Haptic Illusions - Creating Haptic Sensations through Augmented Environments

Dissertation

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Abstract

In recent years, there has been a steady advancement in hardware, technology, algorithms, and digitalization. New applications have emerged and continue to emerge with enhanced visual presentation and increasingly immersive experiences. To further enhance the user experience, many of these applications or devices also have special haptic feedback-generating input and output devices. While these can reproduce certain modalities or types of feedback effectively in specific cases, they are usually not universal and are limited in the type of feedback they can provide. Furthermore, the proliferation of additional hardware and special setups can rapidly consume considerable space and alter the natural environment. However, it is essential to consider the concept of ubiquitous and calm computing. Computers will be ubiquitous in the future, and all objects will be operable like computers. However, the most advanced and promising technologies are so merged with our everyday environment that we cannot distinguish them. As this may further minimize the type of feedback and hardware used, haptic feedback is important for interaction with interfaces and computers. Therefore, a way must be found to combine the two. This is where haptic illusions come in. These can generate various feedback, as they primarily use the human mind and do not require much special hardware. As most illusions are known in cognitive science but not all are used in HCI, this work investigates the basic factors, conditions, and requirements for generating haptic feedback via illusions while following the version of ubiquitous computing. In different works, we demonstrate how haptic feedback can be generated and mapped on everyday surfaces, how haptic feedback in the sense of the tactile perception of vibration can be generated via other senses, and how everyday devices can be extended by minimal changes in the possibility and diversity of the representation of haptic feedback, in this case, the provision of perceptible shapes. These results demonstrate the potential of haptic illusions, contribute to HCI and ubiquitous computing research, and provide a foundation and motivation for future research directions.

Zusammenfassung

In den letzten Jahren haben sich Hardware, Technologie, Algorithmen und Digitalisierung stetig weiterentwickelt. Es sind neue Anwendungen mit verbesserter visueller Darstellung und zunehmend immersiven Erlebnissen entstanden und werden weiterhin entwickelt. Um das Benutzererlebnis weiter zu verbessern, verfügen viele dieser Anwendungen oder Geräte auch über spezielle, haptisches Feedback erzeugende Eingabe- und Ausgabegeräte. Diese können zwar in bestimmten Fällen bestimmte Modalitäten oder Arten von Feedback effektiv wiedergeben, sind aber in der Regel nicht universell einsetzbar und in der Art des Feedbacks, das sie geben können, begrenzt. Darüber hinaus kann die Verbreitung zusätzlicher Hardware und spezieller Aufbauten schnell viel Platz beanspruchen und die natürliche Umgebung verändern. Es ist jedoch wichtig, das Konzept des ubiquitous und calm Computings zu berücksichtigen. Computer werden in der Zukunft allgegenwärtig sein, und alle Gegenstände werden wie Computer funktionieren können. Die fortschrittlichsten und vielversprechendsten Technologien sind jedoch so sehr mit unserer alltäglichen Umgebung verschmolzen, dass wir sie nicht mehr unterscheiden können. Da dies die Art des Feedbacks und der verwendeten Hardware weiter minimieren kann, ist haptisches Feedback für die Interaktion mit Schnittstellen und Computern wichtig. Es muss also ein Weg gefunden werden, beides zu kombinieren. An dieser Stelle kommen haptische Illusionen ins Spiel. Diese können verschiedene Rückmeldungen erzeugen, da sie in erster Linie den menschlichen Verstand nutzen und keine spezielle Hardware erfordern. Da die meisten Illusionen in der Kognitionswissenschaft bekannt sind, aber nicht alle in der HCI verwendet werden, untersucht diese Arbeit die grundlegenden Faktoren, Bedingungen und Anforderungen für die Erzeugung von haptischem Feedback durch Illusionen, wobei die Version des Ubiquitous Computing verfolgt wird. In verschiedenen Arbeiten wird gezeigt, wie haptisches Feedback auf alltäglichen Oberflächen erzeugt und abgebildet werden kann, wie haptisches Feedback im Sinne der taktilen Wahrnehmung von Vibration über andere Sinne erzeugt werden kann und wie alltägliche Geräte durch minimale Änderungen in der Möglichkeit und Vielfalt der Darstellung von haptischem Feedback, in diesem Fall der Bereitstellung von wahrnehmbaren Formen, erweitert werden können. Diese Ergebnisse zeigen das Potenzial haptischer Illusionen, leisten einen Beitrag zur HCI- und Ubiquitous-Computing-Forschung und bieten eine Grundlage und Motivation für zukünftige Forschungsrichtungen.

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Contents

Chapter 1

Introduction

Haptic feedback provides opportunities to enhance interactions and has been shown to improve user performance and attention [6, 8]. Human haptic perception encompasses various sensory channels beyond tactile feedback. Instead, it is composed of cutaneous sensing, including tactile perception and the perception of temperature and proprioception and kinaesthesia, which relate to posture, movement, and perceived internal and external forces [67, 87].

Traditional haptic feedback, mainly provided by vibrotactile actuators, cannot fully cover the diversity of human perception. This limitation restricts the kind of haptic feedback that can be delivered [60]. This is because haptic feedback technology has not evolved as much as visual feedback technology, limiting its potential [1]. These new technologies have improved visual feedback and created new interaction possibilities. Virtual Reality (VR) and Augmented Reality (AR) allow us to move around environments in new ways and interact with them using everyday objects as interfaces. This technological evolution enables the creation of interactive environments that align with ubiquitous and calm computing [100, 101]. In this paradigm, computers are ubiquitous but seamlessly interwoven into our surroundings, making them indistinguishable from the environment.

The challenge lies in developing versatile and rich haptic feedback for augmented and ubiquitous environments and everywhere displays and interfaces [76]. One issue is that conventional feedback through actuators and sensors is limited in diversity, as mentioned before. Additionally, installing actuators and sensors throughout the environment is not feasible [P3.2]. Integrating actuators into large and rigid objects, such as walls, would be complex to implement and maintain. It would also have little effect, as it would be difficult to make objects like walls vibrate using actuators. It would significantly alter the way our homes and the objects within them are constructed and organized. Additionally, it would contradict the concept of ubiquitous and calm computing [100, 101].

One way to expand the range of haptic feedback is through haptic illusions [59]. These illusions can enhance haptic experiences beyond the capabilities of traditional haptic devices while adhering to ubiquitous and calm computing principles. Haptic illusions have been studied in cognitive science and human-computer interaction (HCI). While the first explores the fundamental workings of haptic illusions [22], the latter aims to apply this knowledge to create interfaces, applications, or feedback [56]. Despite the abundance of knowledge on illusions in cognitive science, HCI only utilizes a fraction of it [33, 59].

The advent of new and advanced technologies may have shifted and expanded the subset of illusions studied in HCI. Furthermore, haptic illusions are often studied in relation to specific technologies, and it remains unclear how they can be applied to other surfaces or technologies [P.1.1]. Previous research suggests that there may be differences in the perception of illusions among various technologies and between technology and reality [46, 91, 65].

Therefore, it is necessary to investigate how haptic illusions can provide feedback for ubiquitous and everywhere interfaces in a scalable approach with minimal hardware to maintain a natural and calm environment [69, 101, 100]. Additionally, exploring how existing approaches can be adapted to achieve this goal is crucial.

1.1 Main Contributions

This paper discusses the challenges and provides possibilities for utilizing haptic illusions to offer quality haptic feedback for interactions in ubiquitous environments.

Specifically, we investigate a scalable opportunity to create tactile feedback on everyday surfaces, providing as much additional hardware as possible and how this so-created feedback is perceived by users [P2.1, P2.2]. Further, we explore how illusions can create the feeling of perceiving vibrational feedback through the tactile sense [P3.1, P3.2]. Lastly, we investigate how to extend surfaces or existing devices to induce the feeling of shapes when interacting with flat, rigid surfaces [P4.1, P4.2]. To achieve this, we conduct user research, develop prototypes and applications by adapting existing or creating algorithms and interaction paradigms, and evaluate the systems in empirical studies. Thus, we show new possibilities for using haptic illusions to create rich haptic feedback and contribute to ubiquitous and calm computing. Additionally, we present design guidelines in this research field and suggest possible interesting future research directions.

1.2 Structure of the Thesis

The thesis is structured as follows: Chapter 2 provides an overview of previous research, explains key terms, and defines the area where we position the thesis contributions. Chapter 3 outlines the main challenges and presents the research questions. In Chapter 4, we summarize and evaluate the research paradigms and methods used to arrive at the contributions presented in Chapter 5. Our contributions to providing haptic feedback through haptic illusions in the context of ubiquitous and calm computing environments are discussed in Chapter 6. Chapter 7 positions our work in the broader perspective of haptic illusions in general by giving a summarized conclusion and provides an outlook for potential promising future research in haptic illusions and HCI.

Chapter 2

Background and Definitions

This thesis focuses on providing qualitative haptic feedback using haptic illusions to enrich interactions in ubiquitous environments. It further investigates how this can be achieved with as little hardware as possible and relies on users' cognitive abilities. Therefore, this section starts by explaining illusions and haptic illusions, including their definition and scope in this work. It then explores the use of haptic illusions in HCI and their potential. Additionally, the concept of multisensory perception is explained, highlighting its importance in utilizing haptic illusions.

Finally, this section will explain this thesis' contribution to creating ubiquitous and calm environments and its potential benefits for the user.

2.1 Illusions

The simplest definition of an illusion is the departure from reality or truth. An illusion can be understood as a perception generated by static stimuli, changing the perception based on variable conditions [33]. As science and technology advance, reality can often differ from appearances. However, to call this separation an "illusion" would suggest that most perceptions are illusory[30]. Therefore, a more precise explanation is necessary that considers the subtleties of different illusions.

Illusions can be separated into two groups: those with a physical cause and cognitive illusions [30]. The first can be caused by the interference of light between objects and the eyes and by the interference of sensory signals in the eyes. Cognitive illusions, on the other hand, are caused by the brain's misapplication of knowledge when interpreting or processing sensory signals. In this thesis, the illusions used will always be cognitive ones.

Illusions have been known and studied scientifically for over 100 years, primarily in relation to the visual sense. One example is the Müller-Lyer illusion, discovered in 1889, where a line of the same length is perceived differently depending on whether its ends are enclosed between two angles whose tips coincide with the line ends or the tips point outwards [39]. Such visual perceptions or illusions were described as unconscious inferences from sensory data and knowledge derived from the past [98]. Researchers have investigated existing illusions and discovered new ones during this extended period [29]. It is important to distinguish between existing illusions and their mechanisms to understand how we can create haptic feedback with illusions.

Although illusions were initially studied in relation to the visual sense, research in the early 90s explored whether and how visual illusions can also occur in the haptic modality [90]. Therefore, seven different geometrical illusions were evaluated, and it was discovered that three of them also occurred in the haptic modality, such as the Müller-Lyer illusion. Conversely, three illusions that differed from the original visual outcomes affected the haptic modality. Lastly, one illusion could not be reproduced in the haptic modality. Subsequent research has confirmed the frequent occurrence of discrepant outcomes and conclusions in the literature regarding geometrical illusions in both the visual and haptic domains [28]. The impact of visual illusions cannot be directly applied to haptic illusions. Thus, further research is necessary on haptic illusions related to cognitive perception.

2.1.1 Haptic Illusions

To understand a haptic illusion, defining haptic and explaining the process of perceiving haptic feedback is necessary. While some may interpret haptic perception as solely tactile, it encompasses more than tactile feedback [31]. Haptics includes both interception (internal perception of living beings) and exteroception (external perception of living beings) [31]. Therefore, haptic perception includes the following aspects:

- Haptic Sensitivity (exteroception)
- Proprioception (interception)
- Visceroception (interception)
- Pain Perception (exteroception)
- Temperature Perception (exteroception)

Thus, haptic refers to perceiving a physical object's properties through cutaneous and kinesthetic cues [60, 67]. Humans perform exploratory tasks to perceive objects' properties, such as texture or weight, as haptic feedback [61]. Perception of haptic properties is accomplished by generating or simulating the sensations usually present during haptic exploration based on our experience [83, 88]. Research proposes various approaches and systems to deliver realistic haptic sensations [2, 16, 82, 99]. Providing haptic feedback through various technologies, such as encounter-type systems [66, 17] , wearable devices [13, 34, 109, 103], or touchscreen devices [2], has several limitations. Limitations may arise due to high costs, limited workspace, or the disturbance of natural exploration of objects caused by covering parts of the skin or environment and restricting user mobility. In some cases, incorporating actuators or sensors into the environment may not be practical or feasible. Even if possible, it may not always have the desired effect [P3.1, P3.2]. To address the limitations of active haptic systems, haptic illusions can artificially induce the perception of haptic properties. Further, they can help minimize the need for additional hardware and contribute to inducing haptic sensations regarding ubiquitous computing [59, 100]. In the context of illusions in general and visual illusions, haptic illusions can be explained as sensory illusions that represent an alternate perception of haptic experiences due to a discrepancy between reality and perception [22, 20]. Further, the haptic illusion can be understood as a process where a method, sometimes an illusion, is used to induce an object property that might not be there or differ from it in reality.

Haptic illusions can be divided into two categories: intramodal haptic illusions and crossmodal haptic illusions [28]. Intramodal haptic illusions occur when only haptic perception is present during the exploration and perception of object properties [28]. This category covers only a fraction of the illusions known in cognitive science. On the other hand, crossmodal haptic illusions involve multiple senses during the exploration and perception of object properties. The second category occurs frequently and encompasses many illusions studied in cognitive science. Combining multiple senses to create a haptic illusion is also known as multisensory perception or illusions [23, 20, 22].

2.1.2 Multisensory Perception

Multisensory perception was addressed and explained in prior works in cognitive science [22, 23, 21, 20]. They showed that the visual and haptic senses involved in creating haptic sensations are combined into one perception, similar to a maximum likelihood estimation model (MLE) [75, 70]. In statistics, MLE refers to a parametric estimation procedure [24]. The MLE principle states that the probability distribution that best fits the observed data is the one that maximizes the likelihood function [24, 70]. Therefore, the parameter vector that maximizes the likelihood function must be found.

In HCI, all senses involved in inducing a haptic sensation will detect certain stimuli and induce different haptic sensations that may be discrepant [20]. Individuals rely on their experiences and finally perceive the feedback they trust the most. Therefore, feedback perceived by one sense can overwrite the feedback perceived by another sense. The relationship between the senses and their influence on haptic perception has been extensively studied to determine how they influence each other and if certain senses have a greater impact than others [20]. Results show that there are pairings of senses where it depends on the interaction and the respective scenario, which of the two is the more dominant sense and overrides the other, e.g., in the case of the sense of touch and the auditory sense [38]. However, research indicates that the sense of sight is the most dominant of all the senses and usually overwrites the others [86]. This was confirmed in later studies, such as in the perception of surface texture or the estimation of object stiffness [18, 62].

Multisensory perception is crucial in creating haptic illusions, as both rely on the same phenomenon: creating a discrepancy in our perception of the environment [20]. All senses can be stimulated through others. This feature enables the creation of various haptic sensations and feedback that may not be achievable through hardware, such as weight or stiffness [43, 73, 10, 95].

With an understanding of haptic illusions and their creation, we will explore their usage in HCI.

2.2 Illusions in HCI

The use of haptic illusions in HCI primarily focuses on two domains: (1) visual-induced haptic illusions and (2) tactile-induced haptic illusions, precisely phantom sensations or tactile apparent motion.

The emphasis on the first domain can be attributed to the visual sense's dominance over other senses and ease of stimulation [86]. The rise of new visual feedback technology, such as VR headsets, has increased the influence of new technologies on research related to haptic illusions. VR enables the creation and control of immersive environments and visualizations of users' bodies (avatars), which can be used to extend known illusions, such as the rubber hand illusion [5, 85], and create new ones. On desktops, haptic illusions on textures and force feedback were created using the control-display ratio (CD ratio), mostly indirectly via the cursor [57, 58, 68]. In virtual reality (VR), these illusions can be directly applied to users, creating new illusions such as weight perception [84].

The second domain of focus is phantom sensations, which is the most widely used and researched illusion [P1.1]. This is because they can be created with cheap and easy-to-implement hardware while also producing a variety of haptic sensations, such as funneling [9, 37], saltation [47, 63], or system onset asynchrony [14, 11]. Furthermore, vibrotactile feedback is a familiar concept to users due to its implementation in many everyday devices, providing reliable feedback.

In addition to these two domains, many illusions from cognitive science have yet to be explored in HCI. This is because of impractical requirements, such as the Aristoteles illusion, which requires a very specific set-up [93]. Implementing the illusion would require new methods to make it appear, which might also require new hardware [P1.1]. Lastly, some visual illusions might lead to different outcomes when used as haptic illusions [90].

This demonstrates that individual illusions frequently rely on particular hardware and specialized configurations. Numerous individual setups would be necessary to offer various illusions to exhibit diverse object properties as feedback. This would occupy significant space and significantly alter our familiar environment. In the long run, this would impact users who desire a natural yet interactive environment [108, 64]. Therefore, it would not align with ubiquitous and calm computing [100, 101, 69].

2.3 Ubiquitous and Calm Computing

Ubiquitous and calm computing are two terms Weiser envisioned in the 1990s. While they describe similar principles and aim for the same overall vision, there are still differences [100, 101, 94].

Ubiquitous computing's basic principle describes that the most profound technologies are those that disappear and that they will weave themselves into the fabric of everyday life until they are indistinguishable from it [100]. This means that information processing allows access to personalized services at any time and from any location, regardless of the type of access. This does not just refer to computers that users can carry to use in different places. Instead, it describes the vision that all objects and devices in our environment contain computers or sensors that are networked with each other to collect, analyze, and exchange data and information to relieve people of work and make everyday life easier, for example, by relieving them of routine tasks.

Calm technology should remain in the background until needed but be readily available with full functionality when the user desires interaction [101]. For a technology to be considered calm technology, it should adhere to three core principles:

- The user's focus should primarily be on the task at hand, with technology as a peripheral aid. This means the technology should be accessible and not distract from the primary task.
- The technology enhances the user's peripheral awareness, creating a pleasant user experience by providing just the right amount of information without overwhelming them.
- The technology provides the user with a sense of familiarity and enables them to be aware of their surroundings at all times.

The implementation of calm technology is combined with ubiquitous computing to reduce the noticeable interference of computers in daily life [94]. The aim should be to create haptic sensations through cognitive haptic illusions following these terms.

2.4 Research Gap

Although some illusions and object properties have been extensively researched, others have not been investigated thoroughly. Illusions should be viewed as creating haptic sensations to perceive object properties, and not all illusions are suitable for haptics [90]. Therefore, it is necessary to find new methods to create the illusionary perception of an object's property. Like in multisensory perception, stimulating more than one sense may be necessary to create a robust and rich haptic illusion. Therefore, further research is needed to understand the interaction between different senses and haptic sensations. Some senses are rarely used, and the results of their interaction vary depending on the illusion, object properties, technologies, and whether they are used in real life or with a specific technology [P1.1].

Research was conducted to address the gap in knowledge resulting from the evolution and emergence of new technologies [P1.1]. Additionally, prototypes were developed by extending existing technologies or devices to induce new haptic sensations [7, 49], implement multisensory perception [4, 97], or provide feedback on object properties using new technology [32, 92] in various environments and scenarios [96, 12]. The research primarily focused on prototypes and their potential rather than practical implementations or everyday applications [81, 35, 45]. Additionally, the prototypes were designed for specific scenarios, setups, and locations, often requiring additional hardware and equipment attached to users or the environment [25, 72, 27, 71, 74]. In recent years, research has emphasized the significance of natural users and environments and explored the contribution of haptic illusions to this [108, 64].

In parallel, new technologies have also emerged that can support such approaches. One exemplary technology is AR, which can be seen as calm and ubiquitous. It puts a virtual digital layer onto the existing physical world instead of integrating technology into our environment and surrounding objects.

Research is pointing toward creating haptic illusions while simultaneously having a ubiquitous and calm environment. However, more research has to be done to address the aforementioned research gaps, and this thesis aims to address some of them.

Chapter 3

Research Challenges

The previous section explained important concepts related to this work and highlighted the benefits of creating haptic illusions to establish rich, ubiquitous, and calm computing environments. However, the previous section also identified challenges and research gaps that arise when new technologies or methods are used to create haptic sensations in ubiquitous computing, leveraging existing knowledge. Therefore, this section will define several challenges and research areas in haptic illusions examined in this thesis. These research areas will be discussed in the context of haptic illusions, and the resulting research questions will be presented.

Haptic illusions are constantly evolving due to new technologies and possibilities. The primary objective of this study is to provide an overview of current and past research on haptic illusions.

Research area 1: Survey on Haptic Illusions (Explore the knowledge of haptic illusions in cognitive science and HCI and identify any research gaps).

Following the vision of ubiquitous computing, computers can be everywhere around us but are indistinguishable from the fabric of everyday life [100, 101]. By turning this around, it can also be understood that every object or surface in our environment can be used as an interface. This idea of ubiquitous graphical user interfaces that can be used on all everyday surfaces has been explored in previous work and referred to as everywhere displays [76]. It offers an alternative to carrying laptops and installing displays on furniture, objects, and walls. Additionally, it has the potential for extension through AR. Everywhere displays were initially focused on providing visual feedback from the interfaces. The presentation was displayed on all available surfaces using a projector and mirror from a central location. However, future challenges must be addressed, such as providing haptic feedback. These challenges arise due to the varying characteristics of the surfaces, including their material, size, and weight [32, 43, 26, 106]. Additionally, a research area arises from the challenge of creating natural surfaces that provide tactile feedback, potentially incorporating visual feedback from a central point, even without additionally embedded actuators.

Research Area 2: Everyday Surface Illusions (Creating the perception of calm, qualitative tactile feedback on everyday surfaces).

In this context, the question arises as to which types of tactile feedback can be provided without actuators, as they are either undesired or impossible to implement. Haptic illusions that appeal to the tactile sense are primarily based on vibrotactile feedback [P1.1]. Previous research has shown that vibrotactile feedback can create several haptic illusions, including stiffness, weight, and texture [12, 106, 92]. However, the generation of vibrations is highly dependent on actuators, which conflicts with the intended purpose of this thesis. This conflict gives rise to the second research area.

Research Area 3: Vibration Illusions (Creating tactilely perceptible vibrations on any everyday surface by stimulating other senses, such as sight and hearing, without using actuators).

The two preceding research areas indicate a specific need for further investigation into the provision of tactile feedback. Although visual feedback has improved significantly due to advancements in technology, methods, and algorithms, the same cannot be said for tactile feedback, which is generated using nearly identical methods and hardware [P1.1]. The initial research suggested that providing perceptible feedback could improve perception and user experience. In recent years, research on shape-changing interfaces has increased, leading to the emergence of various experiments, methods, and prototypes [36, 25, 72]. However, many of these prototypes are based on expensive hardware and are large and noisy, as they often focus solely on the prototype itself [1]. This poses a challenge for ubiquitous computing, the third research area.

Research Area 4: Shape Illusions (Creating different perceptible shapes on rigid everyday surfaces and integrating them into daily devices).

The following section provides a detailed outline of the research questions addressed in these areas and the main lines of research within these domains.

3.1 Everyday Surface Illusion

Generating tactile feedback on everyday surfaces is challenging due to their varying characteristics, such as material and size. All surfaces have an individual eigenfrequency that, when played through a loudspeaker, can cause them to vibrate [77, 15]. This method generates tactile feedback on surfaces scalable from a single point, even for different surfaces. However, it is essential to note that the tactile feedback is generated on the entire surface. The objective is to assign feedback to specific elements of an interface located on the everyday surface rather than to the surface as a whole. This raises the following research question.

RQ 1: Can vibrotactile feedback be assigned to a passive graphical object displayed on a wooden board vibrating with a resonant frequency?

Furthermore, it is crucial to consider the generation and assignment of feedback to graphical elements on the everyday interface and any relevant laws from other technologies that may be transferable. Previous research has shown that higher latencies between touch interaction and resulting feedback can cause the pressed element to be perceived as heavier [41]. Furthermore, it is widely recognized that elements within an interface can vary in size and, as research on haptic illusions has shown, size can affect the perceived weight of an object [32]. However, it is unclear to what extent these phenomena occur on everyday surfaces. The absence of perceived latency in the first research question and the potential for variations in perception between technologies raises the following research question.

RQ 2: Does a feedback delay and/or the size of a button on an everyday surface influence the perception of the button feedback when touched?

3.2 Vibration Illusion

Vibrations are commonly used to convey status changes or tactile feedback and to create haptic illusions [P1.1]. To ensure a ubiquitous environment, vibrotactile actuators should be avoided. It is necessary to determine which other senses need to be stimulated and how to create the resulting tactile feedback or the perception of a vibration.

In this context, another problem arises. Usually, the sense of sight is the strongest of all senses [86]. Visual feedback is not commonly used or recognized in the perception of vibrations and may not be familiar to many users. The creation of haptic illusions is based on the idea that most trusted stimuli can override other senses based on personal experience [20]. Therefore, the first step is to determine what a visual representation of a vibration would look like. This leads to the following research questions:

RQ 3: How can we improve the impression of visually perceiving a vibration of an object?

RQ 4: Can we induce the feeling of perceiving a vibration as tactile feedback by stimulating the visual and auditory senses?

3.3 Shape Illusion

Research on shape-changing interfaces exists, but such interfaces are primarily large, expensive, and noisy [1]. Additionally, they have drawbacks in several aspects of their resolution [81]. Furthermore, they are often not application-based, may not be used on the go or in everyday life contexts, and are challenging to integrate into commonly used devices like smartphones or laptop touchpads [1]. To align with ubiquitous computing, the environment should remain as natural as possible, meaning that most surfaces are flat and rigid, which is also the case for the devices this approach can be integrated into, i.e., smartphones. Given these considerations, the following research question must be explored.

RQ 5: Can we induce the feeling of perceiving a shape when touching a flat, rigid surface?

After researching the possibility of conveying different shapes on a flat, rigid surface, the potential for conveying feedback may be limited. Even if you detach a device's screen, such as a smartphone, from the rest of the device and make it movable, the range of motion is limited. The aim was to determine if other senses, like the visual sense, could be utilized to expand feedback, such as through a discrepancy between actual movement and visual perception (C/D ratio), and to what extent this discrepancy goes unnoticed to generate a haptic illusion [P1.1]. This method has broadened the range of other haptic illusions and object properties such as weight [43, 84, 73, 80], texture [57, 68], stiffness [102, 10], and size [3, 107]. The study investigated the following research question.

RQ 6: Can we visually manipulate the actual size of a tactile perceived shape?

Chapter 4

Research Approach and Methods

In this section, we first elucidate how our work is situated at the intersection of computer science and technology and how this relates to research paradigms in HCI. Furthermore, we demonstrate the interrelationship between psychology and cognitive science with HCI and elucidate the necessity of this relationship for our work. The second part continues with a description of our specific research methods. This section describes the rationale behind the development and evaluation methods employed in the various projects, accompanied by a retrospective assessment of the benefits and challenges associated with these methods.

4.1 Research Paradigms

Although this work is fundamentally based on the field of HCI, it also builds to a large extent on fundamental knowledge from cognitive science and psychology. These insights are combined into an overall basis for this work. All knowledge on which the work is based has been repeatedly evaluated and confirmed and can be taken as "reality" due to its long existence [60, 59, 33]. However, it must always be adapted and expanded based on constant developments in science or technology. It is evident from research in HCI that haptic feedback is crucial and capable of enhancing user experiences when interacting with interfaces and devices [8]. This is a valuable outcome in any field. However, feedback provision and generation are constantly evolving due to the emergence of new methods, hardware, interaction methods, and technologies. In AR or other technologies such as projectors and in interaction with everyday objects and surfaces, it is desirable to leave the user, at least the fingers and hands with which interaction such as touch mainly takes place, and the surfaces as natural as possible [64, 76]. Any additional elements would be fatiguing, tactilely, or visually distracting, distorting the experience of touching the surface [108]. This would impair the creation of haptic sensations, as is known from cognitive science [20, 22]. However, cognitive science and psychology also provide initial insights through research and knowledge on illusions in general and haptic illusions in particular, which can be used to improve and adapt haptic feedback and thus enhance the user experience. These three areas thus provide us with the theoretical basis for what is referred to in the research paradigm as research philosophy (ontology and epistemology) [44, 48, 78].

This research philosophy, in conjunction with existing knowledge and identified research gaps, has led to the development and testing of concepts that serve to expand knowledge in the field of haptic illusions, which is referred to as methodology in the research paradigm [44]. The technologies employed were also developed in accordance with the research philosophy and state-of-the-art technologies, such as the Hololens 2 in the AR area. Prototypes and concepts were developed and constructed that are not currently available but can simulate everyday situations and objects (e.g., the simulation of the surface of a wooden table as a possible interface, such as using a projected keyboard). This was done to validate the application of the prototypes and concepts in everyday situations and environments. The precise methodology employed will be elucidated subsequently in this chapter. This potential utilization in everyday contexts and the augmentation of devices, objects, and surfaces employed daily also motivate the individual works presented and discussed in this thesis.

This thesis represents a fundamental investigation into the domain of HCI with regard to haptic illusions [59]. The overarching objective is to identify methodologies and principles for generating haptic feedback with minimal additional hardware, thereby paving the way for the realization of ubiquitous computing. Moreover, this thesis endeavors to utilize the full potential of the surrounding environment as an interface. In this process, existing concepts will be subjected to a comprehensive review, and, where necessary, adapted or new avenues for exploration will be identified. Research contributions of this work in the field of HCI are survey contribution (as we surveyed haptic illusions in the domain of HCI [P1.1]), empirical contribution (assignment of haptic feedback on everyday surfaces, or basic understanding of new illusionary feedback sensations like vibration illusion [P1.1]), artifact contribution (using sound to generate haptic feedback in ubiquitous environments [P2.1, P2.2]), and theoretical contribution (extend existing knowledge to new technologies and provide design guidelines for haptic illusions in certain situations [P2.2, P3.2, P4.2]) [105].

This work builds upon existing knowledge about haptic illusions and applies them to create haptic sensations for calm and ubiquitous environments. At the same time, it identifies potential research areas for the future.

4.2 Design Processes

This work is not designed to target a specific demographic or context. Instead, it aims to establish a foundation of knowledge that can be leveraged to generate reliable haptic feedback through less hardware and a greater focus on the human cognitive sense. To this end, a survey was initially created to gain an overview and, in conjunction with the existing knowledge from all the research areas utilized, identify potential future developments and research gaps [P1.1]. Based on the survey and the resulting research areas and research questions, concepts and prototypes were developed that also build on knowledge from related work. The concepts and applications were designed to be understandable and usable for everyone, which was also considered when selecting the study participants.

4.2.1 Survey

A structured literature review was created to provide a general overview of existing knowledge on haptic illusions from the research areas involved [P1.1]. The survey also served as a general overview of related work, which could later be extended to the individual topics and research questions. However, initially, it provided basic knowledge. Furthermore, the survey made it possible to create the three research areas presented in this work, as it was determined during the survey that there might still be a lack of knowledge in these areas. Moreover, the work demonstrated how multisensory perception is utilized and how the senses interact with each other. Although there is a hierarchy of senses, the relative dominance of each sense varies depending on the method, illusion, and order of technology employed. Additionally, the combination of senses has been observed to enhance haptic feedback perception in certain instances but also sometimes not. The survey thus provided insights into the considerations that should be taken into account in future studies.

4.2.2 Concepts & Prototyping

Based on the existing knowledge, concepts were developed to address existing research gaps. For instance, creating haptic feedback from a central point for several objects via sound was proposed [P2.1, P2.2]. In most cases, these developed concepts were then first evaluated technically to ascertain their feasibility and identify potential challenges, such as system latencies [P2.1, P3.1, P.3,2] or frame rates on devices such as the HoloLens 2 [P3.1, P3.2].

Once the technical evaluation was complete and the prototype was deemed suitable for use, various conditions were tested using existing knowledge, such as the stimulation of different senses. A small team of several researchers tested possible conditions from literature, everyday life, or other areas such as music, art, or computer science. Possible framework conditions, such as limits of stimuli and possible intermediate values, were also tested in such teams. This was done to identify and exclude non-functional cases in advance, thereby reducing the time required for the study without compromising its overall value.

All prototypes were self-constructed and, in some cases, adapted and developed over several iterations. The programs running on them were also written by myself or with team assistance. Still, we also used existing libraries (Capacitive touch on the Arduino) and then adapted them for my own use. These used libraries were mostly basic functions that served more as tools to create a desired illusion, and their development was time-consuming and unnecessary. As the developer and writer of both the prototype and the program, we could identify and solve any problems that arose at any time, especially during a study. This also allowed me to implement automated data collection and use my own evaluation interface, which was relevant to the study and its evaluation. For example, we could immediately implement response buttons after a condition. These points allowed for quick adjustments but still had sufficient functionality for lab studies.

4.2.3 Related Work

As with the survey, the related work helped us to identify research gaps and provided design suggestions. In contrast to the survey, which considered haptic illusions as a whole, the related work enabled us to examine the individual cases in greater detail. This resulted in a more comprehensive understanding of the interplay between the senses and the specific roles that individual senses and methods can play in different types of haptic feedback. It also demonstrated how concepts differ between technologies and the potential adaptation possibilities or alternatives that can be considered. The related work was also crucial in determining the most appropriate methodology for data collection, as there is typically no standardized questionnaire for the assessment or perception of haptic feedback, and single-item questions are frequently employed [P1.1 - P4.1], [80, 79, 89, 42]. All of these considerations were essential in developing a robust study design for the different studies and ensuring the validity and generalisability of the results.

4.2.4 Participants

As this work is not aimed at a specific focus group but instead aims to explore the general principles for creating and improving haptic feedback with the help of illusions, the studies also attempted to recruit participants from diverse backgrounds. This was done to gain a broader spectrum of feedback and prevent the results from being influenced by any particular bias. Participants were recruited from different scientific areas and with different personal backgrounds that differed from HCI, technical, or computer science [P2.1 - P4.2]. The number of participants was generally adjusted to the study design to ensure sufficient data collection for the generation of valid results. When the study design set the number of subjects at an unattainable level, the corresponding specifications and study designs from related studies were adhered to, as exemplified by the work that employed a psycho-physical approach [P4.2].

4.3 Research Methods

Quantitative and qualitative data were collected in almost all the papers to evaluate the concepts, experiments, and prototypes. The only exception is the work on the possible influence of visual stimuli on the tactile perception of the size of shapes on flat surfaces, which followed a psycho-physical approach. Only quantitative data was collected in this work, as the study time would otherwise have been unreasonable and sufficient to obtain the necessary findings. Collecting both quantitative and qualitative data made it possible to obtain the data and identify potential explanations for the observed outcomes.

Furthermore, the qualitative data enabled the identification of potential future research challenges.

As previously stated, most studies employed single-item questions rated on a 7-item Likert scale. Consequently, most of the methods employed were designed to evaluate non-parametric data. When feasible, attempts were made to utilize the aligned rank transformation to transform non-parametric data into parametric data [19, 104]. This was then subjected to appropriate static methods, such as ANOVA, for analysis and detecting potential interaction effects. For other types of data, corresponding statistical methods were employed, such as in the psycho-physical study [P4.2] or when dichotomous data were available (McNemar tests) [P4.1]. All statistical methods used are commonly employed in HCI, focusing on methods used for the specific cases at hand [55]. This allowed for a direct comparison and understanding of the evaluation of the different variables tested.

All studies were conducted in a laboratory setting. This is crucial for the work at hand, as it pertains to the investigation of illusionary haptic feedback. To accurately assess the influence of the individual senses being tested, it is essential to neutralize any external interference factors that could potentially distort or influence perception. Consequently, in some studies, senses that were not tested, such as the sense of hearing, were also neutralized with the help of noise-canceling headphones and white noise to rule out any interference from senses that were not tested. In this case, the sense of hearing could potentially overwrite others, thus falsifying the results. To prevent the influence of extraneous variables on the results, all conditions were counterbalanced in the studies employing a Latin square design. Additionally, all studies were initiated in person, with a study leader present to address any issues or errors in the prototypes or programs.

The qualitative data was collected through semi-structured interviews conducted after each condition. This approach allowed for a comprehensive understanding of the individual conditions and facilitated the interpretation of the quantitative data. During the evaluation of the prototype or the general concept of the possible perceptible shapes on rigid flat surfaces, a final interview was conducted to solicit feedback, suggestions for improvement, and potential application areas. This feedback was essential for the design process and identifying future avenues for improvement and investigation.

All participants were volunteers and free to withdraw from the study at any time. Additionally, all participants provided informed consent before the study's commencement. All data was collected and used anonymously.

4.4 Method Reflection and Limitations

While the advantages of self-built prototypes and self-written programs have already been elucidated, both have certain disadvantages. It was necessary to utilize finite resources to ensure the prototypes remained reasonable in their construction and development. Consequently, precision, speed, or stability functions could have been somewhat limited. This, however, has a negligible disadvantage since it applies equally to all conditions. Furthermore, the results could possibly have been better in themselves, possibly overall, but their weighting to each other would have remained the same. In addition, all used prototypes and programs have been tested to function reliably and clearly provide and convey the desired feedback. Moreover, the prototypes were primarily designed for specific use cases and were constrained from being confused or distracted by additional functions. The focus should be on the variables to be investigated and the interaction possibilities. In essence, the application of these variables would differ in subsequent cases.

The same principle applies to the representation of interface elements. These elements, such as buttons, were designed to be neutral to prevent distortion of the study results due to their appearance. The overall results would be expected to improve in a more realistic design, which would be the case for all conditions.

A small research team evaluated all prototypes before their use in the studies to identify any non-functioning variables. This research group had a similar background, which may influence how interactions are evaluated. In the studies, a heterogeneous spectrum of participants was recruited to obtain a more general, generalizable result across several user groups. Nevertheless, the results are valid primarily for the people also covered in the studies.

Moreover, examining how perceptions and assessments of haptic feedback evolve over time would be valuable. On the one hand, familiarity with interaction and feedback could potentially enhance their effectiveness. Conversely, habituation to stimuli could potentially diminish the impact of haptic illusion. To accurately assess this phenomenon, additional long-term studies are necessary. Nevertheless, the laboratory studies have yielded valuable insights and provided a foundation for understanding the fundamental functions and behaviors. To advance this understanding further, it is essential to implement these concepts in real-world settings. This will serve as the basis for developing and constructing reliable prototypes. However, implementing and developing such prototypes may not be feasible or cost-effective.

Chapter 5

Publications

This chapter presents the publications on the research areas and research questions presented in Chapter 3. The publications are grouped into four sub-domains: 'Survey on Haptic Illusions', 'Everyday Surface Illusions', 'Vibration Illusion', and 'Shape Illusion'. A brief summary is provided for each publication, and the individual papers are placed within the larger framework of this thesis. The publications are presented in the order of the research questions. Table 5.1 presents an overview of the publications by research question, method, contribution, evaluation, and technology.

5.1 Survey on Haptic Illusions

Sensory or haptic illusions have been widely investigated in perception or cognitive research. Over the past few decades, they have also become increasingly important in the field of HCI in generating haptic feedback in various scenarios. Haptic feedback is one of the most crucial input channels to enhance user experience [8]. Human haptic perception is multifaceted and comprises information received through many different senses. These various senses, which are all components of haptic feedback, include, for instance, cutaneous sensing, such as tactile or temperature perception [67], as well as proprioception and kinesthesia, which relate to the body's pose, its movement, and the perceived forces that originate internally and externally [87]. Due to the diverse interplay of different senses and perceptions while exploring objects, devices, or the environment, technical devices such as a controller or a mouse can't generate appropriate haptic feedback that accurately and realistically reproduces all points. One way to enrich this feedback is to use and stimulate the human mind to generate rich feedback covering all aspects. We conducted a systematic literature review to understand and overview how this can be done [P1.1].

This survey examined the current state of knowledge regarding illusions in cognitive science and the application of this knowledge in HCI. One of the findings was that the most recent overview of haptic illusion possibilities in HCI is over 20 years old [59]. Therefore, in our survey, we examined works created after this last survey and used the existing work to expand the knowledge base and demonstrate changes in recent years [P1.1]. The survey

Publication	Contributions	Evaluation Methods	Technology
		Research Area 1: Survey on Haptic Illusions	
[P1.1] Survey (ACM Computing Surveys) [53]	Present an overview of which and how illusions known from cognitive science are used in HCI and which are underrepresented.	Systematic Literature Review	-
		Research Area 2: Everyday Surface Illusions	
[P2.1] Assignment of a Vibration to a Graphical Object (INTERACT) [52]	Explore a scalable possibility to stimulate an everyday object to create tactile feedback (resonant frequency) and investigate parameters to assign the tactile feedback to graphical objects	Within-Subject Lab-Study ($n = 24$) with quantitative and qualitative measurements	Resonance Frequency & Touch Interface Button on Everyday Surface (Wooden Board)
[P2.2] Resonant Sticker Buttons: The Effect of Button Size and Feedback Latency on Perceived Button Weight and Vibrotactile Feedback Strength (MUM) [54]	Using resonance frequency to induce and influence object properties (weight)	Within-Subject Lab-Study ($n = 28$) with quantitative and qualitative measurements	Resonance Frequency & Touch Interface Button on Everyday Surface (Wooden Board)
		Research Area 3: Vibration Illusions	
[P3.1] Increasing Realism of Displayed Vibrating AR Objects through Edge Blurring (MuC) [50]	Present guidelines how vibrations can be presented visually on AR HMDs without the need of powerful computers	Within-Subject Lab-Study ($n = 20$) with quantitative and qualitative measurements	Augmented Reality HMD (HoleLens 2)
[P3.2] Vibrollusion: Creating a Vibrotactile Illusion Induced by Audiovisual Touch Feedback (MUM) [51]	Present factors that have to be considered to induce the tactile feedback of feeling a vibration by stimulating the visual and auditory sense	Within-Subject Lab-Study ($n = 18$) with quantitative and qualitative measurements	Augmented Reality HMD (HoleLens 2)
		Research Area 4: Shape Illusions	
[P4.1] MovPad: Feeling Holes and Bumps using a Moving Touchpad.	Explore the possibility and present guidelines on how we can induce the feeling of perceiving shapes while touching a flat rigid surface	Within-Subject Lab-Study ($n = 20$) with quantitative and qualitative measurements	Self-Build shape-changing interface prototype with touch display
[P4.2] Shape Perception: Influencing the Perceived Width and Height of Shapes Present on a Flat Rigid Surface	Explore how we can change the perceived size of a shape by visual feedback by creating a visual-tactile feedback discrepancy	Within-Subject Lab-Study ($n = 12$) with quantitative measurements (psychophysics experiment)	Self-Build shape-changing interface prototype with touch display

Table 5.1: Overview of all contributing publications in this thesis, structured by research area and summarizing their contribution, evaluation method, and used technologies.

yielded 90 works demonstrating the use of sensory illusions in haptic feedback and their implementation and evaluation in HCI. It also revealed which illusions and senses were most prevalent and which were underrepresented, along with explanations for these findings. The survey indicates that multimodal illusions, or those addressing senses other than sight and touch, have been underrepresented in research. However, they have the potential to contribute to future advancements. Furthermore, the survey identifies current trends and research gaps and discusses ideas for possible research directions. It also provides examples of interfaces and hardware that could benefit from further investigation.

Previous studies have demonstrated that not all known illusions are suitable for creating haptic feedback and, therefore, cannot be utilized in HCI applications [90]. Furthermore, the classification of illusions has thus far been based solely on the haptic property that an illusion targets. However, how we perceive the haptic properties of objects and space can vary depending on the interaction. For instance, forces acting on our hands can be interpreted differently. The perception of force may vary depending on the interaction. For instance, the weight of an object may be perceived as a force when lifting it vertically [84]. In contrast, the resistance or stiffness of an object may be experienced when pushing horizontally against it [49]. This illustrates that a single method of creating an illusion can target different haptic properties by changing objects' perceived shape, texture, and stiffness through a single method. We have developed this overview and introduced a novel dimension to the classification of haptic illusions to enhance their categorization for their utilization in HCI and provide an integrated overview for other scientists to reference and comprehend the specific object property created by which method, sense, and technology. Utilizing this classification, we have provided a comprehensive overview and discussion of how sensory illusions can create haptic feedback. The illusions that generate haptic feedback have remained consistent while the underlying technologies have evolved. Consequently, the fundamental methods utilized to create the resulting haptic illusions have also undergone change.

While ever-evolving technologies have enabled the adaptation and improvement of methods for stronger, more robust haptic illusions and the provision of entirely novel ones, our haptic perception and the haptic properties that these illusions can target remain unchanged. Rather than limiting us to ever-changing technologies, future research could focus on exploring illusions in more natural conditions to understand better how these illusions could improve our lives in the long term. Consequently, such methodologies can facilitate the creation of ubiquitous and tranquil environments while providing comprehensive qualitative feedback with minimal technological or hardware involvement.

5.2 Everyday Surface Illusions

To create a calm and ubiquitous environment while simultaneously providing the opportunity to generate haptic sensations on everyday surfaces that can be utilized as an interface, it would be a promising approach to generate tactile perceivable haptic sensations from a central point, analogous to the visual feedback envisioned in the work about everywhere displays [76]. To achieve this, we employed the phenomenon of resonant frequency. Given that every object, structure, or human body possesses an eigenfrequency, it is possible to induce vibration in the object by stimulating it with this unique frequency, for instance, by playing it via a speaker. This enables the activation of objects over a considerable distance and the stimulation of different objects via a single source without the necessity of directly attaching hardware to the objects or the environment.

5.2.1 Assignment of a Vibration to a Graphical Object Induced by Resonant Frequency

The ability to stimulate different surfaces from a single point provides the opportunity to utilize everyday surfaces as an interface and create haptic feedback on them by allowing them to vibrate. However, ensuring that the provided feedback will not be perceived from the whole surface but rather from a single interface widget or other representation placed on the surface is essential. This concept led to the formulation of the research question.

RQ1: Can vibrotactile feedback be assigned to a passive graphical object displayed on a wooden board vibrating with a resonant frequency?

To investigate this in our work [P2.1], we first explored the eigenfrequency of a wooden board that was part of a cabinet back panel and represented an everyday wooden surface that might be present on a table. We played the measured resonant frequency via a common shelf loudspeaker that is available for everyone. This speaker was placed under the wooden board without contact, so the speaker was out of sight for the participants. Furthermore, a graphical sticker representing a fly was placed on the wooden board. The speaker was activated upon contact with the sticker, playing the resonant frequency and allowing the wooden board to vibrate. Therefore, the capacitive touch library available on Arduino was employed. In addition to the assignment of the tactile feedback, we investigated two different touch durations, additional sound related to the touch interaction, and the latency between touching the graphical object and perceiving the feedback was tested. This was done to account for the system's latency. Inevitably, a specific latency will always be present, with the latency being approximately 100 ms in the absence of an external sound card and 35 ms with the use of an external sound card. Furthermore, it is well-documented that even small latencies, such as those in the range of 50 ms, between interaction and perceived feedback can significantly impact the user experience [40].

A total of 24 participants were recruited for the study, which was conducted in a laboratory setting. The results indicated that haptic feedback is assigned to a graphical object placed on an everyday surface if the feedback duration is equivalent to the duration of the touch and additional auditory feedback is provided. Furthermore, the qualitative feedback suggested that the assignment was supported by the realistic fly of the graphical representation and that the assignment might be increased. The haptic feedback was enhanced when the graphical representation indicated that an elevated shape was touched.

Consequently, we demonstrated that it can generate haptic feedback that can be assigned to widgets on everyday surfaces with minimal hardware and hardware that users may already possess at home. The haptic illusions work contributes to this thesis's overarching approach and the calm and ubiquitous computing domain.

5.2.2 Resonant Sticker Buttons: The Effect of Button Size and Feedback Latency on Perceived Button Weight and Vibrotactile Feedback Strength

By gaining an understanding of the ability to associate vibrotactile feedback generated via resonant frequency with graphical widgets that are part of an interface and present on an everyday surface, as well as the methods by which this can be achieved, it becomes pertinent to investigate the potential for varying the properties of widgets. Since widgets in an interface typically vary in size, it is also interesting to investigate how different weights could be induced for widgets of different sizes. This question is formulated in the following research question.

RQ 2: Does a feedback delay and/or the size of a button on an everyday surface influence the perception of the button feedback when being touched?

While this approach [P2.2] is investigated in the same research area as the work in [P2.1], the setup and method of providing feedback via resonant frequency are the same as described previously. We relied on two previous findings to investigate whether different weights can be induced in widgets that users interact with [41, 32]. Prior work has found that on tablets, the perceived weight of an interface widget is related to the perceived latency between touching the widget and perceiving the associated feedback [41]. Furthermore, the size-weight illusion is a well-known haptic illusion that is also used in current research in VR [32]. While both phenomena are well known, it was also found that haptic illusions and how they are perceived differ between the technologies on which they are implemented [65]. With this knowledge and the overarching goal of creating haptic feedback on everyday surfaces, it is worth investigating how these findings can be adapted.

In a laboratory study with 28 participants, we investigated three different button sizes and seven different latencies on a wooden board, again representing a wooden everyday object. We were able to make several design recommendations based on our findings. We found that a widget should at least be larger than the average finger width so that the widget is not completely covered by the finger, as this could interfere with feedback perception. In addition, a larger button was perceived as lighter and vice versa, and in terms of latency, latencies up to 58 ms were perceived as light, and latencies equal to or greater than 118 ms were perceived as heavy. As an additional insight, qualitative feedback also suggested that the perceived strength of feedback is influenced by button size, where a larger button size leads to weaker perceived feedback and vice versa.

The results help to understand how to design interfaces on everyday surfaces, which can help to design and build calm interfaces that contribute to ubiquitous computing. This could also be important in cases where haptic feedback technology is not feasible. In addition, we could extend previous findings on touch-based interface design and apply them to ubiquitous displays. We also proved that only a minimum of additional hardware is needed to create feedback sensations, such as inducing different button weights, which is one overarching goal of this work.

5.3 Vibration Illusion

The survey [P1.1] and the two papers on everyday surface illusions [P2.1] and [P2.2] demonstrated that vibrations are a prevalent method for inducing various haptic sensations, including those related to textures [12], funnel illusion [9, 37, 47], and others. This is due to the ease of implementation and the ability to create haptic feedback, coupled with the affordability of vibrotactile actuators [P1.1]. However, given the objective of maintaining a natural and quiet environment, installing vibrotactile actuators in all locations is not feasible. Furthermore, affixing vibrotactile actuators to large, immovable objects such as walls would be impractical, as they would not vibrate, and maintenance would be costly and time-consuming. This prompts the question of whether vibrational feedback can be created in a manner other than using vibrotactile actuators, with a greater reliance on the cognitive senses of humans.

5.3.1 Increasing Realism of Displayed Vibrating AR Objects through Edge Blurring

To create the haptic sensation of feeling vibrations due to the stimuli of other senses, it is first necessary to consider which senses can be used. The only senses that might be useful are the sense of sight and the auditory sense. While we are accustomed to hearing a vibration and having an idea of how this would match, this is not the case for the visual feedback of a vibration. Therefore, the following research question arises.

RQ 3: How can we induce the impression of visually perceiving a vibration of an object?

To investigate this in my work [P3.1], we tested 4 different visual presentations of a vibration on a state-of-the-art AR device. The AR device was used because it is a good technology that follows the vision of calm and ubiquitous computing. As mentioned, it can produce visual and auditory feedback while simultaneously allowing hand-free exploration of or interaction with the environment. The four different visualizations consisted of the baseline, which calculated a sine function to represent the object's vibrational motion, and three other visualization methods, like blurring the object and the background or using multiple objects. In addition, a control condition with no motion was added. The baseline method was used because it is common on other devices like desktop computers. However, it has drawbacks on the AR device, as the framerate drops significantly, and therefore, the motion does not look really smooth.

A laboratory study with 20 participants was conducted to evaluate the efficacy of various visualizations. The results demonstrated that the most effective visualization of a vibrating object on an AR device is blurring the edges of the moving object. This visualization is reminiscent of the blurring of vibrating strings on a musical instrument, such as a guitar. Additionally, the qualitative feedback from the participants supported the findings. This visualization can be utilized to investigate the potential for creating feedback sensations through other senses.

5.3.2 Vibrollusion: Creating a Vibrotactile Illusion Induced by Audiovisual Touch Feedback

With the findings of the aforementioned work [P3.1], we could now investigate if we can create the perception of feeling a vibration tactilely induced by other senses.

RQ 4: Can vibrotactile perception be induced by auditory, visual, or audiovisual stimuli?

In this study [P3.2], we employed blurring-edge visualization and auditory stimuli, or a combination of both. We conducted a laboratory experiment with 18 participants using a HoloLens 2, similar to the related study [P.3.1] and for the same reasons. Wearing the AR device, participants touched a virtual representation of an object, which, when touched, showed one of the stimuli or both in combination. Six distinct levels of visual and auditory feedback were presented, with the combination of both stimuli presented in ascending order to ensure the most realistic combinations possible. The virtual object was placed on a large, rigid object, which would make it hard to vibrate with vibrotactile actuators. The virtual object represents a widget of a thinkable virtual interface that might be present on the surface of everyday life.

In both studies [P3.1] and [P3.2], the virtual object used was kept neutral and simple: a square grey cuboid without a texture. This was done to avoid biasing the results, as visualizations that might be known from experiences might influence perception.

The results demonstrated that specific combinations of visual and auditory feedback can evoke the sensation of perceiving a vibrating object through the tactile sense. This study illustrates that haptic illusions can be employed to induce haptic sensations while maintaining the natural environment without the need for embedded actuators. The requisite hardware was designed to be as simple as possible and could be sustained by an AR headset. Furthermore, using even smaller AR glasses might be a viable option, as the method employed for creating the haptic sensation is computationally low. Consequently, it can be concluded that the cognitive perception of users can be relied upon to a significant extent to create a rich haptic sensation.

5.4 Shape Illusions

In recent years, visual feedback devices and methods have continuously evolved, leading to new possibilities for providing visual feedback and enhancing the quality of presented visual feedback, for instance, through increasingly high resolutions. This evolution is also evident in our survey, where the accessibility of new visual feedback hardware, such as VR, has led to the emergence of new haptic illusions and an enhanced user experience. This is also consistent with the visual sense being the most dominant of the five senses. In contrast to the evolution of visual feedback, haptic feedback has remained largely unchanged. As previously mentioned and evaluated in the survey (P1.1), most vibrotactile actuators are utilized to create vibrational feedback. While this can be employed to induce different object properties, there is potential for developing new tactile feedback sensations. As previously stated by the participants in the aforementioned work [P2.1], the assignment of feedback to a graphical object on an everyday surface could be enhanced by inducing the shape of the touched graphical object.

5.4.1 MovPad: Feeling Holes and Bumps using a Moving Touchpad.

Research investigating the possibility of inducing shapes of objects to users has increased over the last few years. These studies have explored different technologies to create shape-changing interfaces. The majority of these approaches have in common that they are large in size, expensive, and noisy. Furthermore, they rely on a lot of hardware that cannot be integrated into everyday life surfaces (like tables or walls) or everyday used objects (like smartphones or laptops). This is because they are constructed from individual pins combined to create a large surface area but with space between the pins, which would not be feasible for everyday surfaces that are commonly flat, rigid, and continuous. Furthermore, these devices have drawbacks in terms of their resolution[81, 45]. These points lead to the following research question.

RQ 5: Can we induce the feeling of perceiving a shape when touching a flat rigid surface?

To reduce some disadvantages, we investigated how to induce the perception of shapes on a flat, rigid surface in this work [P4.1]. Primarily, we targeted the resolution of the shape-changing interface in terms of granularity, curvature, and amplitude [CITEs]. Therefore, we constructed a device consisting of a tiltable and movable touchscreen that tilts and moves while users slide across the screen with their fingers to present a particular shape. To gain first knowledge about whether this can be achieved, we conducted a lab study with 20 participants. The objective was to determine whether subjects could distinguish between perceiving a bump and a hole, at what size this was possible, and whether there was a difference between seeing the operating device or being blindfolded.

The results demonstrated that it is feasible to induce a shape when interacting with a small rigid surface. There was no discernible difference between the perception of bumps and holes or between seeing the device and being blindfolded. In alignment with previous research on the weight perception of widgets on everyday surfaces [P2.2], we found that the perception was more accurate when the shape size was at least as wide as the average width of a finger (18mm). Qualitative feedback indicated that users could rapidly become familiar with such a device and that the most plausible use case might be to provide tactile feedback on topographical data. As an additional finding, we could also explore the fact that the size of the perceived shape was consistently underestimated. Further, for 18 mm and above sizes, this was always the same factor.

This study represents an initial investigation into the potential applications of shape-changing surfaces with high haptic resolution. Integrating such an approach into everyday touch interfaces such as smartphone screens or laptop touchpads could enhance the user experience. Although initially investigated for the aforementioned use cases, this approach could also be further implemented on everyday surfaces with the same setup to move and tilt the surface. Combined with AR, it could also be used to keep the environment and the hardware needed to move the surface as natural and calm as possible. Therefore, this approach could also be used to extend the feedback assignment related to the aforementioned needs of the participants.

5.4.2 Shape Perception: Influencing the Perceived Width and Height of Shapes Present on a Flat Rigid Surface

The preceding work enabled the acquisition of knowledge regarding the potential for presenting shapes to users on a flat, rigid surface [P4.1]. Consequently, the experiment and prototype can be transferred in its essential features to everyday surfaces or integrated into everyday devices such as smartphone screens or laptop touchpads. However, suppose this is accomplished by slightly modifying the touchscreen of a smartphone or touchpad of a laptop so that the screen or touchpad can move and rotate separately from the rest of the device. In that case, the range of possible movement is constrained. The devices have a limited dimension, so large movements are impossible. This can ensure that only a small number of shapes can be represented. Additionally, the difficulty in identifying small movements presents an additional challenge [P4.1]. This leads to the following research question.

RQ 6: Can we visually manipulate the actual size of a tactile perceived shape?

The visual display can be reduced or enlarged without affecting the tactile perception to facilitate the perception of a greater number of potential shapes. This discrepancy between visual and tactile feedback, which is deliberately created, is also referred to as manipulation of the control-display ratio and forms part of the field of pseudo-haptics. This approach allows the representation of object properties, such as size in this case, to be artificially extended without the need to modify the apparatus but by utilizing a haptic illusion. For the illusion to be effective, it is necessary to identify the range within which the discrepancy is not perceived.

A psychophysical experiment was conducted with 12 subjects to examine how much the perception of shape size can be altered. In this study, a specific factor increased or decreased the C/D ratio of three different widths and heights of the shape. Additionally, the prototype was tested in two distinct scenarios. The first involved direct interaction with the prototype's screen, which closely resembles the visual display of a smartphone. The second scenario involved using an additional screen, which simulated the experience of using a laptop with a touchpad.

Our findings indicate that for direct and indirect interaction, as well as for the width and height of shapes, we can manipulate the C/D ratios within a specific range. However, these ratios differ from each other. Nevertheless, we demonstrated that the C/D ratio can also be established on touchscreens to influence the perceived size. Commonly, the C/D ratio was utilized primarily in VR regarding all object properties and only in VR regarding the size of an object. Consequently, we were able to extend the findings in the field of haptic illusions and present design guidelines for the construction of devices in which flat rigid surfaces can be employed to induce the perception of shapes of varying sizes.

Chapter 6

Discussion

In this section, we first summarize and situate our research contributions within haptic illusions and ubiquitous computing. We then reflect on the results and contributions of this work and their corresponding application areas. The present work offers several possibilities for inducing haptic sensations based on haptic illusions to create ubiquitous and calm environments, which are discussed and reflected upon here by addressing limitations.

6.1 Summary of Contributions

The publications in this dissertation demonstrate how to generate rich haptic feedback with minimal additional hardware by leveraging the user's cognitive abilities. We will summarize the findings in accordance with the individual research areas introduced in Chapter 3.

6.1.1 Explore the knowledge of haptic illusions in cognitive science and HCI and identify any research gaps

The survey provides an up-to-date overview of how and which illusions known from cognitive science are used in HCI [P1.1]. Not every illusion is suitable for creating haptic feedback, and not all haptic sensations can be created via usable illusions to make all possible object properties tangible. Consequently, new possibilities must always be created. The development of new methods for creating haptic illusions has increased in recent years, which is also due to the emergence of new technologies that make specific methods possible or can significantly improve them [P1.1]. The survey, therefore, provides an up-to-date overview of which possible methods can be used to make object properties illusionary perceptible and also shows which technologies and senses (individually or in combination) are used. Through the analysis, the survey also shows promising future areas of research. The survey indicates that the continuous evolution of technologies or the advent of new technologies can give rise to novel methodologies. However, it also reveals that the perception of individuals remains unaltered mainly and that the cognitive characteristics of people themselves can contribute to the generation of haptic sensations. Consequently, we demonstrate that an increased use of hardware or the constant urge to develop new technologies is not always necessary. Furthermore, research can also rely on human capabilities in its investigations. This work contributes to the research area of haptic illusions and provides an overview and methods for other researchers exploring the creation of ubiquitous environments [100].

6.1.2 Creating the perception of calm, qualitative tactile feedback on everyday surfaces

To create ubiquitous environments, it is essential to maintain the environment in its natural state and to limit the number of hardware components as much as possible. To utilize everyday surfaces, such as tables, sofas, or walls, as interfaces, it is necessary to be able to generate feedback on these surfaces. Our research has demonstrated that the resonant frequency enables the excitation and vibration of a wide range of surfaces from a single point without the need to embed actuators directly on the surface [P2.1, P2.2]. Furthermore, this feedback can be perceived tactilely. We have demonstrated that the resulting feedback can be mapped to the surface and graphical interface elements located on that surface [P2.1]. Additionally, we have shown that the same setup can be used to assign specific object properties to the interface elements, such as different weights and feedback thicknesses in this case [P2.2]. This demonstrates that adding actuators to surfaces is not a prerequisite for creating haptic sensations or a ubiquitous interface with perceptible feedback and object properties. By elucidating fundamental principles, this knowledge can serve as a foundation for advancing and further investigating ubiquitous and quiet interfaces on everyday surfaces.

6.1.3 Creating perceptible vibration illusions on any everyday surface

The perception of vibrations can convey a wide range of different object properties or other haptic sensations. Consequently, they are often used to create devices or interfaces. However, when actual vibrations cannot be generated, it becomes necessary to stimulate other senses, such as vision and hearing, to achieve the tactile perception of vibration. To make hearing and seeing virtual interface elements available with little technology, we used a current AR device, the HoloLens2 [P3.1, P3.2]. Furthermore, this device enables natural interaction with hands and surfaces without additional hardware. The work demonstrates how the visual representation of a vibration can be rendered as realistic as possible, even in devices that are not particularly powerful [P3.1]. It also illustrates how visual and auditory stimuli must be combined to create the sensation of perceiving a vibration through touch [P3.2]. Through this work, we can provide further foundations for implementing natural interfaces on everyday surfaces without needing additional hardware for the user or changing the surface. This represents a novel foundation for utilizing haptic illusions, as vibrations have hitherto been employed solely to create haptic illusions rather than as an illusion in their own right.

6.1.4 Creating different perceptible shapes on rigid everyday surfaces

Using haptic illusions can be advantageous in the home environment when using everyday surfaces and improving interaction with devices used daily. One object property that has not been represented tactilely to date is the shape of an object. The influence has been brought about via the visual sense but not the sense of touch. The experiment demonstrated that different shapes can be represented via the sense of touch, even on a flat, rigid surface [P4.1]. Such a surface can be found, for example, on a smartphone's screen or a laptop's touchpad. However, these would have a limited range of movement if this experiment were implemented. Nevertheless, the experiment showed that with a few actual sizes that can be represented tactilely, many different sizes can be represented if a visual influence is applied [P4.2]. This approach allows for the representation of a vast array of shapes. By leveraging the human senses and making minimal alterations, the incorporation of enhanced tactile feedback on daily devices can be achieved, thereby enriching the user experience and enabling the utilization of applications in novel ways through haptic illusions.

6.2 Reflection

After summarizing the contributions related to the dissertation context, we will reflect on the findings and limitations within the different research areas and approaches.

6.2.1 Actuality

The results of a study are essentially a snapshot in time. While some results remain consistent and can be corroborated over time, others are contingent upon general advances such as current technologies. This is also evident in the survey we have prepared. Our survey encompasses the findings over a period of time, in our case, from 2004 to 2024. The starting time was chosen because there was another survey on using haptic illusions. The survey demonstrates that the advent of new technologies, computing power, and other developments have enabled the emergence of novel methods and implementations, leading to the generation of entirely new insights. Consequently, the survey represents an up-to-date snapshot that encourages future research aimed at confirming, expanding, or even challenging our findings. Furthermore, the survey covers only a limited range of databases. These were carefully selected according to specific criteria, but individual works may have been overlooked. However, this represents a fundamental limitation of surveys, which is not exclusive to the survey presented in this paper. The findings of the other works in this dissertation also encourage the use and expansion of the basic knowledge. However, since this is also in the interest of research, topicality is a limitation on the one hand but not a real disadvantage or negative effect on the other.

6.2.2 Generalizibility

The generalizability of the individual studies' results is given in some respects and limited in others. For example, the results must be limited primarily to the user group, which has also been covered within the studies. The extent to which individual results can be transferred to other groups of users or where they differ would need further investigation. However, including all possible user groups in a single study is impossible. In addition, the generalizability of the results in terms of hardware and devices must be considered. The prototypes were developed with low-cost and accessible devices, allowing them to be used on other devices with more power, for example, or with faster or more precise hardware. No specialized or unique hardware or technology was used. However, the generalizability is limited to devices or hardware components of the same kind. The results obtained with AR technologies may not be readily transferable to VR technologies one-to-one. It is necessary to distinguish the effect or interaction between the senses, which would require further investigation. The virtual representations used were kept entirely neutral to avoid any influence. A more realistic representation of the object or using textures would have a more positive influence on the results, enhancing the generalizability of the findings.

6.2.3 Everyday Use

The insights gained regarding haptic illusions and their generation of haptic feedback in ubiquitous environments have consistently provided a clear overview of their functioning and the circumstances under which they are most effective. Additionally, the circumstances under which an illusion occurs can be identified more precisely. However, it is essential to note that all studies have been conducted in a controlled laboratory setting, which excludes external influences. Some measures have been taken to exclude undesired stimuli during the setup. This is a valid method, but it must be conducted in a controlled laboratory setting to identify the specific influence of the variables under study. However, additional factors may influence the outcome when the findings are applied in real-world settings. Therefore, after the initial research, assessing the results in a real-world context is essential to ensure the findings are applicable and valuable. Furthermore, it is necessary to consider and investigate how certain phenomena develop over an extended period of time and whether habituation occurs, which may weaken the illusion or whether the effect persists. This is an ordinary side effect and is not only present as a specific limitation in these works.

6.2.4 Haptic Illusions

The research results on haptic illusions have demonstrated another potential limitation within this field. Like all other illusions, Haptic illusions are not universally effective for all users. Some individuals cannot perceive illusions for various reasons that are not fully understood. Furthermore, the use and perception of haptic illusions are relatively unfamiliar to many individuals because they are primarily accustomed to the haptic feedback they experience daily and have learned to interpret it in its intended context. The novelty of haptic feedback on illusions can be confusing, which may result in initial rejection. This may also be due to the unfamiliar interaction with the interface or surface. However, this phenomenon often occurs with new technologies or interactions. The objective is to make this novelty easily accessible so that users can learn it quickly and thus feel comfortable. This phenomenon has been demonstrated in numerous studies. It is evident in the feedback from users, who reported that they quickly mastered the device and interaction despite having no prior experience with it. With the introduction of novel techniques, such as the tactile perception of vibration through the stimulation of the senses of sight and hearing, which are not commonly encountered in one's everyday life, it became evident that users initially struggled due to the discrepancy in their expectations. The experience and the acquired knowledge ultimately facilitate the creation of an illusion. Nevertheless, it is advisable to embrace the testing of novel methodologies, provided that an initially straightforward interaction is employed.

Chapter 7

Conclusion and Outlook

This chapter presents a summary of the knowledge gained about haptic illusion. It discusses its potential future utilization, aiming to contribute to the creation of ubiquitous and calm environments.

This thesis demonstrates how our everyday environments and daily-used devices can be augmented by stimulating the human mind to create haptic sensations. To this end, we investigated the generation of haptic feedback in a scalable manner, its mapping to corresponding digital extensions on everyday surfaces, and the conveyance of object properties such as different weights [P2.1, P2.2]. Furthermore, we demonstrated that vibrations, previously only used as real feedback to generate haptic illusions, can also be generated illusionarily [P3.1, P3.2]. This allowed us to gain important insights into creating and using haptic illusions. Ultimately, we used haptic illusions to augment familiar everyday environments and demonstrated how to enhance everyday devices to generate perceptible tactile feedback and thus create an improved user experience [P4.1, P4.2].

The results demonstrate that by utilizing and addressing the cognitive properties of users, diverse, scalable, and robust feedback can be created, which individual feedback-generating hardware components would not be able to do. At the same time, objects and our environment can be hosted as naturally as possible.

7.1 Outlook

The results presented in this paper will be discussed to determine how they can be used immediately in future research in the presented areas to gain deeper insights or, more generally, about haptic illusions. Furthermore, the potential of this research to enhance the vision of ubiquitous and calm computing will be considered, as well as the ways in which developers, designers, and engineers can use the findings to develop devices, interfaces, or applications. Finally, ideas for long-term possibilities will be presented.

7.1.1 Immediate Future Work

The immediate future work can use the presented results to gain deeper insights by implementing the findings into applications and specific use cases. As the research was conducted with neutral designs and visualizations to gain fundamental findings without any bias, this can be extended by using more realistic graphics or virtual objects and textures in the future. Moreover, potential applications and interfaces could be implemented and tested. For instance, a virtual keyboard could be placed on an everyday surface, and interfaces could be developed to control and interact with the environment, such as a light control, music remote, or map applications on a smartphone with tactile feedback regarding the topography.

In addition, future research on the presented areas and use cases could use additional technology, such as electroencephalograms (EEGs). As haptic illusions are uncommon ways of presenting haptic feedback for most users and illusions might often occur in a brief period of time, or even if they do occur, they might be unrecognized, it is of interest to explore brain activity while exploring haptic illusions to gain deeper insights into how the feedback is perceived.

Overall, these possibilities can all help better understand haptic illusions. As most of this field is yet unexplored, the initial fundamental research must be conducted, as exemplified in the presented works. However, this research can facilitate more precise and detailed investigations in the future.

7.1.2 General Future Work on Haptic Illusions

While the results presented permit in-depth research and the specification of existing findings, they also provide general insights and opportunities for future research. In the survey, for instance, it was demonstrated that certain illusions remain underrepresented in HCI and that new or self-built technologies can create opportunities to use them to make object properties tangible.

Some human senses, such as hearing and smelling, are also underrepresented compared to sight and touch. The work demonstrates the potential and strength of haptic illusions and, most importantly, provides the motivation to test new possibilities. This is exemplified by the work on vibrations, which demonstrates the ability to turn known methods on their head or to make commonly used actuators replaceable. This could also lead to developing new types and methods for designing interfaces.

The use of AR headsets could facilitate the generation of haptic sensations in mid-air, obviating the need for wearable technology on the hands or fingers. It would be interesting to ascertain the potential for creating high-resolution haptic illusions and determine whether fine structures could be recognized. If the human senses are properly addressed, many previously unexplored possibilities become feasible. For instance, a haptic illusion in the perception of temperatures or other skin sensations or feedback of the entire environment perceived by the body, such as the whole room, floor, etc., could be created.

Illusions can be used in areas where hardware has primarily been used and replaced up to now but also where hardware and actuators cannot be used at all. Finally, it is also interesting to consider the potential for combining the findings presented here. One such possibility is combining shape perception with the interaction of graphic or virtual objects on everyday surfaces.

7.1.3 Interface Building and Applications

A considerable number of works in the field of human-computer interaction present methods for realistic haptic feedback that are challenging to implement with conventional hardware and rely on special hardware and setups, such as encounter systems (88) or wearable exoskeletons (97). In contrast, sensory illusions have the potential to provide haptic feedback with less effort and complexity.

Previous illusions frequently target haptic properties that are challenging to achieve with conventional haptic interfaces. Consequently, they rely on specialized hardware. Such specialized hardware must first be integrated into usable haptic feedback-generating devices, making them less scalable and unsuitable for everyday objects being augmented or appropriated. Even in cases where haptic feedback could be achieved by other means, illusions generally reduce the amount and complexity of hardware required.

The requirements also shift as the development of interactive systems shifts towards mobile devices. Such systems and devices must be smaller, lighter, and consume less power while delivering lifelike results. In particular, sensory illusions can help to achieve this. However, certain challenges remain. The effect of an illusion is usually less than what can be achieved with actual hardware. Consequently, it is necessary to couple the illusion with an actual haptic sensation to create realistic virtual objects. Furthermore, physical props or active devices are still required to create realistic sensations.

Developing novel devices that can create illusions without unduly restricting the user's natural interactions remains an open challenge for future research. As with the field of active haptics, the work investigated often relied on custom-built devices to create the illusion as effectively as possible. These approaches must be generalized to enable replication and integration into future systems. Developing standard devices or easily replicable hardware to create specific haptic illusions is essential for future progress.

This thesis presents design guidelines and implementation factors that can be employed to mitigate challenges and expand the scope of possibilities in the future. Developers, designers, and engineers can utilize these guidelines to conceptualize and develop future devices and applications.

7.1.4 Long Term Horizon

As presented in the survey, the last few years have shown an increasing tendency towards the research and use of haptic illusions. As previously mentioned, the emergence and further development of AR devices are also useful and combine haptic illusion with the idea of ubiquitous computing. The further development of such technologies, such as AR contact lenses, and the set of new insights into how the human mind can be used to create haptic feedback shows the future's growing potential. The potential for increasingly realistic representations of virtual objects and the resulting ability to augment real objects also creates better opportunities to appeal to the individual senses and thus create illusions. However, with digitalization occurring in parallel, the necessity for new devices, controllers, or remote controls for various interactions or interfaces is reduced. This can save costs and space while at the same time enhancing the user experience. Consequently, the utilization and investigation of haptic illusions are regarded as a crucial and user-friendly component of future technological advancements.

7.2 Concluding Remarks

Research into haptic illusions to create many haptic sensations has increased in recent decades. Of particular interest has been the ability to make different object properties perceptible. This was because, in virtual worlds or other new technologies, people still desired to display a variety of feedback. The new technologies also supported and simplified the illusionary representation of object properties. Using haptic illusions obviates the necessity for actuators or other feedback-generating technologies while simultaneously enabling the exploitation of cognitive properties to generate a more diverse range of feedback than would be possible with individual hardware components.

In this manner, the utilization of haptic illusions also advances the concept of ubiquitous and calm computing, as it transforms all surrounding objects into interfaces while maintaining the natural character of the environment. This prevents the objects from being identifiable as computers or conventional objects but makes them indistinguishable from them.

This work builds upon previous knowledge and contributes to the creation of new fundamental knowledge for future research. It also suggests the extent to which the future may be able to continue to function without hardware while still creating interfaces and applications that can robustly provide feedback. It can inspire other researchers in the field, thereby improving haptic illusions and the field of ubiquitous computing and making it understandable and usable for everyone.

Chapter 8

Clarification of Contributions

The following table provides an overview of my own and of my co-authors' contributions on each of the included publications. As my primary supervisor, Katrin Wolf participated in each project, providing guidance, ideas, and feedback. This role was consistent across projects, so I will not list these contributions individually.

My Contribution	Contribution of Co-authors
[P1.1] I share first authorship with **Yannick Weiss**. I contributed to the conceptualization and co-led the investigation, analysis, and writing. I examined every record identified through the literature search and independently analyzed all included works in the systematic literature review. I led the initial draft and I co-created the visualizations and the finalization of the manuscript.	**Yannick Weiss** co-led this project, including the investigation, analysis, writing, and visualization. He independently annotated and analyzed all records and co-created the manuscript and visualizations. **Marc O. Ernst**, **Albrecht Schmidt**, and **Katrin Wolf** contributed to the conceptualization, supported and reviewed the writing, and provided guidance throughout the research process.
[P2.1] I was the project lead and first author of the publication. I conducted the study, contributed to the study design and prototyping, performed the data analysis, and led the writing.	**Simon Linke** contributed to the prototyping, measurements for the setup and contributed to the writing. **Yannick Weiss** and **Maximilian Letter** contributed to the writing. **Albrecht Schmidt** and **Katrin Wolf** contributed to the initial idea, study design, interview protocol and writing.
[P2.2] I was the project lead and first author of the publication. I conducted the study, contributed to the study design and prototyping, performed the data analysis, and led the writing.	**Jan Willms** contributed to the prototyping and study design. **Adrien Chaffangeon Caillet** contributed to the writing. **Katrin Wolf** contributed to the initial idea, study design, and writing.
[P3.1] I was the project lead and first author of the publication. I conducted the study, designed the study design, prototyping and writing, and performed data analysis.	**Maximilian Letter** contributed to the writing. **Katrin Wolf** contributed to the study design, writing and initial ideas and effects for the study.
[P3.2] I was the project lead and first author of the publication. I conducted the study, created the study design, prototyping and writing, and performed data analysis.	**Maximilian Letter** contributed to the writing. **Katrin Wolf** contributed to the study design, study setup and writing.

Continuation of Table 8.1

My Contribution	Contribution of Co-authors
[P4.1] I was the project lead and first author of the publication. I conducted the study and data analysis, created the study design, contributed to the 3D-printing and prototyping, and led the writing.	**Jan Willms** contributed to the prototyping, study design, study setup and writing. **Adrien Chaffangeon Caillet** contributed to the writing. **Katrin Wolf** contributed to the prototype setup, study design, and writing.
[P4.2] I was the project lead and first author of the publication. I conducted the study and data analysis, created the study design, contributed to the 3D-printing and prototyping, and led the writing.	**Jan Willms** contributed to the prototyping, study setup and writing. **Adrien Chaffangeon Caillet** contributed to the writing. **Katrin Wolf** contributed to the prototype setup, study design, and writing.

Table 8.1: Clarification of contributions for all core publications included in this thesis.

Chapter 9

Original Contributing Publications

This is a cumulative dissertation made up of research that has been published in peer-reviewed venues. The publications contribute to the overarching narrative and represent the main body of this thesis. When referring to the publications, I use the format "[P i.j]", with $i \in [1..4]$ and $j \in [1..2]$.

Publications

[P 1.1] Marco Kurzweg, Yannick Weiss, Marc O. Ernst, Albrecht Schmidt, and Katrin Wolf. 2024. Survey on Haptic Feedback through Sensory Illusions in Interactive Systems. ACM Comput. Surv. 56, 8, Article 194 (August 2024), 39 pages. https://doi.org/10.1145/3648353

[P 2.1] Marco Kurzweg, Simon Linke, Yannick Weiss, Maximilian Letter, Albrecht Schmidt, and Katrin Wolf. 2023. Assignment of a Vibration to a Graphical Object Induced by Resonant Frequency. In Human-Computer Interaction – INTERACT 2023: 19th IFIP TC13 International Conference, York, UK, August 28 – September 1, 2023, Proceedings, Part I. Springer-Verlag, Berlin, Heidelberg, 523–545. https://doi.org/10.1007/978-3-031-42280-5_33

[P 2.2] Marco Kurzweg, Jan Willms, Adrien Chaffangeon Caillet, and Katrin Wolf. 2024. Resonant Sticker Buttons: The Effect of Button Size and Feedback Latency on Perceived Button Weight and Vibrotactile Feedback Strength. In Proceedings of the International Conference on Mobile and Ubiquitous Multimedia (MUM '24). Association for Computing Machinery, New York, NY, USA, 210–227. https://doi.org/10.1145/3701571.3701591

[P 3.1] Marco Kurzweg, Maximilian Letter, and Katrin Wolf. 2023. Increasing Realism of Displayed Vibrating AR Objects through Edge Blurring. In Proceedings of Mensch und Computer 2023 (MuC '23). Association for Computing Machinery, New York, NY, USA, 16–26. https://doi.org/10.1145/3603555.3603570

[P3.2] Marco Kurzweg, Maximilian Letter, and Katrin Wolf. 2023. Vibrollusion: Creating a Vibrotactile Illusion Induced by Audiovisual Touch Feedback. In Proceedings of the 22nd International Conference on Mobile and Ubiquitous Multimedia (MUM '23). Association for Computing Machinery, New York, NY, USA, 185–197. https://doi.org/10.1145/3626705.3627790

[P 4.1] Marco Kurzweg, Jan Willms, Adrien Chaffangeon Caillet, Katrin Wolf. 2025. MovPad: Feeling Holes and Bumps using a Moving Touchpad. In Proceedings of Mensch und Computer 2025 (MuC '25). Association for Computing Machinery, New York, NY, USA.

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Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eides statt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 26.05.2025

Marco Kurzweg