, three participants still reported that using *SansTouch* made them feel as if the physical and the social distance were reduced. P12 explained that the mediated handshake made him unconsciously move his body closer to the experimenter: "*With the device I feel less distance, maybe because I came closer [towards the person] to handshake*". P4 also felt that *SansTouch* "*established the proximity between people*". Furthermore, P8 and P11 specifically stood up while shaking hands, but they stayed seated while waving. These results suggested that even with a physical distance, some behaviours from the physical touch (i.e., the real handshake) and its benefits for interpersonal communications were transferred into mediated touch, including enhancing social bonding between people [62].

Synchronous interaction helped building the common ground in communication

The interaction design of *SansTouch* requires the two parties mimicking the hand position while moving their hands synchronously to trigger the handshake stimuli. In the study, we observed that the majority (8/12) of the participants followed the movement of the experimenter. The participants moved their hand right after they observed experimenter's hand movement, while keeping eye contact during the whole interaction. The participants reported that they quickly understood the common ground of the communication just by seeing how the experimenters moved they hand as they reached out for a mediated handshake. This suggested that the participants can use *SansTouch* with minimum learning efforts.

Additionally, the behavioural alignment made the participants felt they were closer with the other person, as explained by P10, "*With the device I feel closer to the person, because everything is synchronized, so I feel [we were] more on the similar thoughts.*" P11 also highlighted that the interaction with *SansTouch* affected his perception of how the other person would feel: "*[The colleague] was also wearing the device, so I think she would feel what I felt. That made me feel a better connection with her.*" This highlights the importance of synchronicity between the movements of both users and the triggered touch stimuli.

4.5.2 User perceptions of *SansTouch*

Holding hands and handshakes most favorite, high-fives least

In the scenario-based interaction part, almost all participants (11/12) reported a strong preference on using *SansTouch* to greet as opposed to waving hands. Different descriptions were used to express their positive feelings using *SansTouch*: amazing (P7), fun (P9), natural (P1), surprising (P3, P8), unexpected and intense (P8). In particular, P5 reported "*I'm actually feeling that she is shaking hands with me.*"

From the open-ended self exploration part, we found that among the five touch interactions, 10 out of 12 participants mentioned that they like the mediated holding hands with *SansTouch* the most, while the other two participants preferred the mediated handshake. The holding-hand sensation was described as comfortable, pleasant (P1, P3) and enjoyable (P2). P3 said, "*I really have the feeling that I am holding someone's hand. The sensation really lasts. I really establish a contact with the device [as if it were another person's hand].*" The mediated high-five (9/12 participants) and patting the back of the hand (3/12) with *SansTouch* were their least favorite, mainly because 1) the delay and speed of the mediated high five (7/9 participants), as P8 mentioned "*there is no pain, there is no sound*"; 2) they rarely performed the interactions in real life (2/12). This is in line with the results from the Likert-scale questions related to how realistic each interaction was: mean/median 4.3/4.5 and 4.3/4 for holding hands and handshakes; 3.9/3 for high-five and touching palm; and 3.7/3 for patting the back of the hand. This highlights the importance of a touch device to generate not only a realistic touch sensation, but also other properties like its sound.

Warm pressure was key, visual feedback not so much

The majority of participants (10/12) perceived inflation as the most defining aspect of the interaction. P7 specifically said that the pressure was equally distributed, while P8 highlighted the inflation induced an intense sensation that was essential for mimicking handshakes. Almost half of the participants (5/12) specifically appreciated the warm sensation from the thermal layer. P9 highlighted that the combination of the inflation and the heat "*recreated the feeling of real handshakes*". However, P5 and P6 mentioned that they did not perceive the warmth during the conversation, as they mostly focused on maintaining eye contact. Besides, three participants mentioned using the polyimide tape as the main material of thermal layer reduces the skin-like perception, as P7 explained:"*The material feels not like real hands*". Since the participants were focusing on the conversation and maintaining eye contacts, none of them paid attention to the visual feedback (i.e., LED) while exchanging mediated handshakes. Only P2 and P5 noticed something was blinking, but then it was quickly ignored. P2 actually felt adding visual feedback made mediated touch sensation even less similar to the real touch. On the other hand, some participants mentioned that the visual feedback could be interesting for other type of interactions, for example P5 thought that the visual feedback emphasized the duration of the holding-hand interaction and enhanced the engagement.

Holding a smartphone enhanced embodiment and usability

We observed that holding a smartphone was helpful in enhancing the embodiment of the hand interaction. Some participants (4/12) described that for the mediated holding hands and handshakes, they felt like the smartphone was the hand of the other person, for example P3 said "*I really have the impression that I was holding the hand.*" P10 explained, "*For real handshakes, there is a constrain, [so] I cannot move my hand and fingers any other way [but handshaking] while the other person is grabbing my hand. [If it was only] with the device, this constrain is kind of missing. But the phone here also acts like a constrain, so it works.*" P10 compared the smartphone to a hand while handshaking in real life: he thought that the smartphone provided a constrain on how he should position his fingers and hand during the mediated handshake, in a similar way the other person's hand constrained his hand when he was gripping it in a real handshake. Additionally, P4 confirmed the accessibility of smartphone as a touch communication medium: "*People already have their phones in their hand all day, so shaking the phone [to do the mediated handshake] can be learnt very easily.*" Related to usability, two participants were worried about throwing the phone while doing the mediated high-five. This suggested that the interaction design should also consider the practicality of the interaction (e.g., the device's safety).

4.5.3 *SansTouch* in other context

Beyond conventional social touch

The participants expressed interests in personalizing mediated touch interactions. The examples given by the participants varied from wanting to customize the touch input parameters to creating new interactions such as "*secret handshakes with lights*" (P3). This suggested that *SansTouch* may not only serve as a replacement of conventional social touch, but also support the invention of new touch practices. Further, P10 mentioned:"*This device is like a proxy, you don't really touch the person. Because there is no rule for these new devices, I can do the forms of touch that social norms usually do not allow, like touch or squeezing the hand of your boss.*" This suggested that by touching through *SansTouch* as a communication medium, the original meaning of the touch interaction might also evolve, which consequently might increase the expressivity of a form of social touch. *SansTouch* may also provide an alternative for people who do not like direct physical contacts, as P4 explained: "*I have very moist hands. A real handshake is not comfortable for me and for others, so I would use more virtual handshakes than the real ones.*"

SansTouch for remote communications and different social relationships

In the context of face-to-face communications, half of the participants mentioned that they wanted to use *SansTouch* with friends and colleagues. This was mainly because they did not experience significant social touch breakdowns for intimate relationships while social distancing – a result that echoed our survey's result. P8 explained: "*If I want to do something with intimate people, I won't care [about the social distancing]*". That said, some participants (5/12) wanted to use *SansTouch* in remote communications with their partner and families. For example, P1 mentioned:"*It would be good to hold [my partner's] hand and being held at the same time when I'm in my office.*" Similarly, P11 said, "*I want to hold my grandma's hand remotely when she is crossing the road to make her feel safe.*" This result suggests that *SansTouch* can be used for remote communications with other types of relationships. Finally, they also envisioned other contexts of use with *SansTouch*, including touching isolated people in hospitals (P3), sending a playful punishment gesture (P5), Virtual Reality games (P9), tactile notifications (P11), and high-fives with athletes in a sport game (P11).

4.6 Discussion and Design Implications

Our participants from both studies reported frustrations overcoming social touch breakdowns due to social distancing during the COVID-19 pandemic. Adopting new forms of touch (e.g., bumping elbow) was challenging, as it often involved awkward situation, requiring the participants to explicitly negotiate on the communication ritual. As such, the participants in our study saw *SansTouch* as a preferable alternative to replace the conventional social touch in face-to-face communications. They also perceived the touch sensation of *SansTouch* realistic (i.e., similar to the real touch) and pleasant. This suggested that *SansTouch* can generate realistic touch sensations without inducing uncanny valley issues [152, 216] or machine-like touch sensations [60]. Moreover, while *SansTouch* hand-to-hand interactions are initially designed for co-located face-to-face communication, they also can directly be used in remote communication.

While past research mostly focused on remote touch communications, our work highlights the needs to expand the design space of touch devices, by considering the device to be used in both contexts, especially because a touch interaction designed for remote communication might not be effective for face-to-face interaction, due to different reasons, as follow.

4.6.1 Trade-off of combining different modalities

When designing *SansTouch*, we followed design guidelines on touch devices from past studies focusing on remote touch communications, including combining different modalities such as touch and visual feedback [251, 259, 213]. Nevertheless, when evaluated in face-to-face communications, we found that the visual feedback was largely ignored since their attention was highly directed on the eyes and the facial expression of the other person. Thus, in the context of face-to-face communication, adding visual feedback to touch stimuli may interfere with the verbal communication, as it often relies on the visual modality as well. On the other hand, the comments related to missing high-five's sound point to a possibility of including audio feedback to touch communication tools. Designers should consider the balance between modalities and practicality in different mobility contexts.

4.6.2 Synchronicity in face-to-face communication is a key

As highlighted in the results, synchronicity between the initiator's hand movement, the receiver's hand movement, and the touch stimuli generated by the touch device is critical for building a positive shared, bi-directional experience. As such, the interactions should be intuitive and easy to remember, to avoid delays and reduce the efforts for grounding the touch communication. This is especially critical if the touch communication tool will be used face-to-face in public spaces – users should be able to spontaneously start up the communication. On the other hand, delays and asynchronous interactions are more suitable for remote communications, perhaps even more desirable, for example if the users live in different time zones. To accommodate both contexts, designers should allow users to customize and personalize the touch interactions. Allowing customization would also help balancing between different modalities used in the touch interactions under different mobility contexts.

4.6.3 Accessibility and social acceptability of the touch communication medium

For face-to-face communications, designers should take into account the social acceptability of the touch medium when it is being used within relationships with different levels of intimacy or in public when strangers can see the interaction. The participants appreciated our design choice of combining a wearable device and a smartphone: the wearable was always there and the smartphone embodied the other person's hand. They also highlighted the accessibility and the social acceptance of grabbing smartphones in public.

While we only used the smartphone to enhance the sensation of touching another person's hand and to capture touch input, ideally, the smartphone should also have the capacity to independently generate touch feedback. Current smartphones can only generate limited touch signals, mostly in the form of vibrations, which tend not to induce human-touch-like sensations [164]. Miniaturizing other types of actuators, or using substitutes such as tactile illusions [88] for generating more human-like touch stimuli is an interesting path for future research. Another alternative solution is to develop extensions that can be easily embedded (e.g.,

[164]) or plugged into an existing smartphone (e.g., [216, 218]). Considering how widespread smartphones are and the potential demand for mobile mediated touch communication, this can be a valuable direction towards developing a new type of mobile devices, and this will be discussed in the next Chapter.

4.7 Conclusion

In this chapter, we presented *SansTouch*, a mediated touch communication tool that combines a wearable hand sleeve and a smartphone. We presented our exploration of the pneumatic actuation design, multimodality in touch stimuli, as well as the implementation of the device. Furthermore, based on the context of COVID-19 pandemic, we provide a deeper understanding on social touch breakdowns with physical distancing and the challenges in establishing new touch habits. By combining these understanding with *SansTouch* design, we discussed the different design factors that designers and researchers should take into account when adapting remote touch communication tools in the context of face-to-face touch communication, thus pointing out the future design directions for touch communication tools.

This chapter is a response to RESEARCH QUESTION 2: *How can we generate more human-like tactile stimulation to improve multimodal touch interaction?* From the insight of the evaluation, we can see that the perception of this pneumatic actuation was appreciated by almost all the participants, and the similarity between the mediated touch and the real touch has been frequently mentioned. Furthermore, previous research mainly investigates the touch perception of mediated touch devices in controlled experiments in which the context is often ignored. Despite positive feedback on the perception, it is still unclear what role mediated touch device plays in real communication. In *SansTouch* evaluation, we can see clearly that the human-like feature of the *SansTouch* makes it naturally integrate into face-to-face communication without disturbing the conversation, and the *SansTouch* indeed worked as an enhancement of interpersonal connections in face-to-face communication. This point is especially important in affective touch communication, as mediated touch stimuli should never override the verbal communication by recruiting too much attention to perceiving and interpreting the touch.

Furthermore, our investigation into the use of visual and thermal modality yields answers to RESEARCH QUESTION 1(A): *Can we use multimodality stimuli to improve the emotional perception of current social touch technology?* By combining different modalities in mediated touch stimuli, *SansTouch* provided a human-like touch sensation to the participants. However, we also found out that the adding of more modalities is not always an efficient way of improving touch communication. Even though we discussed in Chapter 3 the enhancement of visual modality to touch communication, the additional visual layer in *SansTouch* poorly improved affective communication. Thus, this chapter indicates that to answer RESEARCH QUESTION 1(A), we should not ignore the importance of the *context* factor when designing mediated touch device.

Our work points to future design directions for touch communication tools, highlighting the different design factors that designers and researchers should take into account when adapting remote touch communication tools in the context of face-to-face touch communication. We see combining touch devices with smartphones as a concrete step in enabling mediated touch communications that users can access anytime, anywhere, considering different social relationships. It also raises our interest in how to integrate the affective touch device with smartphones in more general contexts and increase the usability of the touch device. I will further discuss this point in the next chapter.

5

Go Beyond Social Touch: Improving Generalizability and the I/O Capability of Mediated Multimodal Touch Device

In previous chapters, I presented my approach to improving the tactile perception of multimodality stimuli. The multimodal touch stimuli enhanced interpersonal connections in face-to-face communication, and the human-like perception was well appreciated by the participants. However, I encountered a problem that many wearable social touch devices suffer from: these devices are designed for a specific purpose (e.g. *SansTouch* is designed for enabling hand-to-hand interaction in face-to-face communication), while extra efforts are required to use these devices in real life, which diminishes the user's willingness to communicate with these devices.

According to the Technology Acceptance Model (Figure 5.1) by Davis et al. [41, 42], the user's attitude towards using a certain technology depends on two factors: *perceived usefulness* and *perceived ease of use*. *Perceived usefulness* is defined as the prospective user's subjective probability that using a specific application system will increase his or her job performance or life experience within an organizational context. *Perceived ease of use* refers to the degree to which the prospective user expects the target system to be free of effort. *Perceived usefulness* is even more important as it can directly influence the final intention to use the technology. Thus, to improve user acceptance of mediated touch device, we need to consider how to increase the perceived usefulness of the device, as well as decreasing the difficulties of using it.

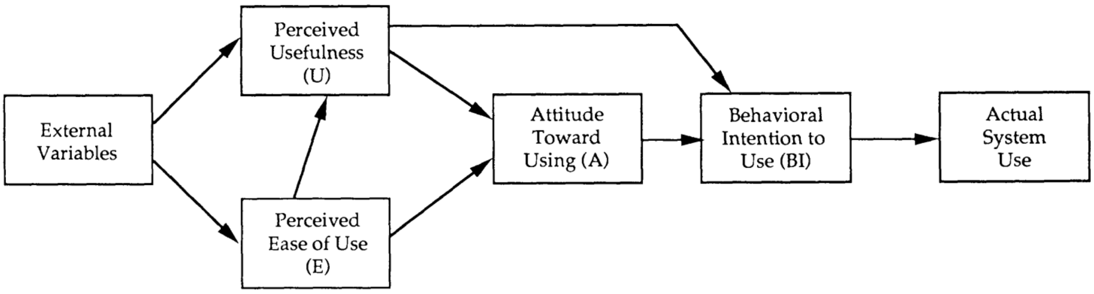

Figure 5.1: Technology Acceptance Model (TAM) by Davis et al.(1989)

Considering this Technology Acceptance Model and the problem we encountered, the research question I want to address in this chapter is: is it possible to incorporate mediated touch interactions into more general contexts and use multimodality touch devices in our everyday communication and interaction? To this end, I present one possible approach: combining human-like multimodality touch actuation with smartphone interaction. More specifically, we[1] designed *In-Flat*, an inflatable phone case that can provide both human-like touch sensations and a variety of pressure inputs. As the smartphone is the most frequently used digital device in our daily lives, we assume that combining mediated touch interaction with mobile phone can increase the *perceived ease of use* of users, as they don't need to carry additional devices. And the multimodality property of smartphone can also improve tactile perception, as we discussed in Chapter 3. Furthermore, the rich input and output (I/O) capability of the tactile phone case can in return enhance mobile interaction and increase the *perceived usefulness* of the device.

The objective of this chapter is to answer RESEARCH QUESTION 3 of this thesis: *How can we incorporate multimodal touch interactions into our everyday communication and interaction?* In this chapter, I first present our motivation and the background of mediated touch input and output on smartphone. Then I introduce the design and implementation of *In-Flat*, along with our exploration of the fabrication approach

[1]Main portion of this section has been submitted and accepted at the 2022 International Conference on Advanced Visual Interfaces (AVI'22). Thus, any use of "we" in this section refers to the authors of this work: Zhuoming Zhang, Jessalyn Alvina, Françoise Détienne and Eric Lecolinet.

of highly transparent and stretchable overlays for smartphones, which enables in-place coupling between visual objects displayed on the smartphone and touch I/O interactions. To illustrate how we can incorporate *In-Flat* in our everyday communication and interaction, I present several potential applications and use cases of *In-Flat* into our daily mobile interaction and communication. To assess if users can perform pressure input with *In-Flat*, as well as the perception of the dynamic visual+touch output, we designed a controlled experiment and an open-ended exploration with *In-Flat*. Based on the insights from the study, I discuss how we should incorporate multimodal touch interactions into our everyday communication and interaction.

5.1 Background

As mentioned, by combining human-like multimodality touch actuation with smartphone interaction, we may improve our touch communication and mobile interaction in three ways: 1) The mobility of smartphone can increase *Perceived ease of use* of the device; 2) the powerful multimodal output of smartphone, especially the high definition screen, can improve the tactile perception; and 3) the I/O capability of mediated touch device can in return enhance mobile interaction. In this section, we focus on past research that specifically explored these three aspects.

5.1.1 Generating touch feedback on smartphone

One important technical challenge when building touch devices is choosing the right actuators. Due to the high mobility requirement, the sophisticated mechanical structures that have been used in desktop tactile devices such as Phantom [170] may not be suitable for smartphones. Most smartphones already include vibration motors to generate various tactile feedback [195] thanks to their compact size and low energy consumption [176]. Furthermore, previous works investigated the implementation of extra vibration motors on the smartphone to increase the expressivity of the smartphone. For example, Sahami et al. [191] implemented six addition vibration motors on the smartphone to generate rich tactile notifications. Similarly, Brewster et al. [19] used a vibration motor on the back of the phone to generate tactile feedback while typing. This functionality has now been widely implemented in smartphones using the internal vibration motor. Past works have also explored the possibility of embedding vibrotactile grids on the back of the smartphone to enable rich vibrotactile feedback for GUI interactions (e.g., [256]) or vibrotactile notifications (e.g., [5]). Furthermore, vibration motors are also implemented on smartphone for communication purposes. Multi-moji device [251] implemented a vibration motor on the back of smartphone. Using along with thermal and visual feedback, a large range of emotions can be conveyed with this device. Similarly, KUSUGURI device [60] generates tickling perception with two vibration motors. By showing the animated finger movement on the screen, it can generate the illusion and perception of being tickled in the palm.

However, as discussed in Chapter 2 and Chapter 4, the vibrotactile stimuli has been shown to be insufficient to generate expressive and realistic social touch [60]. Thus, other actuators have also been implemented on mobile devices. Maiero et al. [136] have explored the use of actuated pins on the back of the smartphone to provide tactile guidance on visual objects displayed on the screen, in order to improve user performance for selection tasks on small objects (Figure 5.2(a)). Jang et al. [110] used an array of actuated pins on the edge of the smartphone (Figure 5.2(b)). Aside from using it as an output device to enable tangible notifications and tactile guidance, the device can also be used as an input channel by creating buttons or sliders with the pins. However, even though the actuated pins can enhance mobile interaction with different haptic feedback, the touch perception of the pins has low similarity to human touch.

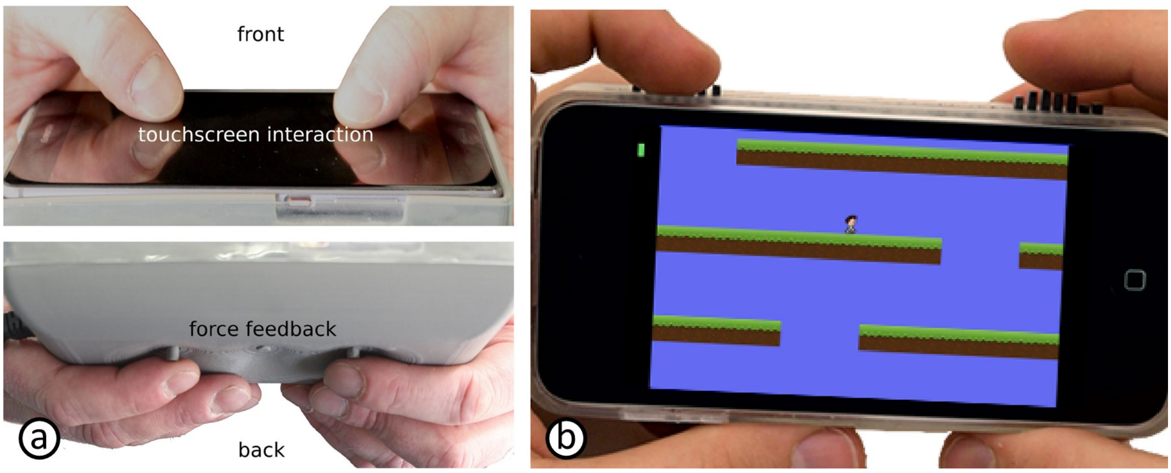

Figure 5.2: Two examples of tactile device that use actuated pins. (a)Maiero et al. used actuated pins on the back of the smartphone to provide tactile guidance on visual objects displayed on the screen [136]. (b)Jang et al. placed actuated pins on the edge of the smartphone to enable tangible notifications and tactile guidance [110].

In Chapter 4, we discussed the use of pneumatic actuation in mediated touch devices to generate human-like touch stimuli. Past works also implemented pneumatic actuation in mobile devices. For example, in POKE [164], two inflatable airbags are attached to the front and back of the smartphone. The front airbag is used as the touch output and generate a poke on the face while phone calling; the back airbag is used as an input which records and sends the touch signal to the other device. Similar to the *SansTouch*, the inflatable airbag generates human-like perception and supports well the communication. Thus, based on past work, our exploration of human-like touch stimuli, as well as insights from *SansTouch*, we implement pneumatic actuation on the smartphone.

5.1.2 Augmenting visual display with touch interactions

As previously stated, the second advantage of incorporating mediated touch stimuli into the smartphone case is that the smartphone's high definition visual display can improve touch interaction. For example, even though the vibration motor used in the KUSUGURI device [60] has been shown not like a human touch in their study, the addition of animated finger movement on the screen of a smartphone improved the perception and created the illusion of being tickled on the palm.

On the other hand, the powerful haptic output capability of a mediated touch device can in return enhance visual display. Augmenting touchscreens with touch feedback has been found to increase interaction speed, reduce operating errors, and minimize visual and cognitive load, for example when scrolling [174], typing [20, 97], and interacting with virtual buttons [256], due to enhanced spatial and temporal perceptions. Beyond enhancing GUI interactions, touch feedback has also been used to generate pressure sensations on graphical objects or images [136] (Figure 5.2(a)) and to enhance interpersonal mobile communications. For example, accompanying emojis with vibrotactile patterns may enhance the emotional perceptions of emojis [251] (Figure 2.20). These tactile systems often spatially decouple the touch feedback from the virtual objects displayed on the screen to avoid occlusions and enable full access to the touchscreen capacities.

Furthermore, past works have highlighted the benefits of spatially coupling visual and tactile feedback [83, 112, 259], including generating direct physical feel to the virtual objects. For example, the dynamic physical buttons in [83] included visual displays via rear projections, forming a coupling between touch I/O and visual display, which not only enhanced the visual perception of the buttons with physical shapes (i.e., making them easier to find), but also provide bi-directional pressure feedback as the users physically interact with the buttons. Sahoo et al. also used projectors on an elastic fabric surface to form a tabletop display with touch I/O capabilities [192]. However, using projectors to generate the visual display may limit the mobility aspect of the touch device.

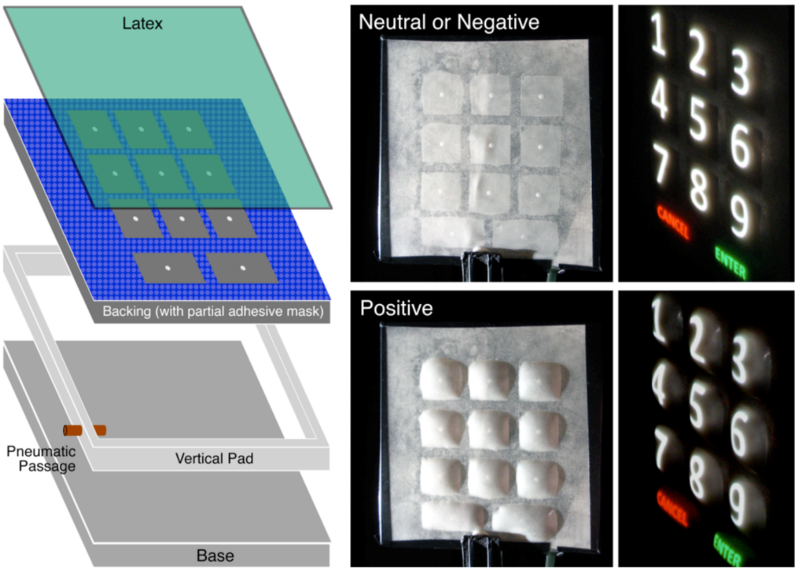

Figure 5.3: Harrison et al. placed inflatable buttons over visual displays and formed a coupling between touch I/O and visual display. For example, when the tactile layer was inflated, it provide additional tangible affordance to the keyboard on the screen [83].

Instead of projectors, *In-Flat* uses the smartphone's screen as the visual display. Few papers explored this approach and we tried to address their limitations: [142] uses a transparent gel overlay that turns opaque when activated, thus occluding the visual cues; [188] uses transparent silicon, but only with limited shapes and size (i.e., small buttons).

5.1.3 Capturing touch input gestures

The third advantage of implementing pneumatic actuation to the smartphone case is that it enables additional force input with a deformable interface, and thus expands the input capability of the flat and rigid screen of the smartphone. Force input (i.e., pressure) is a powerful alternative to mobile interactions as it is space-efficient: it only requires a finger and fingertip-sized interactive surfaces [37, 58]. Past works on force input have shown the benefits of force input, including supporting rich and more efficient GUI interactions such as picking values from a long ordered list [37] or selecting parametric commands [20]. Force input captured with

Force Sensing Resistor (FSR) enables users choose up to ten items with their fingers at 85% accuracy with continuous visual feedback [252]. Users can control a menu of ten items with 89% accuracy when a FSR is embedded on the bezel of a tablet [141], but only up to five items when the sensor was embedded on the back of a smartphone [36]. Heo and Lee embedded several FSRs on the back of a smartphone to enable force gesture inputs like slides or drags [91]. In this case, the gesture recognition process considers the combination of several touch dimensions, including spatial movements, pressure levels, and the change of pressure levels over time.

Smartphones like Apple's iPhones 6s or Huawei's Mate S also include embedded force-input sensors on the touchscreens. With Apple's iPhone 6s, users can customize a preference of light, medium, or firm press on the iPhone's screen with a pressure ranging from 0 to 3.3 Newtons [9, 120, 10]. Some smartphones that do not embed pressure sensors can capture simulated force input values by calculating the size of the contact area between the screen and the fingertip. Nevertheless, applying pressures on a flat, rigid surface limits the pressure sensation and the perception of complicity, as the users can hardly feel the surface bents according to the pressure [58].

Alternatively, silicons can also be used to capture force input, as they can offer a high level of complicity [58, 83]. Fruchard et al. [58] conducted a study to evaluate force input performance on hard, medium, and soft materials for controlling visual objects. The input was captured with a FSR400 pressure sensor embedded on a silicon block. Their results suggested that controlling high-pressure inputs on soft surfaces (i.e., high complicity) takes more time and is more prone to errors compared to on hard surfaces, but the participants found applying pressure on soft surfaces was more comfortable. Pressure input can also be captured through pneumatic actuations and air pressure sensors, for example in the form of dynamic physical buttons [83, 232] or inflatable silicon bubbles [164, 68]. They highlighted the benefits of using inflatable silicons with air pressure sensors as a touch input device: supporting continuous pressure input with controllable levels of complicity (i.e., how stiff or soft the material feels when pressured) [83]. A longitudinal study on the use of inflatable silicons as a communication medium showed that users can create personalized touch patterns using the silicons, combining different pressure levels, the number of press, and temporal aspects [164]. With *In-Flat*, we found that inflatable silicons can be used to capture not only *press* (Figure 5.5) but also *pinch-and-pull* gestures (Figure 5.6), including the combinations with temporal aspects. In contrast to previous evaluation studies that mostly focused on press gestures only [83, 58, 68], we evaluated the performance of the pinch-and-pull gestures, and compared it with the press gestures.

5.2 *In-Flat*: Transparent Smartphone Touch Overlay

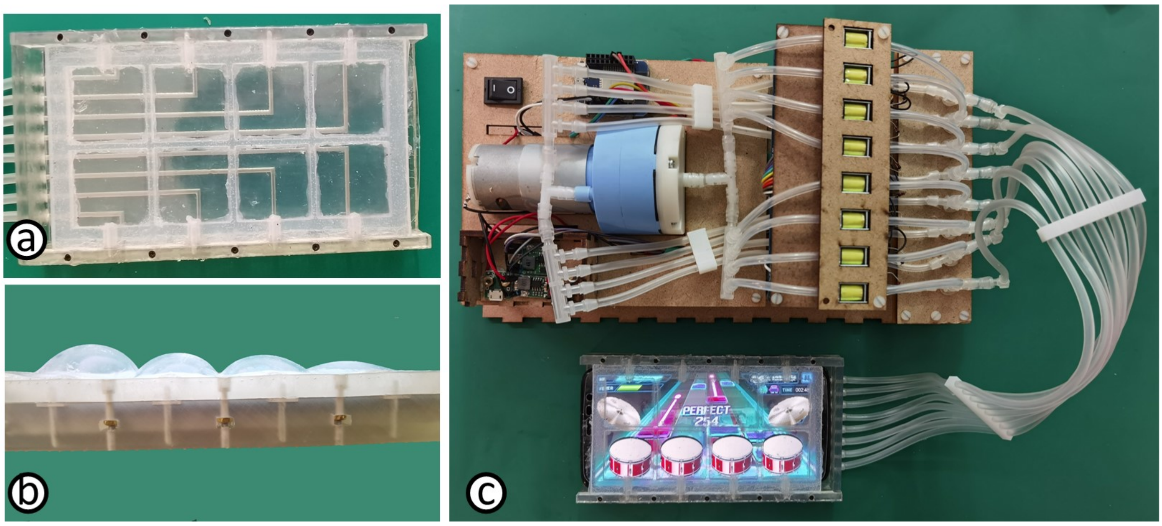

Figure 5.4: *In-Flat* is a touch I/O device in a form of (a) a transparent phone case with (b) a touch I/O overlay made of inflatable silicon. (c)The actuation of *In-Flat*.

In this section, we present the *In-Flat* prototype that we built and its input and output capabilities. *In-Flat* is a novel visual+touch display using inflatable silicon layers in the form of a phone case. *In-Flat* uses transparent and translucent materials to accommodate visual display using the smartphone's screen. The silicon layers can be installed on the back of the smartphone to preserve the screen's touch input and visual output capabilities; or on top of the smartphone's screen (as an overlay) to enhance the visual output displayed on the screen with in-place pressure input/output capabilities. A silicon layer consists of one or more airbags (e.g., 2x4 grid as in Figure 5.4(a)). Each airbag can capture continuous pressure input independently. As such, a silicon layer with multiple airbags can enable multi-finger pressure interactions. Each airbag can also be inflated with different amount of air (Figure 5.4(b)), enabling dynamic controls over the complicity levels of the surface. Altogether, it creates a general-purpose visual+touch display with dynamic pressure input/output capabilities on smartphones.

5.2.1 Output

Touch output

As a tangible device, *In-Flat* can provide a skin-like touch sensation to the contacted area. When the user's finger has a direct contact on the surface of *In-Flat*, a pressure is exerted to the airbag and the air inside the touched airbag gets compressed. Thus, the tension of the silicon and the pressure difference between the airbag pressure and atmospheric pressure give a force feedback to user's fingertip. In this way, by controlling the different initial inflation pressure, as well as the force exerted to the airbag, we can control the compliance level of the surface (i.e., how soft or stiff the surface is when pressured), and the users can perceive different sensations accordingly.

3D Visual output

In-Flat can display static 3D visual information by changing the inflation level of the airbags. When the airbag is inflated, the silicon surface will deform according to the amount of air injected into the airbag. Thus, this static deformation can give direct visual feedback (i.e., tangible affordance) to the users. *In-Flat* can also display dynamic 3D visual effects by adjusting the level and the duration of inflation dynamically. Thus, we can create dynamic inflation effects like breathing (slowly inflating and deflating the airbag) or vibrating (inflating to a certain level first, and then switching to a series of inflation and deflation in a high frequency). As the *In-Flat*'s overlay is transparent, the screen of smartphone provides 2D visual output that can be coupled with the 3D visual output of *In-Flat*, forming an in-place visual+touch display.

5.2.2 Input

When an airbag is inflated, the surface of the silicon stretches outwards and enables direct manipulations of the surface. When the user manipulates the inflated airbag by pressing or pulling the silicon surface, the required force to deform the elastic silicon layer has a positive correlation to its deformation and has a negative correlation to the volume change of silicon airbag. Thus, by measuring the air pressure change of the airbag, we can measure different touch forces from users and enable continuous pressure controls.

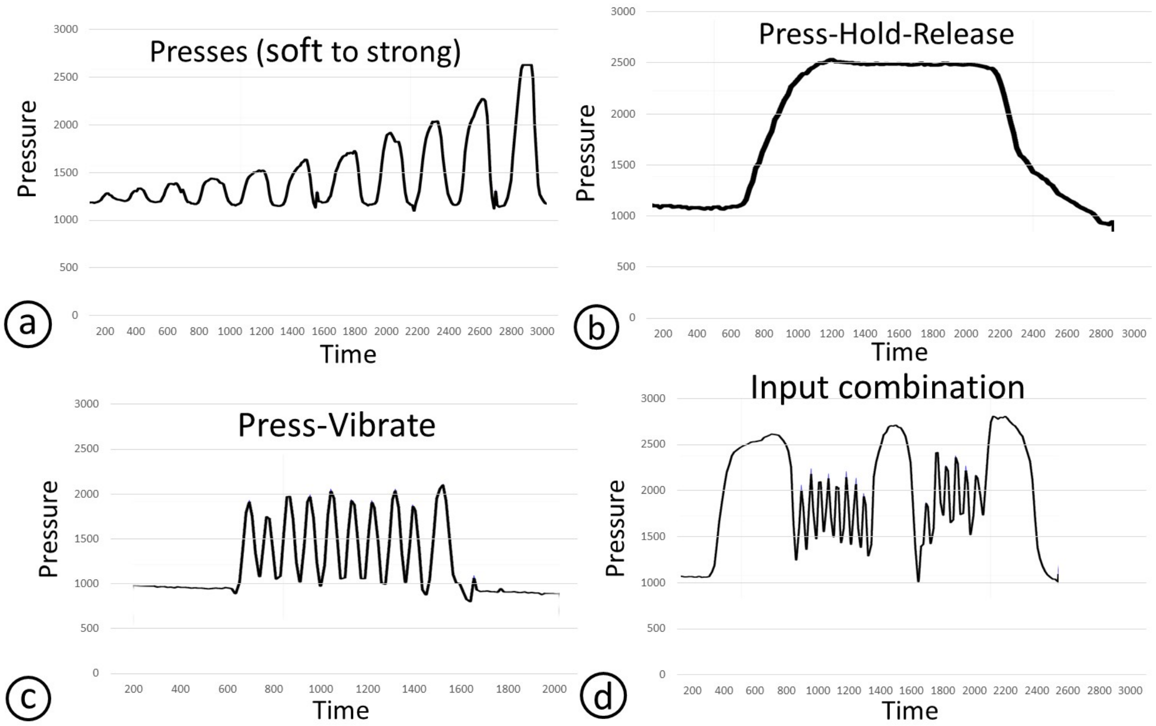

Figure 5.5: Examples of possible *press* touch input gestures. The airbag is inflated to 5kpa, thus the baseline pressure is 1000. (a) Pressing with different levels of pressure. (b) A long press. (c) A high-frequency finger vibration. (d) An example of combining different input methods.

When inflated, the users can *press* the convex silicon surface with different force levels, speed, and duration. When the airbag is pressed, the silicon surface is stretched and the volume of the airbag decreases. As such, we can combine these three dimensions of touch input to generate rich touch gestures on *In-Flat*, as shown in Figure 5.5. Users can also *pinch and pull* the silicon surface with two fingers and have different touch patterns (Figure 5.6).

5.3 Implementation and design choices

In-Flat consists of two parts: 1) the transparent screen overlay + transparent resin case; and 2) the inflation and pressure control. In this section, we describe our design and fabrication approach, as well as the control system.

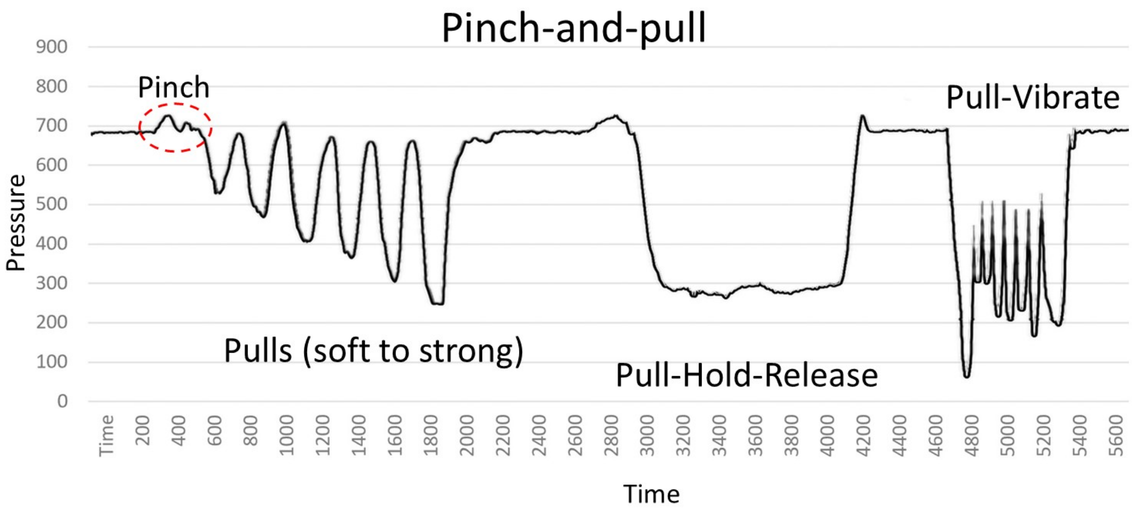

Figure 5.6: Examples of possible *pinch and pull* touch input gestures. The airbag is not inflated, thus the baseline pressure is 500.

5.3.1 Fabrication approach

Soft and transparent overlay

Material choice. As a smartphone screen overlay, *In-Flat* requires materials that have following features: easy-to-get, transparent, stretchable, robust, soft, and skin-contact friendly. Fabricating an overlay that combines all those characteristics remains challenging. Different materials have been implemented to pneumatic systems in previous research, such as latex [164, 83], silicon [260, 254], or PE sheets [212]. Latex is robust and highly stretchable, but the transparency is not high enough to allow the users to see the visual display when placed on top of the screen. PE sheet is highly transparent, but non-elastic. We saw the potential of using silicons, as sili-

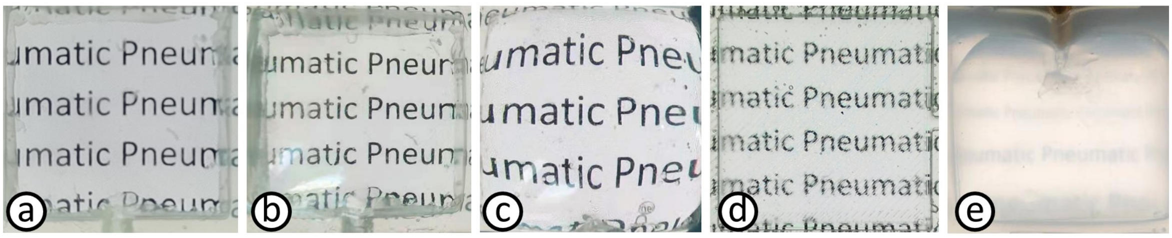

Figure 5.7: Different fabrication methods. (a) Silicon airbag made of *SORTA-Clear 18* and fabricated with tape-covered PLA mold. (b) Silicon airbag inflated with air. (c) Silicon airbag filled with water. (d) Silicon airbag directly fabricated with 3D printed PLA mold. (e) Silicon airbag made of *Ecoflex 20*.

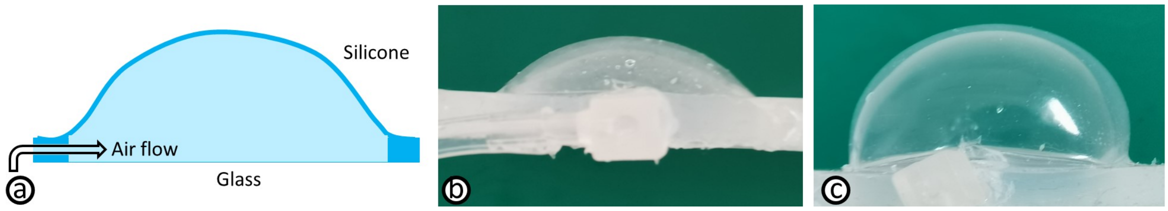

Figure 5.8: Composite structure of the airbags. (a) Two-layer structure. (b) Uni-directional inflation with 1.5mm thick silicone layer. (a) Inflation with 0.8mm thick silicone layer.

cons have been widely used in medical field, industry, and movie modeling, thanks to its stretchability, robust, diversity and bio-capability. Silicons are also often used to induce skin-like sensations [218, 260, 164] in touch devices. Thus, we explored different types of silicon from Smooth-On Inc. to make the inflatable layers. *Ecoflex* series are highly stretchable (elongation at break: 845% [201]) and durable, but the transparency cannot support screen overlay interactions (Figure 5.7e). *SORTA-Clear* series have a high transparency (Figure 5.7a), even though they are not as stretchable (elongation at break: 425% [202]) as *Ecoflex* series, its stretchability can already meet the requirements for screen overlay interaction. Furthermore, it can also provide a skin-like touch sensation to the users.

Each airbag can be considered as a balloon with a specific shape (e.g., square shape). Physicists in stability studies found that modeling the inflation and deflation of a balloon is a complex problem due to the non-monotonic pressure-radius characteristic [149] of such a device. That said, generally speaking, the thicker the silicon layer is and the higher elastic modulus the material has, the higher air pressure it can bear, and the higher air pressure is needed to inflate it. After exploring different materials and thickness of the silicon layer, we chose skin-safe *SORTA-Clear 18* (100% Modulus: 35psi [202]) as the material of the inflatable layer, and set the thickness of the inflation layer to 1.5mm (Figure 5.8b).

Composite structure. When *In-Flat* is placed on the smartphone, the deformation of the airbag should only face outwards. Thus, we designed a two-layer composite structure for the inflatable overlay. First, we created the inflatable silicon layer with a 3D-printed mold. After that, we glued the silicon layer to a screen-protection glass with silicon rubber adhesive (*ref: Sil-Poxy*). As such, when the amount of air changes in the airbag, the deformation only happens on the silicon side (i.e., outwards) (Figure 5.8).

3D-printed mold. The silicon layer is created using a mold, which shapes can be designed differently (e.g., a rectangular grid, keypads with circular or triangular buttons, etc.). The mold for the airbags is printed by a PLA 3D printer. *In-Flat* requires high transparency, but due to the resolution of the 3D printer, the clearness of the silicon layer is highly limited by the smoothness of the mold (Figure 5.7d). To increase the clearness with current laboratory equipment, we pasted a layer of plastic tape to the surface of the printed PLA mold, hence the smoothness of the silicon airbag is largely increased (Figure 5.7a).

Transparent case

As previously mentioned, *In-Flat* can also be placed on the back of the smartphone to enable back-of-device interactions. With this setting, the screen of smartphone is faced towards the rigid phone case. Similar to the selection of silicons, the transparency is crucial to ensure the visibility of the screen. Thus we fabricated a phone case using the commonly-used resin 3D printer, with built-in air channels in the case to avoid tubes (Figure 5.9c). We then applied a thin layer of transparent nitrocellulose coat on the surface of resin case to increase the transparency (Figure 5.9d).

Inflation medium

We can potentially inflate the grid with different fluids. Previous research explored different fluids in inflatable touch devices, including air [164, 83, 260], water [129], and other specialty fluids [228]. *In-Flat* requires a high transparency level and short response times, so we explored the use of water and air to actuate the device. Comparing these two fluids, water can be considered as non-compressible liquid in *In-Flat* pressure range, thus it can have a very quick response speed to both the input and output. However, when the silicon bag was filled with water, the surface of the silicon stretches outwards. Due to the high refractive index of water, the water-silicon bag works as a plano-convex lens which deform the content on the screen (Figure 5.7c). Finally, we chose air as the inflation medium in our design (Figure 5.7b).

5.3.2 Pneumatic control

Actuators

To better control the movement of *In-Flat*'s inflation and to better support accurate pressure input, we implemented a closed-loop inflation/deflation system for each airbag. The 8 airbags of *In-Flat* are inflated with a 12V DC vacuum pump

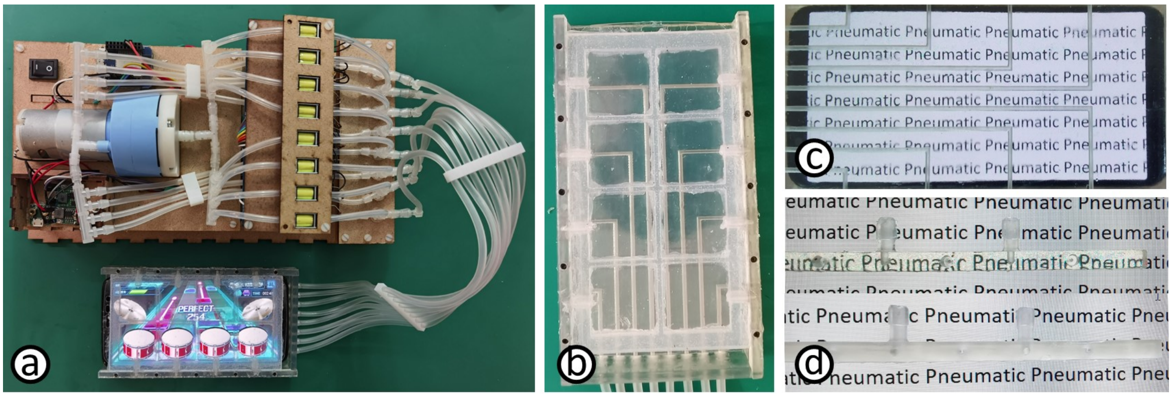

Figure 5.9: *In-Flat*. (a) The structure of *In-Flat*. (b) Highly transparent screen overlay and the highly transparent resin case. (c) Transparent resin case. (d) Comparison between resin after and before nitrocellulose coated.

(*ref: WP36C*). The inlet of the vacuum pump is used for inflations and the outlet of the vacuum pump is used for deflation. By changing the voltage of pump power supply, the speed of inflation can be controlled. After equally distributing the inflation and deflation air flow into 2x8 flows with air distributor and silicon tubes, the 2*8 air flows are controlled by 2x8 DC solenoid valves (*ref: CJAV08-2B05A*) to control the inflation and deflation separately. The solenoid valves are actuated by two 8-channel relay boards and powered separately to isolate the actuators from the control system. A 16-channel PWM motor driver (*ref: PCA9685*) is used to control the states of all the solenoid valves.

Pressure detection and Inflation control

As a continuous input device, the accuracy and speed of touch input detection is crucial. Different technologies have been explored to detect touch, such as conductive threads [217], conductive fabrics [105], force sensing resistors [58]. But none of these can be used in our case considering the high requirement of transparency of the screen overlay. To this end, we used air pressure to detect the touch forces (as done in previous works [212, 164]) and built a force-detection system with 8 air pressure sensors (*ref: XGZP6847A*) with a sample rate of 40Hz. The sensors are directly connected to the silicon tubes that transport the air to the phone case. When the user touches the airbags, they are deformed and the pressure changes accordingly. As the sensors and the airbags are communicating vessels, the air pressure stays the same all the time. Thus, by detecting the pressure value in the airbags, we can get the equivalent touch pressure indirectly.

When a airbag is inflated to a certain level, the inflation and deflation valves are closed to ensure air impermeability. Furthermore, we added close-loop pressure control. When the current pressure is outside the desired value range, the inflate or deflate valve is activated until the targeted pressure value is obtained. The real-time pressure value is sent to the interface and used for pressure-related control.

5.4 Application and Use Cases

In this section, we present several potential applications and use cases of *In-Flat* depending on whether it is used as a communication medium, as an information channel or as a tool.

5.4.1 As a communication medium

Social touch

Around 40% of smartphone use is for communication purpose [21]. As one of the most important non-verbal communication channels, touch plays an essential role in interpersonal affective communication. In addition to the commonly-used visual and audio channels, *In-Flat* allows users to generate and send touch patterns to each other with expressive skin-like sensation, as opposed to vibrations in current smartphones that do not resemble human-like touch [260, 164]. There are different ways of using *In-Flat* to support affective touch communication. As the user is having a phone conversation by holding the phone against the face, *In-Flat* can generate pressure patterns such as a caress, a poke, or a vibration on the cheek to express different emotions, as shown in POKE [164]. If the *In-Flat* overlay is placed on the back of device, when the users are having a video chat by holding the phone with one hand and contact the palm with the overlay, they can also send touch gestures like stroke, hit, pat, caress to each other's palm (Figure 5.10d). This functionality can also be used when there is no verbal communication going on.

Parametric and tangible emojis

Past work has proposed tools that can generate dynamic emojis that are parameterized through typing input variations [6]. Similarly, *In-Flat*'s continuous pressure input can be used to parameterize the dynamic emoji. Furthermore, the emoji can be sent along with its pressure values (i.e., visual emoji enriched with inflated airbags).

As such, the receivers can also dynamically interact with the emoji by pressing or pinching the corresponding inflated airbags, which will animate the visual emoji (Figure 5.11a).

Supporting visually-impaired users

Touch-based interactions support eyes-free interactions, offering an alternative interaction channel for visually-impaired users. For example, Rantala et al. [181] added six actuators under the touchscreen to enable Braille reading. Similarly, the airbags of *In-Flat* can also be used as Braille outputs, as well as to input Braille characters. *In-Flat* can also be an alternative channel to support emoji accessibility for visually-impaired users, as they often struggle to perceive emojis [221].

Anthropomorphic smartphone

Anthropomorphism is defined as *"the tendency to attribute human characteristics to inanimate objects, animals and others with a view to helping us rationalise their actions"* [50]. Anthropomorphic affordances project human functioning and behaviour to the attributes of an object [214]. With *In-Flat*, we can project human behaviors such as breathing, moving, heart beating on smartphones, and thus produce a "human-like" interaction with smartphones. For example, *In-Flat* can mimic human breathing or heartbeat by using different inflation-deflation patterns to show the load of the CPU; it can also actuate the physical movement of mobile device on the desk when the overlay is placed face to the desk. Furthermore, these anthropomorphic affordances can also be used for bio-signal sharing between users like BreathingFrame [121]. For example, users can share a beating red heart with an airbag beating synchronously to express their joy and excitement.

5.4.2 As an information channel

Multimodal feedback of the content

On smartphones, users can manipulate graphical objects directly by touching them through the touch screen. Thus, the action and the visual feedback are co-located, which fits the mental model of interacting with physical objects and minimizes learning effort [106]. However, touch feedback remains limited due to the limitation of using a rigid glass screen. *In-Flat* improves direct manipulation by providing additional touch feedback that lets the user feel the physical property of the

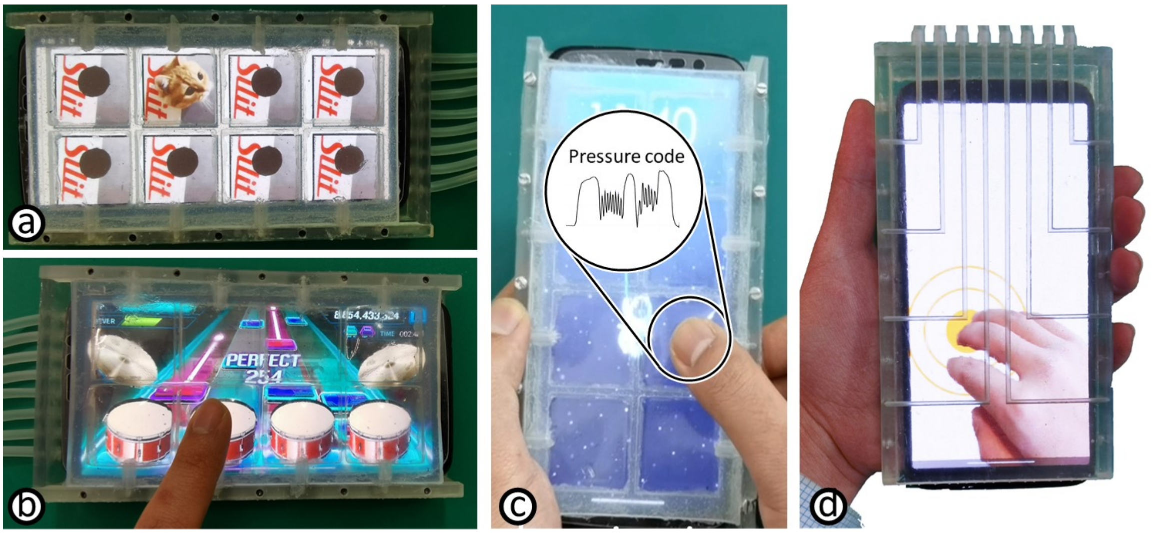

Figure 5.10: Scenarios of *In-Flat*. (a) Interactive game "Catching the cat". (b) Interactive music game. Users can hit the drum with different force and perceive the realistic touch feedback. (c) Users can use personalized pressure patterns as the code of smartphone. (d) Users can send each other social touch gestures like a pat in the palm, and the airbag of *In-Flat* will inflate accordingly.

manipulated objects. For example, in the case of a remote medical consultation, the user can communicate his lung breathing via *In-Flat*, while the doctor can see the lung movement and touch the overlay to perceive the breathing remotely and directly with her finger (Figure 5.11c). Similarly, a field can be simulated by inflating the airbags to different levels, and an earthquake by vibrating the airbags or the vibration motor of the smartphone (Figure 5.11b).

Interactive games

The gaming experience can be enhanced by combining visual, audio, and touch feedback. For example, in the *"Catching the cat"* game (which is similar to the "whack-a-mole" game), a cat would appear at a random place and the corresponding airbag would inflate accordingly (Figure 5.10a). Users can perform *press* and *pinch-and-pull* gesture on the corresponding airbag. The cat would emit a pleasant sound on a gentle press, a scream on a pinch-and-pull, a loud sound and run away on a strong press. The airbags would inflate or deflate accordingly.

Eyes-free interaction

In-Flat can support eyes-free interactions, thus allowing to control the smartphone without looking at the screen. It can also be used for delivering rich tactile notifi-

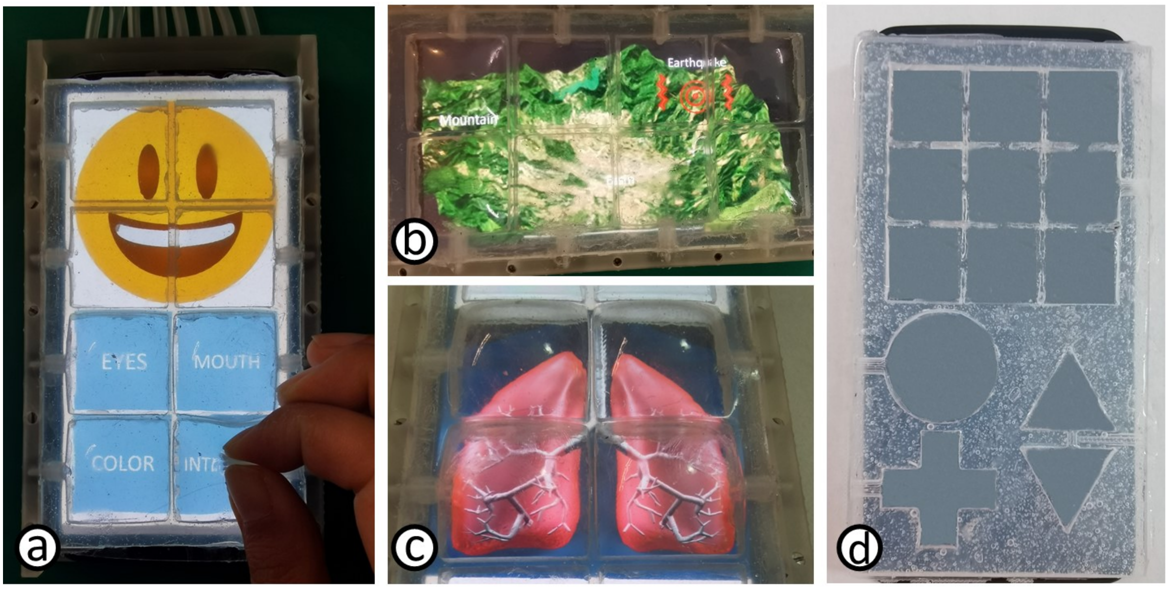

Figure 5.11: More examples of possible application of In-Flat. (a) Senders and receivers can dynamically interact with the emoji. (b) Dynamic tangible affordances on visual objects, for example to visualize an earthquake or (c) a breathing lung. (d) In-Flat's overlay can include different shapes of airbags.

cations. For instance, the device can perform a breathing inflation pattern to notify the arrival of a message, with the intensity of the inflation depending on the importance of the message. Conversely, a user receiving a call can hang-up the call by patting the airbag, or have a preset quick reply to a message by pressing a certain airbag with a certain intensity.

5.4.3 As a tool

Continuous pressure input

In-Flat enables continuous pressure input, which can be mapped to the widgets of a mobile application, thus adding one additional dimension to the input channel. For example, *In-Flat* can be used for controlling the scroll bar: a pinch-and-pull would scroll up the page while a press would scroll it down. The harder the user presses/pulls the airbag, the faster the page scrolls.

In-Flat can also serve to generate expressive dynamic input. For example, it can be used in music applications to control the instruments, for instance the loudness of drums (Figure 5.10b) depending on the force when hitting the airbags. It can also be used to control a virtual DJ set, e.g., to control the pitch, the speed, or even generate a vibrato by pinch-and-pulling airbags. In these examples, *In-Flat* not only acts as an input device, it also provides dynamic force feedback to users, which a rigid screen cannot provide.

Pressure authentication

Current smartphones rely on passwords like PIN codes and gestural patterns. However, people tend to choose weak passwords [261] and gestural patterns are vulnerable to shoulder surfing attacks and smudge attacks [61]. *In-Flat* would allow users to use a pressure-enriched pattern to unlock the smartphone (Figure 5.10c). The movement when pressing the airbag is subtle, so it lowers the risk of being discovered. The uniqueness of the user's finger size, her hand position when holding the phone and the level of applied force can also contribute to making such passwords harder to discover.

Screen protection

In-Flat can not only act as a normal rigid phone case that protects the edge of smartphone from breaking, but the inflated airbags can serve as a safety airbag for protecting mobile phone when it falls.

5.5 Evaluation

Considering our goal to augment smartphones' touchscreens with rich touch input and output (I/O) capabilities via *In-Flat* interface, it is important to evaluate if users can perform continuous pressure input with *In-Flat* and if the dynamic visual+touch output can enhance mobile interactions. Our goals were 1) to assess *quantitatively* if users can perform both *pinch-and-pull* and *press* input gestures with *In-Flat*; 2) to probe on user perception of the coupling between touch I/O and visual display *qualitatively*. To this end, we conducted a two-stage study: 1) an experiment on continuous input control where participants were asked to play a game similar to "Flappy bird" [240]; 2) a semi-structured interview where we presented four pre-designed demo applications of *In-Flat* and asked the participants to share their perceptions when using *In-Flat*.

5.5.1 Evaluation Design

Stage 1: Controlled experiment on continuous input control

The experiment was a [2x6] within-participant design with one primary factor *InputTechnique* (*pinch-and-pull* and *press*) and one secondary factor *PressureLevel* (Level 1 to Level 6). The game we designed for the experiment was inspired by the game "Flappy bird" [240], in which the players need to control the movement of a bird so that it flies through small gaps between pipes (Figure 5.12). In our game, the bird is always flying on the left side of the screen while the pairs of pipes are moving towards the bird with a uniform speed (80 pixels per second). The bird can only move vertically (i.e., movement on y-axis), so the participants only needed to position the bird on the correct height so that it does not fly onto the pipes (Figure 5.12a). Participants *press* the airbag to make the bird fly down, or *pinch-and-pull* the airbag to fly up. The airbag located at the bottom-right corner was used to control the bird movement to ensure the hand movement did occlude the objects on the screen (Figure 5.12b).

Past studies showed that users can accurately control pressure input with 10±2 different levels [28, 143, 252]. Similarly, we tested 13 different pressure levels in our experiment: Level 1 to 6 of *press*; Level 1 to 6 of *pinch-and-pull*; and Level 0 when no input gesture was captured (i.e., baseline value when the airbag was not touched). To ensure comfortable force interactions for each participants, a calibration session was conducted where we recorded the pressure value for the maximum *pinch-and-pull* gesture (mapped to the Level 6 of *pinch-and-pull*), the pressure value for the maximum *press* gesture (mapped to Level 6 of *press*), and finally the pressure value when no input was performed (baseline pressure, mapped to Level 0). The mapping of the other levels (Level 1 to 5) was equally distributed in between the pressure values of Level 0 and 6.

We then divided the screen's height into 13 rows (height=21.4 pixels or $0.5Dh$) and mapped each pressure level to each row (the middle point of a row was illustrated as a grey line in Figure 5.12a). In each trial, we included a pair of pipes that created an empty gap the size of two rows (Dh=42.8 pixels), with the center of the gap representing a pressure value. By default, when the participant did not touch the airbag at all, the bird was flying on Level 0. The goal of the game was to make the bird fly through the gap between the pair of pipes.We also drew a dotted red line to give a visual guideline on the exact path the participants needed to follow.

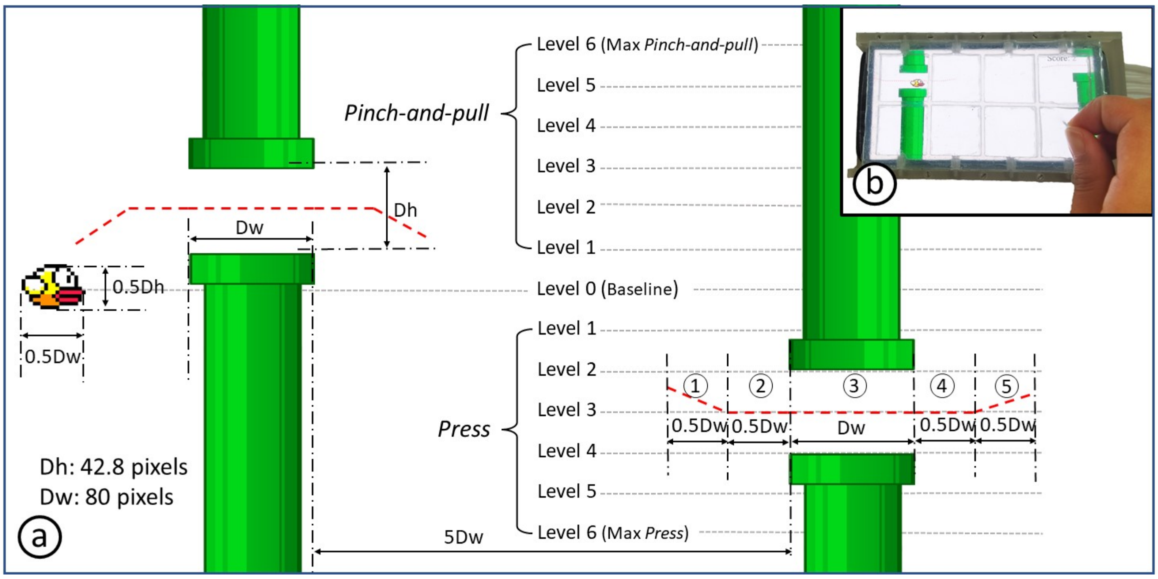

Figure 5.12: The experiment setting of Stage 1. (a) The parameters of the experiment interface and the illustration of the targets. (b) The interface used in the experiment and how participants control the bird.

For example, in Figure 5.12a, the center of the pipes on the left side is mapped to Level 2 of *pinch-and-pull*, while the bird was at Level 0. Hence, the participant needs to *pinch-and-pull* the airbag to make the bird fly up, in order to be on the red line. After passing through the first pair of pipe (i.e., end of trial), the participant can lift their finger from *In-Flat* to rest.

The first task of the game is to control the bird passing through the gaps without touching the pips. To better measure the performance of the *pinch-and-pull* and *press* gesture, we also added an additional task in which the users need to keep the center of the bird as close to the center of the gap as possible. An horizontal red dashed line is marked at the center of gap of each paired pips to help participants to track, and direction of the start (Part 1 in Figure 5.12a) and the end (Part 5 in Figure 5.12a) of the red line is towards the center of previous and the next pair of pips, as the guidance of entering and leaving the target height.

The experiment consisted of three blocks of 12 trials: *BLOCK-1* consisted of 6 *PressureLevel* x 2 replications trials of *pinch-and-pull*; *BLOCK-2* consisted of 6x2 trials of *press*; and *BLOCK-3* consisted of 12 mixed trials of *pinch-and-pull* and *press*. The order of *PressureLevel* was counter balanced using Latin Square across participants. *BLOCK-3* was always the last block in the experiment, while half of the participants started with *BLOCK-1* and the other half with *BLOCK-2*. Thus, each participant completed 36 trials: 2 *InputTechnique* x 6 *PressureLevel* x 3 replications.

Stage 2: Semi-structured interview on user perception

We designed and presented 4 demo applications to participants. The first demo was the game named ”Catching the cat” (Figure 5.10a), as described in Section 5.4. The second demo was related to social touch (Figure 5.10d). *In-Flat* was placed face to the back side of the smartphone, and the participants were asked to hold the smartphone with the silicon airbags facing their palm. An image of a hand was presented on the screen and a ”stroke” gesture would be performed by the hand. The image would move from the top to the bottom of the screen. While the image was moving, the corresponding airbags were also inflated as soon as the image entered the area, and deflated when the hand left the area. The third demo was about dynamic visual and haptic output. In this demo, an animated breathing lung was presented on the screen, and the corresponding airbags were inflating and deflating along with the movement of the animation of the lung (Figure 5.11c). The fourth demo was about the generalizability of *In-Flat*. In this demo, other shapes of airbags were presented to the participants, and they were asked to reflect what kind of interaction they might have with these different shapes of airbags, and what other shapes of airbags they might needed in interaction. The shape presented in the study were 9-button keyboard layout, a cross, a circle and two opposite triangle (Figure 5.11d).

5.5.2 Participants and Apparatus

Twelve participants took part in our study (3 women, 9 men, 24-43 years old, median age 28.5). 11 participants were right handed, all participants used their right hand to interact with their smartphones in daily life. We used a OnePlus 5T smartphone in the evaluation, and the interface was displayed full screen (on 300 x 600 pixels). All the games and application demos were web-based and connected with *In-Flat* through WiFi. For each participant, the calibrated pressure value for maximum *press*, maximum *pinch-and-pull* and the baseline pressure were recorded and used throughout the experiment session. The application also logged the distance between the bird and target red line, and the data are measured and recorded every 25ms during the experiment.

5.5.3 Procedure

We followed the health protocol advised by the WHO [34]. The participants sat in a wide meeting room with opened windows to ensure air circulation. Participants were asked to sit in front of a desk, and *In-Flat* was placed on the desk. We disinfected the surface of *In-Flat*, the table, and the smartphone before starting each study session. Everyone involved in the study cleaned their hands and wore a mask during the session. All the participants read and signed the informed consent.

Stage 1 started with the calibration session: the participants were asked to perform the press and pull gesture with the maximum strength they will likely use in mobile interaction with the hand they used in daily mobile interaction. Then, the training session started: the participants could play the game as long as they wanted. Most participants finished the training session in less than 5 minutes. Finally, the testing session started: the participants were asked to perform all three blocks of trials as accurately and stably as possible. After performing all the trials, we asked them to share their experience of using *In-Flat* as input device in this game. Stage 1 took around 25 minutes. In Stage 2, four different demos were presented to the participants. Participants were asked to play around each of them. They were encouraged to think aloud and shared their perception after each demo. Stage 2 took around 25 minutes.

5.5.4 Measurement

To better evaluate the user performance of each input gesture, we divided the target path (i.e. the dashed red line in Figure 5.12a) into 3 parts: the *preparation phase* (part 1), the *test phase* (parts 2, 3 and 4) and the *exit phase* (part 5) as shown in Figure 5.12a. We evaluated the user performance with three metrics: 1) *success rate*, the percentage of successfully completed trials (a trial is successful if the distance between the bird's position and the red line is always lower than half of the bird size (distance $<$10.7 pixels or 0.25Dh) in the test phase); 2) *accuracy*, the average distance between the location of the center of the bird and the red line; and 3) *stability*, the standard deviation of the distance between the center of the bird and the red line. We then performed the statistical analysis using JMP[2] with REML method followed by a post-hoc analysis with Tukey HSD.

[2]https://www.jmp.com/

5.5.5 Quantitative Results

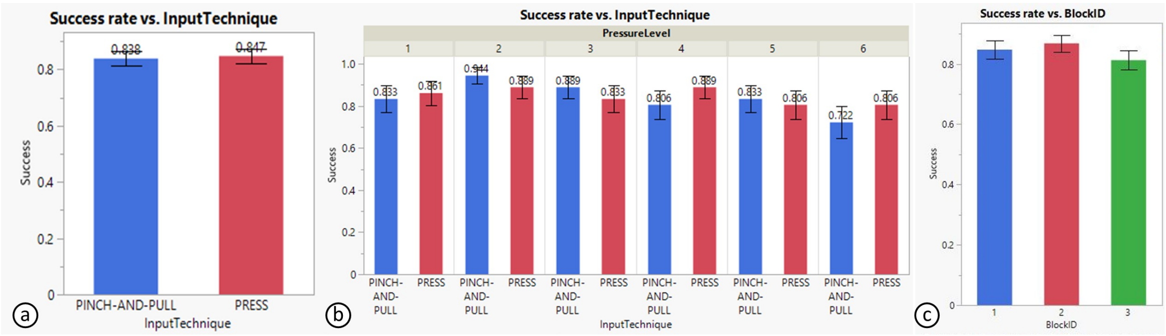

Figure 5.13: Red: pinch-and-pull; Blue: press. The error bars are constructed using 1 standard error from the mean. (a) The overall success rate for each input technique; (b) The success rate for each input technique in each pressure level; (c) The overall success rate for three blocks.

Participants performed pinch-and-pull gestures as well as press gestures

Overall, participants performed well in both *press* and *pinch-and-pull* conditions, with 84.7% and 83.8% respectively (Figure 5.13a). Given that the *pinch-and-pull* gestures were a relatively new interaction technique for mobile interactions, we were surprised to find that there was no significant effect of *InputTechnique* ($F_{1,11}$=0.05, p=0.82) on *success rate*. *PressureLevel* ($F_{5,55}$=1.36, p=0.23) (Figure 5.13b) and *BlockID* ($F_{2,22}$=0.84, p=0.43) (Figure 5.13c) also did not have any significant effect on *success rate*.

We also did not find any significant effect of *InputTechnique* on the input *accuracy* (i.e., the average distance between the bird and the target path), neither during the *preparation phase* ($F_{1,11}$=1.44, p=0.23), the *test phase* ($F_{1,11}$=2.59, p=0.11), nor the *exit phase* ($F_{1,11}$=2.43, p=0.12). Similarly, there was no significant effect of *InputTechnique* on the input stability (i.e., the standard deviation of the distance) during the *preparing phase* ($F_{1,11}$=1.32, p=0.25), *test phase* ($F_{1,11}$=2.93, p=0.09) and *exit phase* ($F_{1,11}$=1.88, p=0.17). This suggested that the participants could perform *pinch-and-pull* gestures as accurately and as stably as *press* gestures.

That said, we acknowledged this result might be impacted by some of the failed trials in which the participant gave up right away and released their finger(s) once the bird hit the pipe. Hence, we performed another analysis in which we only considered the 84% of successful trials. This statistical analysis yielded similar results for *success rate* and *accuracy* (i.e., average distance). The only difference was a significant difference of *InputTechnique* on the *stability* (i.e., the standard deviation) during the *test phase* ($F_{1,11}$=21.7, p<0.0001). This suggests that keeping the *pinch-and-pull* performance stable throughout a trial might require more physical demand. This was supported by some of the participants' comments that found *pinch-and-pull* gestures slightly more tiring as they require two-finger interactions. That said, the difference between the two standard deviations was rather small (only 0.25 pixels: $SD_{PINCH-AND-PULL}$=1.82 pixels and SD_{PRESS}=1.57 pixels) and the two other measurements were unaffected, so that we can still conclude that the participants performed *pinch-and-pull* gestures as well as *press* gestures.

Performing the highest level of pinch-and-pull gestures was more challenging

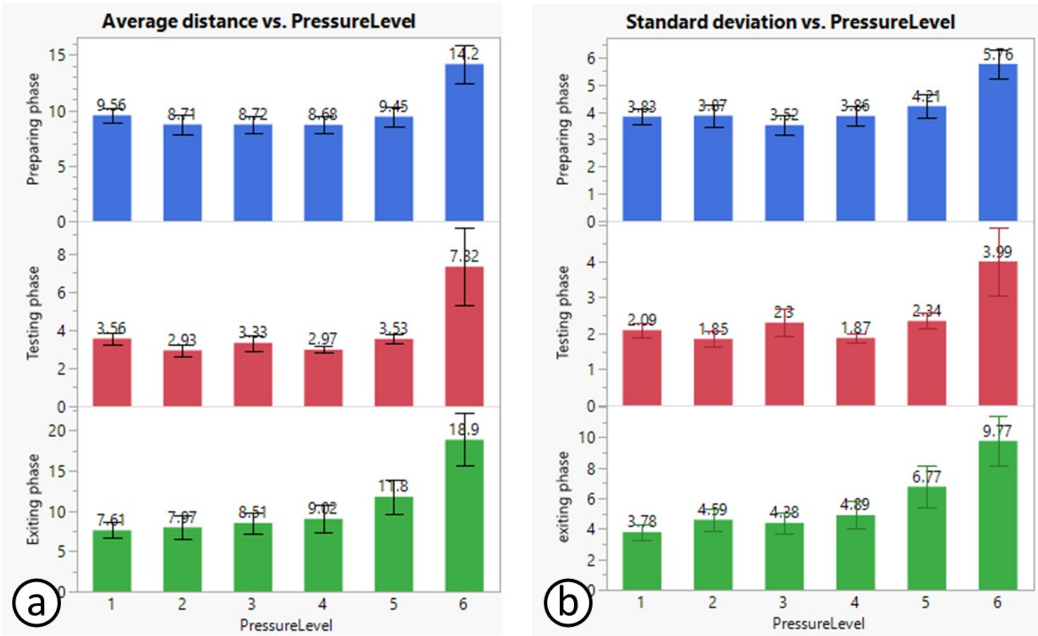

Figure 5.14: Blue: preparation phase; Red: test phase; Green: exit phase. The error bars are constructed using 1 standard error from the mean. (a) The average distance and (b) the standard deviation for all *PressureLevel* in all three phases.

Although *PressureLevel* did not have a significant effect on *success rate* ($F_{5,55}$=1.36, p=0.24), the success rates for *PressureLevel*=6 for both *InputTechnique* were lower than the other five levels: 76% for overall success rate, 72.2% and 80.6% for *pinch-and-pull* and *press* respectively (Figure 5.13b). That said, we found a significant effect of *PressureLevel* on both the *average distance* and the *standard deviation of distance* during all three phases (all p<0.05). A post-hoc analysis with Tukey HSD revealed that Level 6 had significantly higher *average distance* and *standard deviation of distance* in all three phases (Figure 5.14).

Figure 5.15: (a) to (d) show some typical movement trace examples for success trials: (a) good performances in all three phases (trial 21 of P5, *press* Level 3); (b) a low performance in the *preparation phase* (trial 20 of P1, *press* Level 1); (c) a low performance in the *exit phase* (trial 11 of P3, *pinch-and-pull* Level 5); (d) low performances in both the *preparation phase* and the *exit phase* (trial 35 of P4, *pinch-and-pull* Level 6)

There might be several possible explanations for this result. Considering the *preparation phase*: 1) As the target path for Level 6 is located at the edge of the screen (Figure 5.12a), the distance that the bird need to travel from the baseline to the target location was the largest, thus increasing the physical preparation needed to perform the gestures, leading to lower performance (Figure 5.15d,f); 2) The participants might have performed the input gesture as intensely as possible to reach the top or the bottom of the screen for Level 6 as they knew that these trials required the largest amount of force, hence, reducing the accuracy and the stability of the gestures. Considering the *test phase*, as Level 6 was more physically demanding than the other levels, this might led to less accurate and less stable control. Considering the *exit phase*, even though there was still a part of the red line that they needed to follow, some participants just prematurely released their finger(s), back to the default position (Level 0), as shown in Figure 5.15e,f. Notably, some participants released their finger(s) prematurely more often than the others. For example, 91% of the successful trials with an *average distance* over 20 pixels in the *exit phase* came from P1, P3, P5 and P7. Similarly, 80% of the trials with an *average distance* over 30 pixels came from P5 and P7.

To summarize, given that we calibrated the maximum pressure levels (i.e., Level 6) for each gesture based on each participant's maximum "comfortable" pressures, the data suggested that while they were still able to perform successfully, the accuracy and the stability might be slightly compromised. This can be potentially reduced by imposing a better calibration session: instead of performing just one pressure input and record its value as the maximum pressure level (as done in our current experiment design), we can ask the participants to perform several pressure inputs and record their average or median value as the maximum pressure level. Their perception of maximum "comfortable" pressure might also change over time as they get more used to the interaction.

More preparation was needed when the participants switched between pinch-and-pull and press gestures

As explained above, the BLOCK-1 only consisted of *pinch-and-pull*, BLOCK-2 only *press*, while BLOCK-3 consisted of both gestures in a mixed order. We found that the *BlockID* had a significant effect on the *average distance* ($F_{2,22}$=24.6, p<0.0001) and the *standard deviation of distance* ($F_{2,22}$=33.6, p<0.0001) during the *preparation phase*, as well as on the *standard deviation of distance* during the *exit phase* ($F_{2,22}$=6.32, p=0.002) (Figure 5.16). A post-hoc analysis on the three conditions revealed that the performance was significantly lower for BLOCK-3 than for the other blocks.

There might be two possible explanations to this result. First, given that in BLOCK-3 the *pinch-and-pull* and *press* gestures were mixed, some participants might have to constantly switch their finger position between *pinch-and-pull* with two fingers and *press* with one finger. This might make performing the gesture a bit more challenging. Second, with 12 different pressure levels (i.e., 6 levels each for *pinch-and-pull* and *press*) mixed within one block, the target level's heights in one trial to another had a larger difference to BLOCK-2 and BLOCK-1 that only included 6 levels. This implied more travelling distance when switching between trials. Thus, the challenge to prepare the gesture was higher in BLOCK-3, which might lead some participants to exit the area earlier to prepare for the next trial.

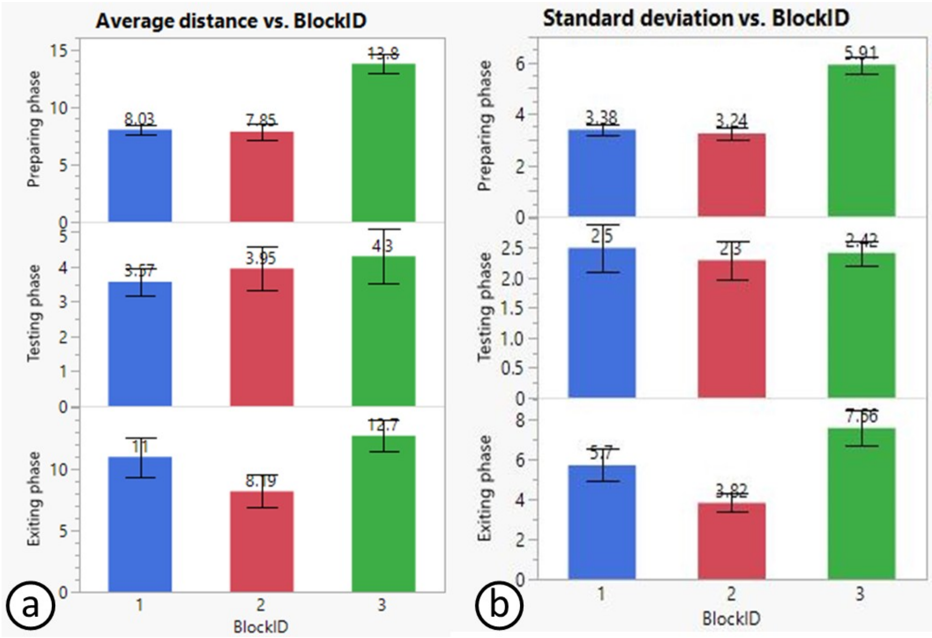

Figure 5.16: (a) The *accuracy* (average distance) and (b) the *stability* (standard deviation of distance) for all *Blocks* in all three phases.

5.5.6 Qualitative Results

Participants felt having more control when performing the pinch-and-pull gestures

Surprisingly, even though the participants' performances in terms of success rate, accuracy, and stability were quite similar for *pinch-and-pull* and *press* gestures, half of the participants (6/12) reported that they felt that they had a better sense of control for *pinch-and-pull*, while only 2 participants felt that they could control the *press* gestures more accurately. Several reasons were given to explain this feeling: 1) Some participants (4/12) mentioned that they had more rooms to pull the airbag towards themselves with *pinch-and-pull*, in contrast with *pressing* the airbag towards the screen which at some point blocked their finger movement; 2) Half of the participants (6/12) mentioned that, with *pinch-and-pull* gestures, the elastic property of the silicon provided additional sense of resistance onto their finger, and this resistance kept increasing when they pulled harder. In contrast, with *press* gestures, when pressing hard, the silicone surface eventually touched the rigid screen, so that the perception became somewhat similar to just touching the screen. That said, most participants (8/12) still reported that the perception of pressing the airbag provided more feeling of control compared to touching the rigid screen directly, especially when the airbag was inflated, because the soft airbag deformed under the pressure of the user's finger, consequently providing additional sensory cues and enabling more freedom of finger movement.

Participants appreciated the coupling between visual display and touch I/O interactions

All 12 participants appreciated the sensation of touching *In-Flat*'s overlay. They perceived the texture of the silicon we used as "*comfortable*" (8/12) and found that the "*bouncy feeling*" of the airbag was "*interactive*" and "*fun*" to play with (5/12). For visual perception, most of participants (10/12) thought the transparent silicon layer allowed them to see the visual display with no issues. More than half of participants (7/12) highly appreciated the visual effect of dynamic movement of the airbag in the animated breathing lung demo, and found that it "*follows well the movement of the GIF*" (6/12) and that it was "*vivid and [looks] natural*" (3/12). The participants thought that, thanks to the combination of two modalities (visual+touch), they "*can feel what [they] see*" (P2) and it was "*dynamic and playful*" (P5) and "*makes the phone alive*" (P1,P10). Additionally, P5 thought touching the airbag was quite stress-relieving as it worked like a bubble wrap.

The participants envisioned different future use cases of *In-Flat*

Even though airbags with other shapes were presented to the participants, half of the participants said they would prefer the 2x4 grid layout rather than having a specific shape on their smartphone, in order to make it possible of using the overlay for different tasks. That said, some participants also proposed use cases for other airbag shapes. For example, P3 mentioned that the screen overlay could work as a detachable button that can be attached on anywhere of the smartphone's screen, so that the function and position could be changed for different tasks. Beyond smartphones, P5 though that input/output pressure capabilities of *In-Flat* would be also useful on game consoles. As such, the game console would provide more dynamic control as well as additional tactile feedback, hence enhancing the eyes-free interactions on the game console.

The participants also expressed willingness to use *In-Flat* in their daily life and proposed different ways of using it. P10 regarded the smartphone as an artificial partner, and thought the inflatable overlay could serve to trigger different emotional feedbacks; P4 thought the inflated airbags could work as landmarks on the screen and help guiding the movement of the finger, especially with a grid with a higher resolution; P7 mentioned that *In-Flat* could provide full tactile experience when watching a movie, with the movement and level of inflation changing dynamically according to the movie, so that the user can feel the movement of the environment or of the characters.

5.6 Discussion, Limitations, and Future Work

In this Chapter, I introduced the design of *In-Flat*, a novel visual+touch I/O overlay using inflatable silicon layers in the form of a phone case. I presented the design and fabrication approach, possible use cases as well as the evaluation of its input capability. This Chapter is a response to RESEARCH QUESTION 3: *How can we incorporate multimodal touch interactions into our everyday communication and interaction?* Furthermore, the multimodality aspect partially responds to RESEARCH QUESTION 1(B) and the skin-like touch stimulation partially responds to RESEARCH QUESTION 2 of this thesis.

I reflect on our fabrication approach, implementation, and evaluation to discuss the future work on improving the pressure-based I/O capabilities on touch devices that can be used together with smartphones, to better support visual+touch interactions.

5.6.1 Affective touch communication on smartphones

Given the lack of sufficient touch interaction in current mobile systems, *In-Flat* is designed to augment the mobile touch interaction experience with skin-like pneumatic actuation.

The augmentation embodies in two ways: 1) The approaches proposed by research in material science, actuation and social touch interaction provide a practical solution for improving the perception of tactile feedback on smartphone; and 2) the availability and mobility of smartphone in return increase the usability of social touch generation device like *In-Flat*. Correspondingly, the expressive touch stimuli increases the *perceived usefulness* of the touch devices as well as the smartphone; and the integration of touch stimuli with the smartphone case increases the *perceived ease of use* of the touch device.

Furthermore, benefits from the communicative affordances of smartphone, this combination enables various forms of touch communication in different contexts. It can be a stroke in the palm while video chatting; it can be a tickle while texting; and it can also be a gentle caress on the cheek during a phone call. Meanwhile, thanks to the rich output capability of smartphone, it is also possible to introducing other modalities such as audio or vibration into the interaction, without adding new actuators or components.

5.6.2 Improving pressure-based control on smartphones

Thanks to the high stretchability of *In-Flat*'s silicon layer, users can perform not only *press* but also *pinch-and-pull* input gestures. To the best of our knowledge, previously proposed touch devices did not specifically discuss nor investigate user performance of *pinch-and-pull* gestures. Our evaluation with *In-Flat* indicated that the participants were able to perform *pinch-and-pull* gestures as accurately as *press* gestures, despite the fact that they mentioned of never using *pinch-and-pull* gestures to interact with digital devices in their daily lives. This shows a promising opportunity to leverage inflatable silicon layers for rich pressure-based input capabilities.

Reflecting on the results of our evaluation, we see different ways to improve pressure-based controls on inflatable silicons. We only tested six levels of *pinch-and-pull* and six levels of *press*. The participants can perform both gestures with high success rate and high accuracy. Fruchard et al. suggested that pressure-based input like *press* on a soft surface was underestimated for far. Similarly, the performance of the *pinch-and-pull* gestures might also be underestimated. A future study on *pinch-and-pull* is needed to better determine its full potential, i.e., how many levels of *pinch-and-pull* gestures can the users control reliably.

Some participants in our evaluation mentioned that performing the *pinch-and-pull* gestures required more physical demands to pinch the airbag because the silicon's surface was too smooth. To make the surface easier to pinch, we can consider using different materials that can induce larger frictions or fabricate the silicone to include a small handle that is easier to pull. However, this might compromise the transparency that is needed to enable clear visual display when put on top of the screen.

5.6.3 Improving the technical implementation

The current version of the prototype, which was conceived as a technological probe to experiment on the *press* and *pull* gestures and to explore applications and use cases, still has some limitations. First, due to the electrical insulation property of the silicon we used, our current *In-Flat* prototype does not support touchscreen interactions when the overlay is placed on top of the screen. New materials that are not only stretchable and transparent, but also conductive have been recently proposed by researchers in material science [262, 236]. Combining *In-Flat* with these new materials would thus solve this limitation. Second, pneumatic technology limits the mobility because of the relatively important size of the actuation device. This problem can be solved by adopting a new, more compact, pneumatic technology such as FlowIO [196]. Moreover, because of its reduced size, this new technology would allow using more cells than in the current prototype (2x4 grid).

5.6.4 Exploring the use of different inflation media

Another interesting research direction would be to use another medium than air to inflate the silicon bags. For example, we explored water-inflated silicon bags in Section 5.3. The observed plano-convex lens effect then affects the visual display on the screen, a feature that may be interesting for certain tasks, such as showing details on the screen [223] or performing fish-eye effects [172]. As participants mentioned, fluids with different colors can be used to make the airbags work as physical filters, and the tactile feeling (e.g. stiffness, density, temperature) can be made different by changing the medium of inflation.

5.6.5 Beyond Augmenting Smartphones

The current design of *In-Flat* focused on smartphone interactions, but it can potentially be adapted to larger devices, by increasing the number of airbags. As some participants mentioned in the evaluation, the *In-Flat*'s overlay can be designed to be detach-and-play on any device such as a smartwatch or a tabletops. One factor to be considered is the trade-off between size and mobility: the bigger the overlay is, the more complex pneumatic control it needs, hence, limiting its mobility. This may not be an issue for fixed devices like tabletops, but future work should address this issue for bigger mobile devices like tablets.

6

Conclusion and Perspectives

When we look back into history, the need for a more convenient and expressive communication channel has pushed the development of technology, which in turn has enabled a variety of new possibilities for people to communicate with each other [248]. Likewise, the strong need for mediated touch interaction encourages us to consider how to improve the expressiveness of current devices. New technologies, in the other way around, expand the design space and provide different approaches to improve touch interaction. This thesis strives to bridge the gap between touch communication and HCI, by taking the stance that multimodal touch interaction can support affective communication in our daily life [230].

In this thesis, I described my attempts to improve touch interaction with multimodal stimuli. My exploration proceeds from three directions: 1) utilizing multimodal stimulation to improve affective touch communication; 2) employing pneumatic actuation to improve the generation of tactile stimuli; and 3) incorporating multimodal touch interaction into our daily interaction.

To address the research questions of this thesis, I presented three devices that provide empirical contributions to multimodal touch interaction. In this chapter, I summarize the insights and research contributions of this thesis, as well as the perspectives, implications, and future research directions in this domain.

6.1 Response to research questions

6.1.1 RESEARCH QUESTION 1(A): *Can we use multimodal stimuli to improve the emotional perception of current social touch technology?*

Figure 6.1: The works presented in this dissertation identified how the multimodal stimuli, especially visual modality, improve the emotional perception of tactile stimulation.

The first step is to understand if multimodal stimuli can improve the emotional perception of touch stimuli. For this purpose, I introduced the design and implementation of *VisualTouch* as well as two studies with *VisualTouch*, to quantitatively explore the effect of dynamic visual cues on emotional perception of vibrotactile stimuli. The results show that although the vibration motors employed in *VisualTouch* prototype are still limited for generating expressive emotional touch stimuli, the addition of congruent visual effects to the touch modality still expands the spectrum of emotion perception, thus opening new opportunities to support emotional communication in social touch. This work also provides the foundation for further investigations into combining visual and tactile modalities in touch devices.

Inspired by the *VisualTouch*, I went one step further to investigate the use of different modalities in real touch communication. I presented the design of *SansTouch*, based on a specific research context: touch breakdowns during the pandemic of COVID-19. From the structured observation on social touch with *SansTouch*, I found that in face-to-face communication, the visual modality could be ignored, because the attention of user was highly directed on the eyes and the facial expression of the other person. And adding visual feedback to touch stimuli might even interfere with verbal communication. In the meantime, the thermal modality significantly improved the touch perception, and the warmth of the device was associated with the perceived warmth in the relationship.

This work provides not only further insights for using different modalities in affective touch communication, but also design implications of mediated touch interaction in face-to-face communication, which has seldom been discussed in previous research. In summary, these works provide insights for how multimodal stimuli improve the emotional perception of tactile stimulation.

6.1.2 RESEARCH QUESTION 1(B): *Can we use multimodal stimuli to improve touch interaction outside social touch context?*

In-Flat goes one step forward on the use of multimodal stimuli in daily interaction. By coupling rich touch I/O interactions with visual display, *In-Flat* improves the expressiveness of mobile interactions that usually lack tangible affordances. Furthermore, the high-definition screens of smartphones also improve the tactile perception of the tactile layer with various visual effects. Pictures, colored patterns, animations or even videos can all be combined with the tactile stimuli. Meanwhile, other built-in modalities of smartphones such as the audio speaker or vibration motors can also potentially be used in the affective touch communication. Benefiting from the rich I/O capability of smartphones and their communicative affordance, coupling touch I/O interactions with visual display can be used in not only mediated touch, but also many other mobile interactions. Thus, this work provide insights on the usage of mediated touch devices in a more general context, and also a better understanding of the role mediated touch devices play in daily interaction.

6.1.3 RESEARCH QUESTION 2: *How can we generate more human-like tactile stimulation to improve multimodal touch interaction?*

The first question considers the possibility of improving current mediated touch communication with different modalities, while the second research question tries to improve the tactile perception of multimodal touch interaction. To address this problem, I used pneumatic actuation to generate skin-like touch perception in multimodality touch devices.

Even though the dynamic vibro-tactile stimuli in *VisualTouch* can express various emotions and were appreciated by the participants, the sense of ”vibrate” still has a low similarity with real touch. To generate a skin-like perception, I presented two prototypes using pneumatic actuation with soft silicon as the actuator. In Chapter 4, I presented the design of *SansTouch*, along with the exploration of skin-like material and pneumatic actuation. From the structured observation with *SansTouch*, I evaluated the perception of each modality, especially the tactile stimuli generated by the inflatable airbags. The touch perception of the silicon airbag was well appreciated by the participants, and we also observed a strong enhancement of thermal modality to the skin-like touch perception. The results indicate that the pneumatic actuation in *In-Flat* can effectively generate a skin-like touch perception for users.

In line with prior research [164, 263], the works presented in this thesis indicate that it is possible to use skin-like pneumatic actuation to generate human-like tactile stimulation. Moreover, the inflatable airbags also reinforce the input capability of mediated touch device, which enables various forms of mediated touch interaction in different contexts.

6.1.4 RESEARCH QUESTION 3: *How can we incorporate multimodal touch interactions into our everyday communication and interaction?*

The above two questions focus on improving the perception of multimodality touch stimuli, while the ultimate goal of these mediated touch devices is to improve our affective communication. Several design factors need to be concerned in order to better integrate multimodality touch into our daily communication and interaction.

Choice of modalities in the interaction

Even though our studies confirm that multimodal stimuli are able to improve mediated touch interaction, these modalities work differently in our everyday communication and interaction. For example, when we are having a video chat on a smartphone or computer, our arms and hands are usually within our vision field during the communication. In this case, the visual modality of the wearables on our arm or hand, like *VisualTouch* or *SansTouch*, is visible during the interaction. Thus the visual modality can be used to enhance the mediated touch interaction. On the other hand, when we are on a phone call with one arm raised, the thermal modality can be more effective, considering that the visibility of the device is limited. Similarly, as we observed in the evaluation of *SansTouch*, the visibility of the device on our hand or arm could also be decreased when we are having a face-to-face communication. Users are trying to maintain eye contact during communication. As a result, additional visual cue may interfere rather than enhance the communication by attracting extra attention to the device.

Thus, the choice of modality is highly related to the context of communication. Different modalities, including communication channels that are not mediated by the ICT systems, are impacting each other during communication.

Social acceptance of mediated touch device

Social aspects (i.e. factors that are related to social relationships and interactions) are also key to incorporate the multimodal touch interaction into our everyday communication. According to the Social Acceptance Model proposed by Buenaflor et al. [67], designers should take into account the social acceptability of the device, when designing interactions for relationships with different levels of intimacy or in different contexts.

Social influence. One important factor is the social influence [67]. The opinion of the social environment also influences the acceptance of mediated touch devices. In the *SansTouch* evaluation, the participants appreciated the design choice of combining a wearable device and a smartphone. Grabbing a smartphone in public receives a high level of social acceptance. For the same consideration, I integrated a mediated touch device into the smartphone case in the *In-Flat* design.

Culture difference. The culture factor [67] also influences the social acceptance of mediated touch devices. In line with prior research [45, 182], cultural differences in touch behavior were observed in our study of the social touch breakdown. Similarly, as discussed in Chapter 3 and in previous research [207, 250], the perception and understanding of colored vision cues of *VisualTouch* may also be influenced by cultural differences.

Personal privacy. Personal privacy [67] also have an impact on social acceptance. According to one participant's remark in *SansTouch* evaluation, the "visible" touch interaction may not be appreciated in a public setting. Even though the visual modality can enhance emotional touch communication, many touch interactions are expected to be intimate and private. Thus, users should be able to switch off some modalities when a certain modality is not suitable for a certain context.

6.2 Reflection and future perspectives

The presented explorations of multimodal touch interaction are only examples of how we can use different modalities to enhance or even broaden the range of interaction. This thesis aims to provide some insights into designing multimodality touch devices and inspire future research, and meanwhile this research has also thrown up many questions in need of further investigation. In this section, I reflect on my work to discuss some research directions for the future.

6.2.1 Synchronicity is a key to fluent touch communication.

Another interesting research topic of multimodal touch interaction is the synchronicity of touch communication. Synchronicity is a key to a fluent communication, and it has a significant impact on social presence and connectedness [107].

In synchronous communication, the conversation and interaction between the involved interlocutors are in real-time. Mediated touch stimuli should be synchronized in real-time with other communication channels such as audio or video. Once a touch gesture is performed, the other side should be able to perceive the touch gesture at the same time, so that the emotion that the touch gesture intends to express can fit into the context. To enable real-time touch communication, input methods such as real-time editing and sending in *VisualTouch* or sending preset gestures in *SansTouch* should be considered. The delay in processing the touch signal as well as the stability of the network connection should also be a concern. On the other hand, for asynchronous remote communication such as SMS chatting, the latency between the touch sending and touch receiving does not influence the expression of the emotion. However, the synchronicity of modalities (i.e. the temporal synchronicity between the message and the tactile stimuli) becomes a challenging topic for research. Despite the fact that researchers have made a few preliminary attempts to discuss tactile stimuli in asynchronous communication [186, 156], further exploration in this field is still required.

6.2.2 Human-like touch interaction or new touch languages?

Recently, questions have been raised about the relationship between mediated touch and real interpersonal touch. Previous research [23, 219, 177] mainly emphasized the importance of replicating the characteristics of real touch in mediated touch, while recent studies [113, 92] argued the importance of designing new forms of touch experiences other than mimic real touch. Both aspects are encountered during our exploration, which provides the following insights for future research.

Human-like touch interaction encourages behavior alignment in mediated touch

Like other non-verbal languages, interpersonal touch is usually performed intuitively. When we meet our colleague, we don't need to remember how to perform a handshake. When the intention of touch appears in our mind, our body acts on instinct for the intended touch interaction. Likewise, mediated touch interaction should also be able to be understood and used intuitively to increase the usability of the system [56]. This design approach is usually named *intuitive design* [27, 147]. In chapter 4, I discussed how *SansTouch* diminishes the learning efforts of the touch interaction by mimicking the hand movement as in real life. Combined with the human-like perception of the pneumatic actuation, *SansTouch* not only decreased the user's effort in understanding, learning and remembering the touch interaction, but also increased the willingness of using the device.

Benefiting from the human-like touch interaction, two levels of behavior alignment [65, 134] are observed in our evaluation. From the perspective of mediated touch interaction, user's actions (posture, body movement, etc.) in mediated touch align with the real touch gestures. They spontaneously lean their bodies and stretch their arms towards each other as if in real touch, while their eyes are looking at the other person's face. Furthermore, from the perspective of communication, users that engage in communication also align their behaviors with each other, as in non-mediated communication. This approach enables users to perform and perceive mediated touch stimuli intuitively, and thus the users are able to coordinate their behavior as in traditional non-mediated communication [134]. These findings suggest that using human-like touch interaction can encourage behavior alignment and build a common ground between the users, thus narrowing the gap between a mediated touch interaction and a real touch.

Moving beyond replicating real-touch brings new social touch experiences

The development of technology not only benefits communication, but may also creates new languages and communication channels that do not exist before. Even though debatable, these new languages such as meme [245], internet slang [244], emoji [243] or emoticon [246] enrich the language we can use in communication. Similarly, the existence of mediated touch devices should not just act as a replacement when real touch is not accessible. This new approach provides users a new way to communicate with each other. Thus, as suggested by Jewitt et al. [113], moving beyond replicating real touch can let us think outside the box, and bring more innovative and creative digital social touch experiences to users.

Note that designing human-like touch interaction and creating new touch language are not two opposed approaches [93, 92]. More exploration on these two approaches would help us to establish a deeper understanding of the role mediated touch plays in our communication.

6.2.3 Social conventions of mediated touch may also evolve

Another interesting topic that relates to the understanding of mediated touch is social touch convention. Usually, interpersonal touch interactions are regulated by cultural conventions [74, 208]. For example, interpersonal touch is only considered proper within a certain range of relationships [45, 182] or certain body locations [208] in daily communication. Holding each other's hands is considered as comfortable and intimate within intimate relationships, but can be considered uncomfortable and offensive if a stranger holds my hand. However, mediated touch may have the possibility of being used beyond traditional social conventions. In the evaluation of *SansTouch*, participants mentioned that when using *SansTouch*, there was no direct skin contact between the receiver and the performer of the touch gesture, and there was no rule for mediated touch interaction. Users felt less uncomfortable when performing mediated touch with someone that they would not touch in the real world.

This finding implies that by using a mediated touch device as a communication medium, the original meanings of the touch interactions might evolve. Thus, mediated touch could be used beyond social conventions, which consequently increase the expressivity and range of social touch.

7

List of Publications

- Zhuoming Zhang, Robin Héron, Eric Lecolinet, Françoise Detienne, and Stéphane Safin. 2019. VisualTouch: Enhancing Affective Touch Communication with Multi-modality Stimulation. In *2019 International Conference on Multimodal Interaction (ICMI '19)*. Association for Computing Machinery, New York, NY, USA, 114–123. DOI:https://doi.org/10.1145/3340555.3353733

- Zhuoming Zhang, Jessalyn Alvina, Robin Héron, Stéphane Safin, Françoise Détienne, and Eric Lecolinet. 2021. Touch without Touching: Overcoming Social Distancing in Semi-Intimate Relationships with SansTouch. *In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 651, 1–13. DOI:https://doi.org/10.1145/3411764.3445612

- Zhuoming Zhang, Jessalyn Alvina, Françoise Détienne, and Eric Lecolinet. Pulling, Pressing, and Sensing with In-Flat: Transparent Touch Overlay for Smartphones. *In Proceedings of the 2022 International Conference on Advanced Visual Interfaces (AVI 2022), June 6–10, 2022, Frascati, Rome, Italy.*.ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3531073.3531111

- Heron, Robin, Françoise Detienne, Stéphane Safin, Michael Baker, Zhuoming Zhang, and Eric Lecolinet. "Analysing meaning making of social touch in computer-mediated interaction." *In IASAT Congress, International Association for the Study of Affective Touch. 2019.*

A

Appendix

A.1 Questionnaire: Social touch before and after the lockdown

Social touch before and after the lockdown

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Robin Heron, PhD Students, SES, i3-CNRS & Télécom Paris, France, robin.heron@telecom-paris.fr

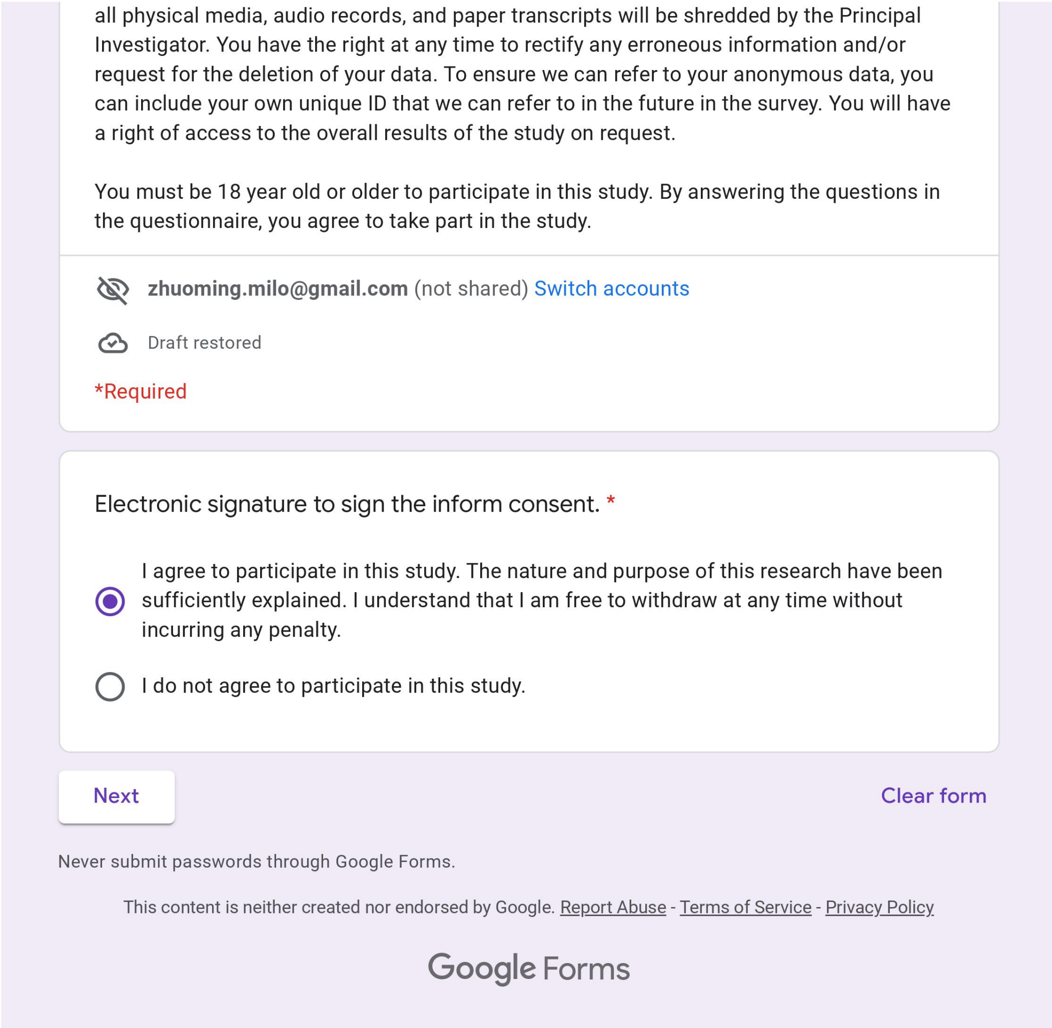
Project Purpose
The purpose of this study is to investigate the impact of lockdowns and physical distancing to social touch habits and communication patterns. The study consists of a questionnaire and a follow-up interview (optional).
In the questionnaire session, we will ask you questions about your social touch habits, such as the forms (e.g., handshakes, hugging, etc.), the different group of people you touch, and the issues related to social touch that emerges due to the lockdown or physical distancing. The questionnaire session should take approximately 15 minutes. You can write down your email if you would like to participate in the follow-up interview.
If you agree, we might contact you for a follow-up interview. We will prone further about the stories you shared in the survey. The interview session should take 30 to 45 minutes and will be audio recorded. The interview might also take place by video, but the video part won't be recorded.

Confidentiality
Your identity will be kept confidential. You are not expected to share anything you are not comfortable sharing. The questionnaire data will be stored electronically and anonymously. We will audio record the follow-up interview (no video will be recorded). To protect the voiceprint information of participants, only the transcript of the audio record will be saved. In all cases, your identifying information will not be associated with the data after it has been analyzed. The results will be made public through scholarly publications, presentations, and academic theses; however, no identifying information will be included in any of these.

Risks
We do not anticipate any significant risks for taking part in this study. Your participation is voluntary. You are free to stop your participation at any point. Refusal to participate or withdrawal of your consent or discontinue participation in the study will not result in any penalty or rights to which you might otherwise be entitled.

Data Retention
All electronic files will be stored in an encrypted hard drive of a password-protected laptop. Five (5) years after the completion of the research, the electronic data will be deleted, and

Figure A.1: Questionnaire - Page 1



all physical media, audio records, and paper transcripts will be shredded by the Principal Investigator. You have the right at any time to rectify any erroneous information and/or request for the deletion of your data. To ensure we can refer to your anonymous data, you can include your own unique ID that we can refer to in the future in the survey. You will have a right of access to the overall results of the study on request.

You must be 18 year old or older to participate in this study. By answering the questions in the questionnaire, you agree to take part in the study.

zhuoming.milo@gmail.com (not shared) Switch accounts

Draft restored

*Required

Electronic signature to sign the inform consent. *

- (x) I agree to participate in this study. The nature and purpose of this research have been sufficiently explained. I understand that I am free to withdraw at any time without incurring any penalty.
- ( ) I do not agree to participate in this study.

Next

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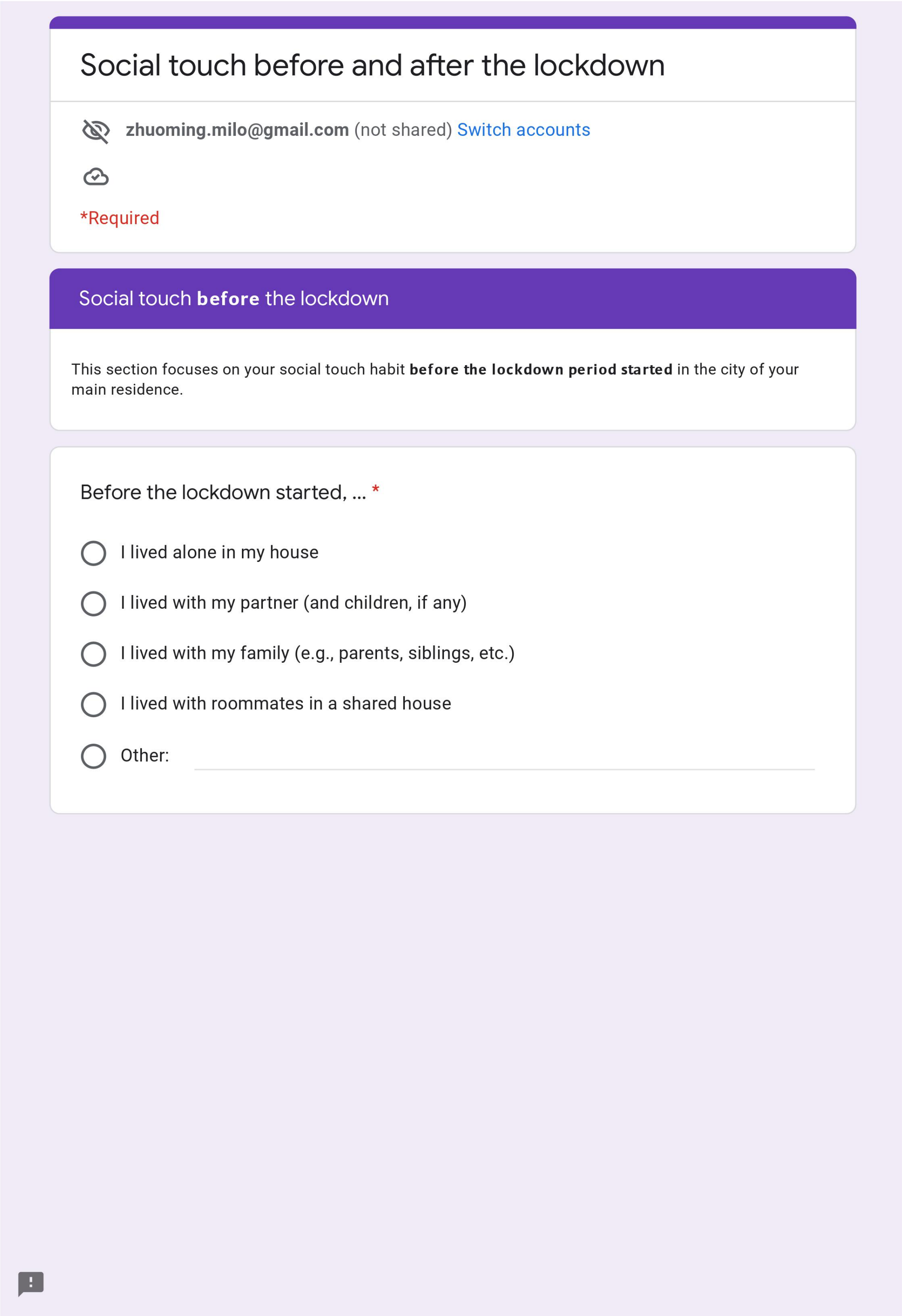
Figure A.2: Questionnaire - Page 2



Social touch before and after the lockdown

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Social touch **before** the lockdown

This section focuses on your social touch habit **before the lockdown period started** in the city of your main residence.

Before the lockdown started, ... *

- I lived alone in my house
- I lived with my partner (and children, if any)
- I lived with my family (e.g., parents, siblings, etc.)
- I lived with roommates in a shared house
- Other:

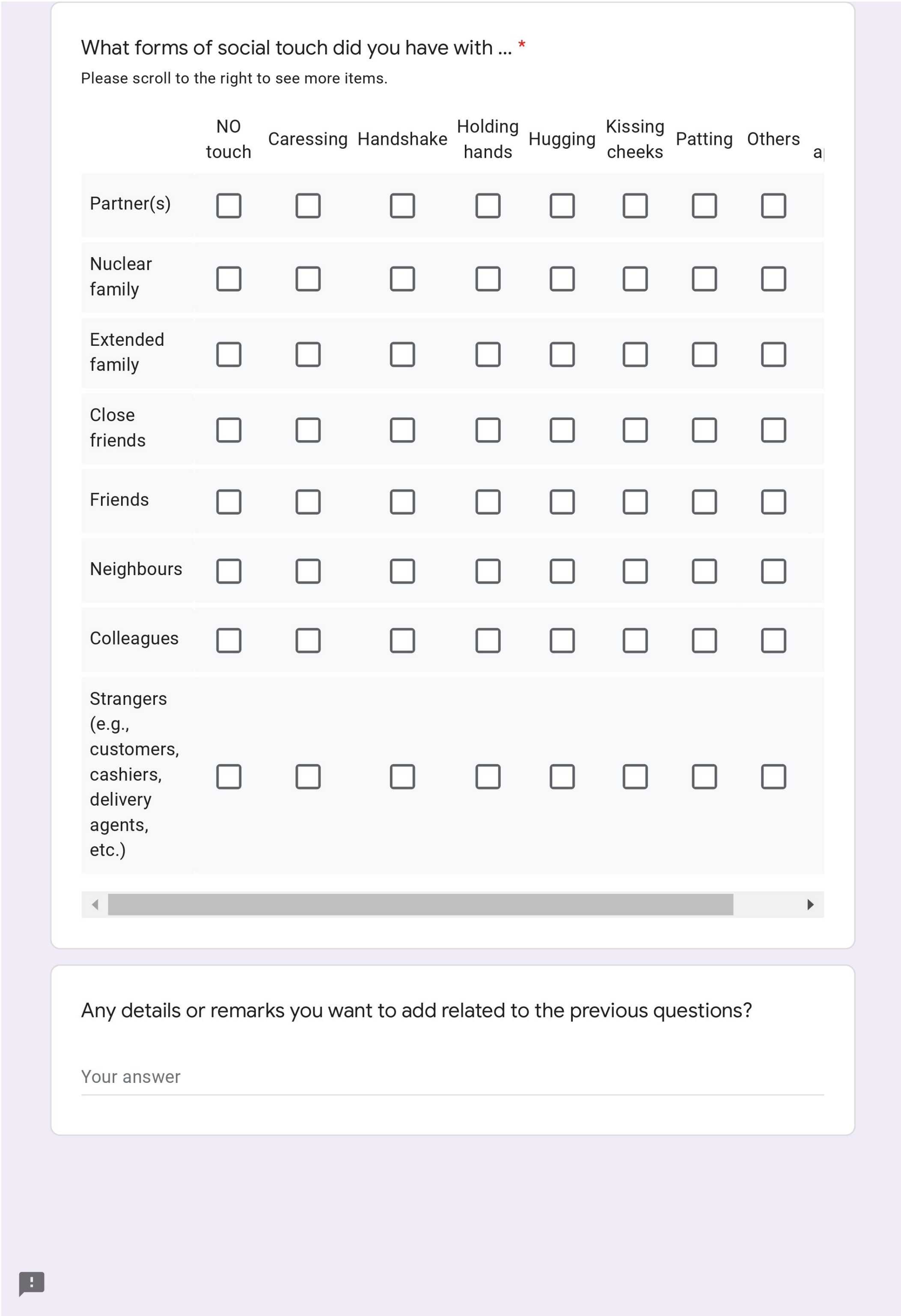
Figure A.3: Questionnaire - Page 3

In the last six months before the lockdown started, how often did you touch (e.g., handshakes, hugs, a pat of the back, etc.) with... *

"Nuclear family" refers to your children (if any) or your parents if you live with them.

	Always	Frequently	Occasionally	Rarely	Never	Not applicable
Partner(s)						
Nuclear family						
Extended family						
Close friend(s)						
Friends						
Neighbours						
Colleagues						
Strangers (e.g., customers, cashiers, delivery agents, etc.)						

Figure A.4: Questionnaire - Page 4



What forms of social touch did you have with ... *

Please scroll to the right to see more items.

	NO touch	Caressing	Handshake	Holding hands	Hugging	Kissing cheeks	Patting	Others
Partner(s)	☐	☐	☐	☐	☐	☐	☐	☐
Nuclear family	☐	☐	☐	☐	☐	☐	☐	☐
Extended family	☐	☐	☐	☐	☐	☐	☐	☐
Close friends	☐	☐	☐	☐	☐	☐	☐	☐
Friends	☐	☐	☐	☐	☐	☐	☐	☐
Neighbours	☐	☐	☐	☐	☐	☐	☐	☐
Colleagues	☐	☐	☐	☐	☐	☐	☐	☐
Strangers (e.g., customers, cashiers, delivery agents, etc.)	☐	☐	☐	☐	☐	☐	☐	☐

Any details or remarks you want to add related to the previous questions?

Your answer

Figure A.5: Questionnaire - Page 5

During the lockdown, ... *

If you had several living arrangements during the confinement, then please specify in "Other".

- ◯ I lived alone in my house
- ◯ I lived with my partner (and children, if any)
- ◯ I lived with my family (e.g., parents, siblings, etc.)
- ◯ I lived with roommates in a shared house
- ◯ Other: ____________

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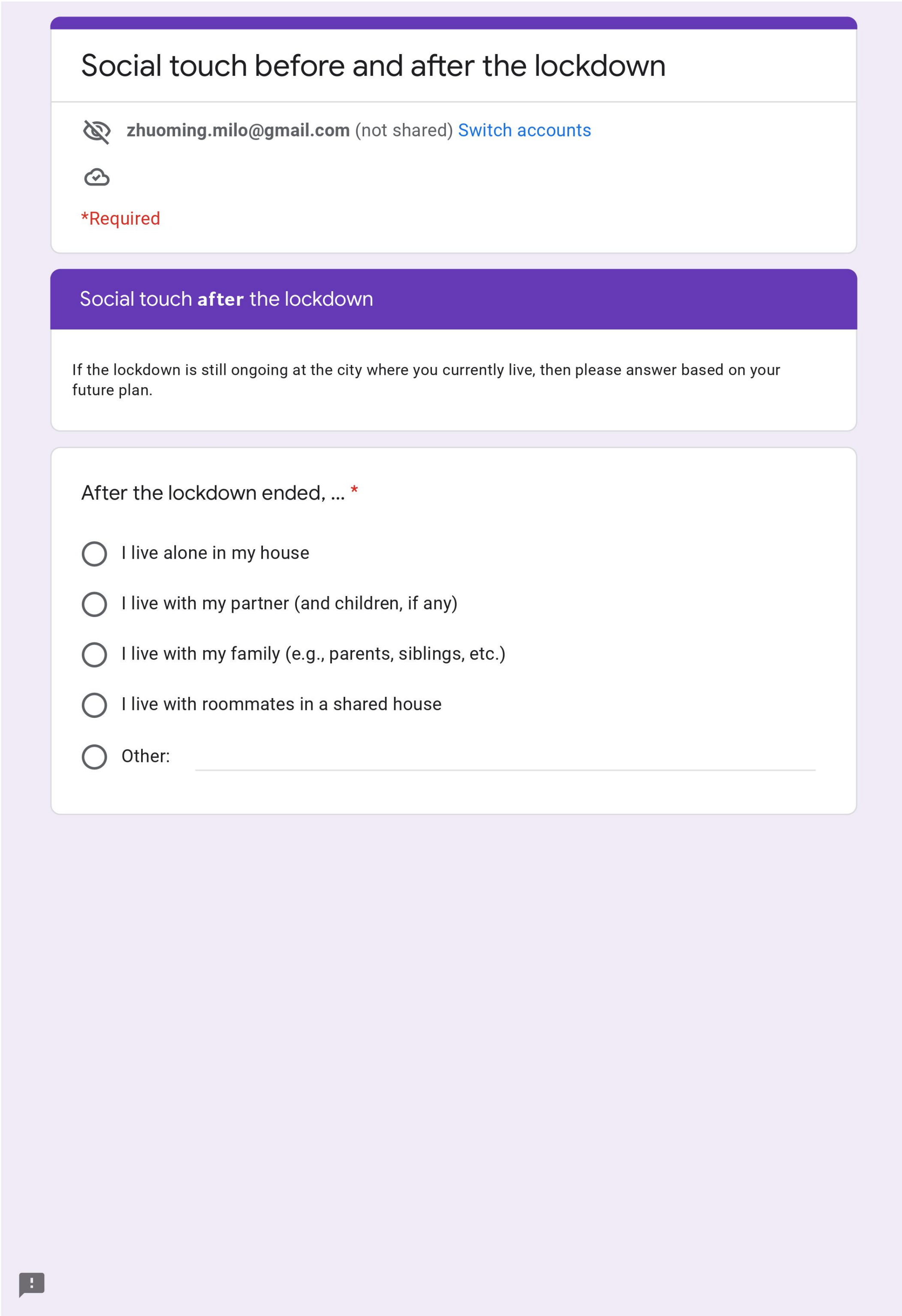
Figure A.6: Questionnaire - Page 6



Social touch before and after the lockdown

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*Required

Social touch **after** the lockdown

If the lockdown is still ongoing at the city where you currently live, then please answer based on your future plan.

After the lockdown ended, ... *

- I live alone in my house
- I live with my partner (and children, if any)
- I live with my family (e.g., parents, siblings, etc.)
- I live with roommates in a shared house
- Other: ____

Figure A.7: Questionnaire - Page 7

After the lockdown ended, how often do you touch ... *

If you have not met a certain category of people, check "Not applicable".

	Always	Frequently	Occasionally	Rarely	Never	Not applicable
Partner(s)	○	○	○	○	○	○
Nuclear family	○	○	○	○	○	○
Extended family	○	○	○	○	○	○
Close friends	○	○	○	○	○	○
Friends	○	○	○	○	○	○
Neighbours	○	○	○	○	○	○
Colleagues	○	○	○	○	○	○
Strangers (e.g., customers, cashiers, delivery agents, etc.)	○	○	○	○	○	○

Figure A.8: Questionnaire - Page 8

What forms of social touch do you have with ... *

Please scroll to the right to see more items.

	NO touch	Caressing	Handshake	Holding hands	Hugging	Kissing cheeks	Patting	Others
Partner(s)	☐	☐	☐	☐	☐	☐	☐	☐
Nuclear family	☐	☐	☐	☐	☐	☐	☐	☐
Extended family	☐	☐	☐	☐	☐	☐	☐	☐
Close friends	☐	☐	☐	☐	☐	☐	☐	☐
Friends	☐	☐	☐	☐	☐	☐	☐	☐
Neighbours	☐	☐	☐	☐	☐	☐	☐	☐
Colleagues	☐	☐	☐	☐	☐	☐	☐	☐
Strangers (e.g., customers, cashiers, delivery agents, etc.)	☐	☐	☐	☐	☐	☐	☐	☐

Figure A.9: Questionnaire - Page 9

What forms of social touch do you **wish to have** to have with ... *

Please scroll to the right to see more items.

	NO touch	Caressing	Handshake	Holding hands	Hugging	Kissing cheeks	Patting	Others	a
Partner(s)	☐	☐	☐	☐	☐	☐	☐	☐	
Nuclear family	☐	☐	☐	☐	☐	☐	☐	☐	
Extended family	☐	☐	☐	☐	☐	☐	☐	☐	
Close friends	☐	☐	☐	☐	☐	☐	☐	☐	
Friends	☐	☐	☐	☐	☐	☐	☐	☐	
Neighbours	☐	☐	☐	☐	☐	☐	☐	☐	
Colleagues	☐	☐	☐	☐	☐	☐	☐	☐	
Strangers (e.g., customers, cashiers, delivery agents, etc.)	☐	☐	☐	☐	☐	☐	☐	☐	

After the lockdown ended, have you ever **thought of touching others but chose not to**? Please tell us one story, and specify: 1) **with whom**; 2) **the context** (including why you did not touch them in the end); 3) **the form of touch**; 4) **why** you wanted to touch them (e.g., reassurance, social conventions, etc.), and 5) **what you did** instead.

Your answer

Figure A.10: Questionnaire - Page 10

Any other stories?

Your answer

How do you feel about your new social touch patterns with physical distancing rules? *

	Extremely happy	Somewhat happy	Indifferent	Somewhat frustrated	Extremely frustrated	Not applicable
Partner(s)	○	○	○	○	○	○
Household family	○	○	○	○	○	○
Family	○	○	○	○	○	○
Close friends	○	○	○	○	○	○
Friends	○	○	○	○	○	○
Neighbours	○	○	○	○	○	○
Colleagues	○	○	○	○	○	○
Strangers (e.g., customers, cashiers, delivery agents, etc.)	○	○	○	○	○	○

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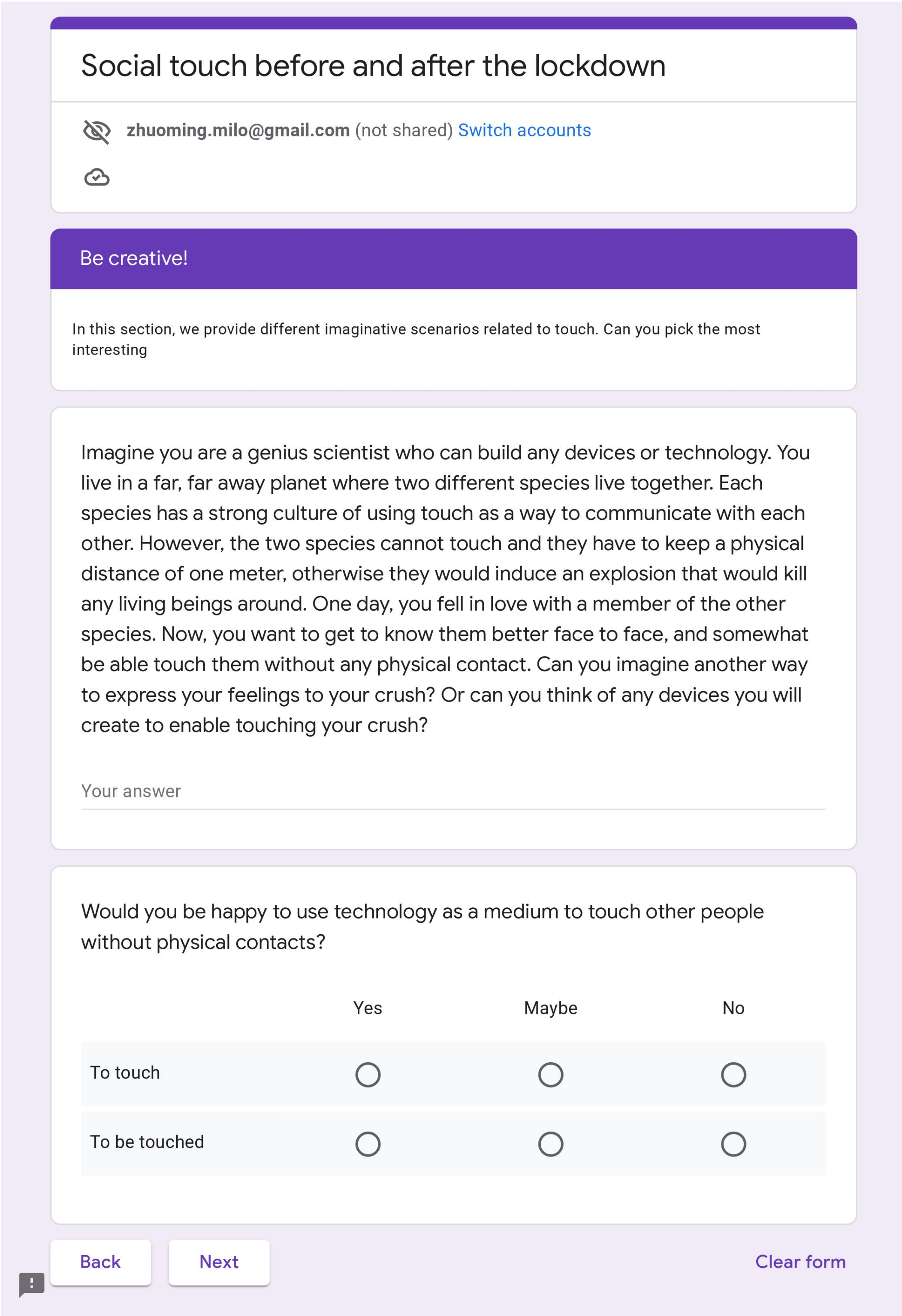
Figure A.11: Questionnaire - Page 11



Social touch before and after the lockdown

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Be creative!

In this section, we provide different imaginative scenarios related to touch. Can you pick the most interesting

Imagine you are a genius scientist who can build any devices or technology. You live in a far, far away planet where two different species live together. Each species has a strong culture of using touch as a way to communicate with each other. However, the two species cannot touch and they have to keep a physical distance of one meter, otherwise they would induce an explosion that would kill any living beings around. One day, you fell in love with a member of the other species. Now, you want to get to know them better face to face, and somewhat be able touch them without any physical contact. Can you imagine another way to express your feelings to your crush? Or can you think of any devices you will create to enable touching your crush?

Your answer

Would you be happy to use technology as a medium to touch other people without physical contacts?

	Yes	Maybe	No
To touch	○	○	○
To be touched	○	○	○

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Figure A.12: Questionnaire - Page 12

Social touch before and after the lockdown

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*Required

Demographic Information

How old are you? *

Your answer

Gender *

- Male
- Female
- Non-binary
- Prefer not to answer

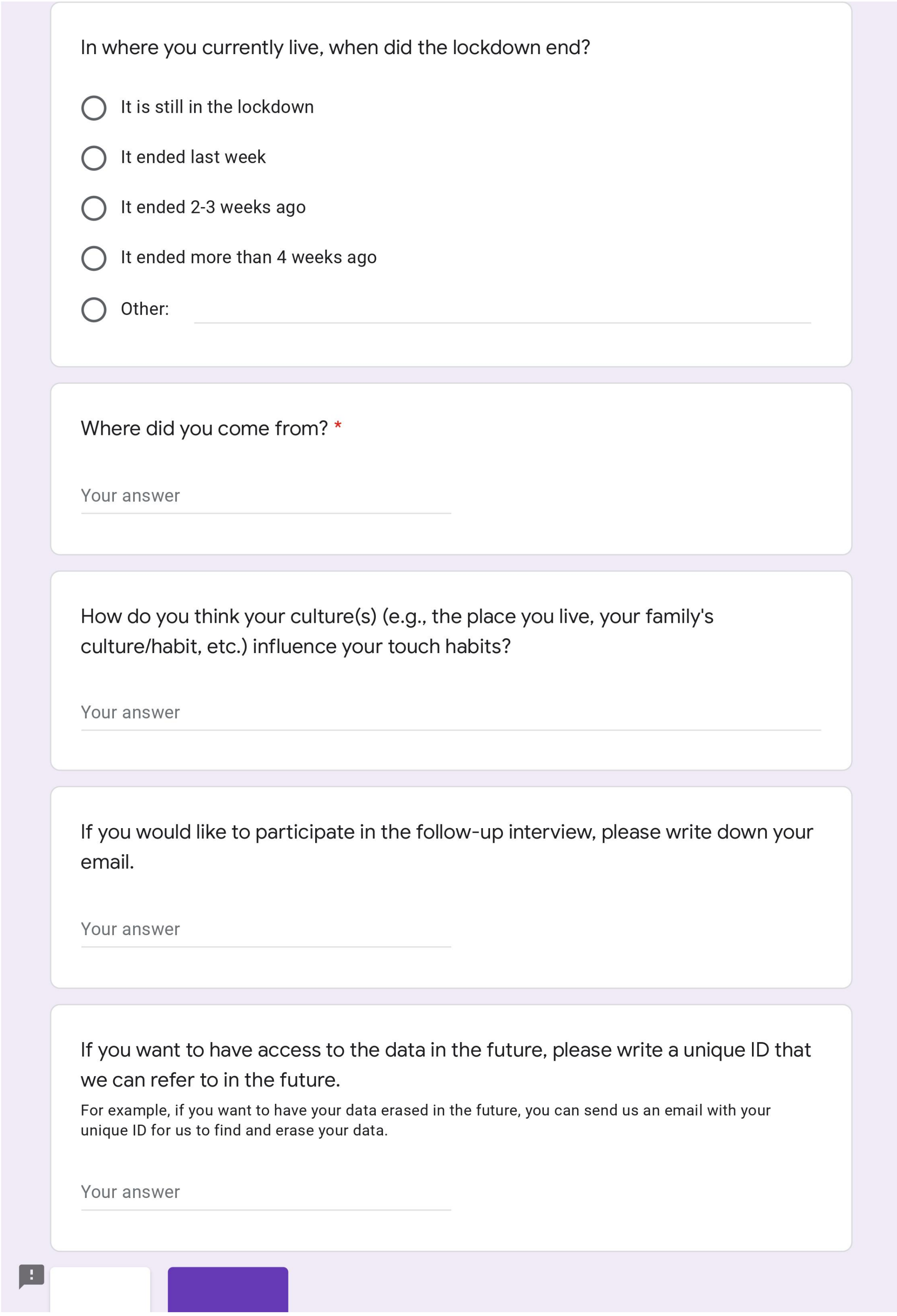
Occupation and domain (e.g., a student in computer science) *

Your answer

In which city and country do you currently live? *

Your answer

Figure A.13: Questionnaire - Page 13



In where you currently live, when did the lockdown end?

- It is still in the lockdown
- It ended last week
- It ended 2-3 weeks ago
- It ended more than 4 weeks ago
- Other:

Where did you come from? *

Your answer

How do you think your culture(s) (e.g., the place you live, your family's culture/habit, etc.) influence your touch habits?

Your answer

If you would like to participate in the follow-up interview, please write down your email.

Your answer

If you want to have access to the data in the future, please write a unique ID that we can refer to in the future.

For example, if you want to have your data erased in the future, you can send us an email with your unique ID for us to find and erase your data.

Your answer

Figure A.14: Questionnaire - Page 14

B

Second Appendix

B.1 Informed consent

INFORMED CONSENT

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Project Purpose

The purpose of this study is to evaluate our touch device in the form of a smartphone's screen overlay that can capture rich pressure input. First, we will ask you to play a mini game in which you have to apply a pressure input on two different touch devices to control the visual objects displayed on the smartphone's screen. The pressure test session should take approximately 40 minutes. The game will log the pressure values throughout the session. Second, we will also ask you to fill in a questionnaire asking about your qualitative assessment of your experience controlling the pressure with the two different devices. We will also ask about your perceptions interacting with the device verbally in a semi-structured interview. The interview session should take approximately 15 minutes, and will be audio recorded.

Confidentiality

Your identity will be kept confidential. You are not expected to share anything you are not comfortable sharing. The questionnaire data and the log data will be stored electronically and anonymously. We will audio record the semi-structured interview. In all case, your identifying information will not be associated with the data after it has been analyzed. The results will be made public through scholarly publications, presentations and academic theses; however, no identifying information will be included in any of these.

Risks

We do not anticipate any significant risks for taking part in this study. Your participation is voluntary. You are free to stop your participation at any point. Refusal to participate or withdrawal of your consent or discontinued participation in the study will not result in any penalty or rights to which you might otherwise be entitled.

Figure B.1: Informed consent - Page 1

Data Retention

All electronic files will be stored in an encrypted hard drive of a password protected laptop. 5 years after the completion of the research, the electronic data will be deleted, and all physical media, audio records, and paper transcripts will be shredded by the Principal Investigator. You have the right at any time to rectify any erroneous information and/or request for the deletion of your data. You will also have the right to access the overall results of the study on request. To ensure we can refer to your anonymous data, you can include your own unique ID that we can refer to in the future in the survey.

You must be 18 old or older to participate in this study. By answering the questions in the questionnaire, you agree to take part in the study.

Place and date: ____________________________

Check to sign the inform consent.

- ☐ I agree to participate in this study. The nature and purpose of this research have been sufficiently explained. I understand that I am free to withdraw at any time without incurring any penalty.
- ☐ I do not agree to participate in this study.

Check to sign the agreement to be audio recorded.

- ☐ I agree to be audio recorded in this study.

Figure B.2: Informed consent - Page 2

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ECOLE
DOCTORALE

Titre: Vers une amélioration de l'Interaction Tactile Médiée par la Multimodalité

Mots clés: Interaction Homme-Machine, Tactile Médié, Multimodalité, Communication Affective, Interaction Mobile

Résumé: Comme l'un des plus importants canaux de communication non verbale, le toucher est largement utilisé à des fins différentes. Dans le développement physique et psychologique humain le toucher participe à la construction des liens sociaux et à la communication des émotions. Cependant, même si les technologies de l'information et de la communication actuels permettent l'utilisation de divers langages non verbaux, le soutien à la communication par le sens du toucher est encore insuffisant. Inspiré par les interactions intermodales dans la perception humaine, l'approche que j'adopte dans cette thèse est d'utiliser la multimodalité pour améliorer l'interaction tactile médiée.
Afin de comprendre si les stimuli multimodaux peuvent améliorer la perception émotionnelle du toucher, je développe *VisualTouch*, et j'évalue quantitativement l'interaction entre la modalité visuelle et tactile. Pour étudier l'utilisation de différentes modalités dans la communication tactile, je présente *SansTouch* et fournis des aperçus empiriques sur l'interaction multimodale et la génération de contact cutané dans le contexte de la communication en face à face. Enfin, pour aller plus loin dans l'utilisation de stimuli multimodaux en interaction tactile, je présente *In-Flat*, une superposition tactile entrée/sortie pour smartphones. *In-Flat* fournit non seulement des informations supplémentaires sur la génération du toucher de la peau, mais aussi une meilleure compréhension du rôle que joue le toucher médié dans des contextes plus généraux.
En résumé, cette thèse vise à combler le fossé entre la communication tactile et l'IHM, en contribuant à la conception et la compréhension des stimuli multimodaux dans l'interaction tactile médiée.

Title: Improving Mediated Touch Interaction with Multimodality

Keywords: HCI, Mediated touch, Multimodality, Affective communication, Mobile interaction

Abstract: As one of the most important non-verbal communication channels, touch is widely used for different purposes. It is a powerful force in human physical and psychological development, shaping social structures and communicating emotions. However, even though current ICT systems enable the use of various non-verbal languages, the support of communicating through the sense of touch is still insufficient. Inspired by the cross-modal interaction of human perception, the approach I present in this dissertation is to use multimodality to improve mediated touch interaction.
To understand if multimodal stimuli can improve the emotional perception of touch, I present *VisualTouch*, and quantitatively evaluate the cross-modal interaction between visual and tactile modality. To investigate the use of different modalities in real touch communication, I present *SansTouch*, which provides empirical insights on multimodal interaction and skin-like touch generation in the context of face-to-face communication. Going one step forward in the use of multimodal stimuli in touch interaction, I present *In-Flat*, an input/output touch overlay for smartphones. *In-Flat* not only provides further insights on the skin-like touch generation, but also a better understanding of the role that mediated touch plays in more general contexts.
In summary, this dissertation strives to bridge the gap between touch communication and HCI, by contributing to the design and understanding of multimodal stimuli in mediated touch interaction.

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