

# A Survey on Haptic Feedback through Sensory Illusions in Interactive Systems

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A growing body of work in human-computer interaction (HCI), particularly work on haptic feedback and haptic displays, relies on sensory illusions, which is a phenomenon investigated in perception research. However, an overview of which illusions are prevalent in HCI for generating haptic feedback in computing systems and which remain underrepresented, as well as the rationales and possible undiscovered potentials therein, have not yet been provided. Existing surveys on human-computer interfaces using sensory illusions are not only outdated but, more importantly, they do not consider literature across disciplines, namely perception research and HCI.

This paper provides a systematic literature review (SLR) of haptic feedback generated by sensory illusions. By reporting and discussing the findings of 90 publications, we provide an overview of how sensory illusions can be used and adapted to produce haptic feedback and how they are implemented and evaluated in HCI. We moreover identify current trends and research gaps and discuss ideas for possible research directions worth investigating.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; • **General and reference** → **Surveys and overviews**.

Additional Key Words and Phrases: systematic literature review, haptic feedback, sensory illusions

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## 1 INTRODUCTION

Haptic feedback offers great opportunities to enrich the experience of interactions and has been shown to increase users' performance [15] and attention [18]. Human haptic perception comprises cutaneous sensing, such as tactile or temperature [86], as well as proprioception and kinesthesia, which relate to the body's pose, its movement, and the perceived forces that originate internally and externally [123]. Due to these many aspects of haptic perception and our high reliance on it during the exploration of our environment, it is very difficult to generate accurate and realistic haptic feedback through technology. Vibrotactile actuators, for example, which are the most frequently used components for creating haptic feedback, cannot fully exhaust the complete range of human haptic perception and, therefore, limit the kind of haptic feedback that can be delivered [75]. One opportunity to enhance the spectrum of possible haptic feedback is the use of sensory, often multisensory, illusions. They can enrich haptic experiences in ways that would be

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difficult or even impossible to achieve using existing haptic output devices, such as through changing the perceived stiffness of everyday life objects dynamically [144].

Hayward defines an illusion as a perception generated by static stimuli, with the perception changing based on variable conditions [44]. Consequently, haptic illusions are sensory illusions concerned with an altered percept of haptic experiences resulting from a discrepancy between reality and perception. For instance, it has been shown that the perceived compliance of a rigid surface can be altered during haptic exploration by visual deformation [144] or timed vibrations [60].

Haptic illusions have been explored both in perception research and HCI. While perception research mainly focuses on exploring how haptic illusions fundamentally work [32], HCI uses this knowledge to create applications, interfaces, and feedback [70]. Although a wide range of illusions is investigated in perception research, only a subset of them are used in HCI [44, 73]. Improvements in computing and new immersive technologies, such as Mixed Reality, allow researchers to target and influence users' perceptions more accurately. Therefore, founded on the emergence of these new and advanced technologies, the subset of investigated illusions in HCI may have shifted and expanded. This may result in enhanced ways of applying established methods as well as entirely novel possibilities for eliciting sensory illusions. To the best of our knowledge, no survey relating to this topic considers the recent evolution of these methods. Furthermore, no overview of which illusions are prevalent or underrepresented in HCI, and the rationales behind this preference, has been presented yet.

To remedy this, we conducted a systematic literature review (SLR) of the current state of haptic feedback induced by sensory illusions. With this systematic approach, we aim to answer the question of how haptic illusions known to occur in perception can be adopted and adapted to introduce haptic feedback in computing systems.

To be able to address this question adequately, we contribute a comprehensive overview of which haptic illusions are explored for haptic feedback in computing systems (4) and examine the reasons for this prevalence and underrepresentation of other illusions known from perception research (5.1). Further, we address what general considerations must be taken into account when generating feedback through illusions (5.2). We present a novel dimension to classify and compare haptic illusions more efficiently for the purpose of developing haptic feedback for computing systems (5.3) and define and explain it in detail (5.4). Furthermore, we discuss which future research directions could consequently be of interest to this field (5.5).

## 2 RELATED WORK

Realistic haptic feedback when interacting with technology has been an interest for a long time, resulting in many research directions. In the following, we present an overview of conventional approaches for haptic feedback (2.1), as well as research on haptic illusions occurring in perception (2.2) and their use in HCI for interactive systems (2.3).

### 2.1 Haptic Rendering

Haptics refers to the perception of a physical object's properties through cutaneous and kinesthetic cues [75, 86]. To perceive these properties, such as surface texture, stiffness, weight, and geometry, humans employ specialized exploratory tasks [74]. For instance, estimation of an object's stiffness generally involves putting pressure on it to produce normal forces with the index finger or by pinching from both sides of the object. On the contrary, judging roughness often involves rubbing a finger in a lateral motion across the surface, producing skin deformations and vibratory signals. Consequently, providing the perception of these haptic properties in interactive systems is commonly achieved by the artificial generation or simulation of the sensations usually present during haptic explorations [114, 123].

Research proposes numerous approaches and systems aimed at delivering realistic haptic sensations, ranging from encounter-type systems, hand-held and wearable devices, to surface haptics for touchscreen devices (see [9, 27, 97, 140] for detailed reviews). In the spectrum of encounter-type interfaces, we can find sophisticated robotic devices such as the PHANTOM [84] or Omega [28], which allow for high-fidelity rendering of haptic sensations such as geometry or stiffness, but are very costly, and their workspace is severely limited. To overcome this, mobile hand-held and wearable devices have been developed. For instance, research proposes haptic controllers providing force feedback by employing motors that actuate single fingers [24], propulsion forces generated by propellers [45], or drag caused by adjusting air resistance through shape-change [150]. Efforts have also been made to provide other haptic sensations, such as simulating different surfaces using a revolving wheel under the fingertip [143]. Wearables range from bulky exoskeletons [91] to more agile gloves [48, 50] and devices mounted directly onto single fingers [35, 98]. These allow for the generation of various haptic sensations, including large forces for kinesthetic feedback, but disturb the natural exploration of objects by covering parts of the skin and restricting the mobility of users. Lastly, another field of research is concerned with surface haptics for touchscreen-based devices. These devices mostly employ vibrotactile actuators to produce virtual textures and friction, but other methods, such as electrostatic and ultrasonic actuation, have been proposed to widen the spectrum of haptic properties, which may be simulated [9]. However, these approaches still pose challenges regarding their possible workspace, the richness of feedback, and lack of kinesthetic feedback [9].

To overcome the limitations of the presented active haptic systems, research proposes haptic illusions to induce the perception of haptic properties artificially. We will discuss their theoretical grounding in perception and their application to interactive systems in the following sections.

## 2.2 Intramodal and Multisensory Illusions

Traditionally, illusions have been widely researched in the visual domain, such as the classical Mueller-Lyer illusion, in which two equal-length lines do not appear to be equal based on whether arrow-heads or arrow-tails are drawn at the end of the lines [109]. In 1992, Suzuki and Arashida [127] showed these illusions and misjudgments to also occur in the haptic modality by evaluating seven different geometrical haptic illusions, originally explored in the 1930s. They show three of these illusions, including the Mueller-Lyer illusion, working in the haptic modality analogously to their optical counterpart. However, another three had an effect in the haptic modality, which differed from the original visual outcomes, and one illusion could not be reproduced in the haptic modality at all. In 2008, Gentaz and Hatwell [37] presented and confirmed the often occurring discrepant outcomes and conclusions found in the literature for geometrical illusions in the visual and haptic domain. These findings show that geometric illusions and misjudgments do occur in haptic perception, but their effect cannot be simply inferred from visual illusions. However, intramodal haptic illusions, i.e., illusions that occur when haptic perception alone is used during exploration [37], only constitute a fraction of discovered illusions. The presence of multiple senses during the exploration of objects additionally evokes crossmodal interactions. Ernst and Banks [32] address this effect originating in the integration of multiple senses. They show that the visual and haptic senses are integrated into a combined percept following a maximum-likelihood estimation model. This means that the resulting percept is weighted based on the reciprocal variances of each of the senses in the current task. Consequently, vision may affect the haptic perception of physical properties and may, if it is judged to be more reliable, even overwrite it to a degree. For instance, research shows visual cues influence the texture perception of surfaces [76]. Drewing et al. [30] also demonstrate that vision affects the stiffness estimation of objects by showing that objects were judged to be softer when participants were allowed to see their interaction.

## 2.3 Haptic Illusions for Interactive Systems

The effect of visuo-haptic illusions on haptic perception sparked research into the deliberate creation and manipulation of haptic information in interactive systems using vision, called pseudo-haptic feedback. This concept describes altering the percept of a haptic property (e.g., the stiffness of an object) by combining visual and haptic information into a coherent representation differing from the physical environment. Lécuyer [70] reviewed the field of pseudo-haptics in 2009, presenting the haptic properties it can target (friction, stiffness, mass, and texture) and the application areas pseudo-haptics have been proposed for (e.g., video games and graphical user interfaces). He discussed that the devices used for pseudo-haptics differ but share their reliance on altering the control-display ratio, which describes the relationship between the physical inputs given (e.g., mouse movement) and the virtual representation of them (e.g., cursor movements). Altering this ratio during interaction with the system elicits pseudo-haptic effects, which he argues makes it an effective and simple alternative to expensive active haptic interfaces. Pusch and Lécuyer [110] later provide insights into the theoretical foundations of this pseudo-haptic feedback. They reviewed and built on established models of human perception to provide concrete design guidelines, such as adding complementary stimuli to target additional haptic properties or deliberate user priming to increase the effect. Recently, Ujitoko and Ban [135] surveyed pseudo-haptic feedback techniques, showing that they can be categorized into displacements, surface deformations, color changes, and size changes. For example, a cursor on a screen would move slower than the actual mouse movements, the texture behind it would indent, or the cursor's color and size would change at different locations. Furthermore, they provide design recommendations and possible application fields, such as training, assistance, and entertainment. These works provide great insights into pseudo-haptic feedback. However, pseudo-haptics has been defined narrowly to only relate to haptic percepts being altered by visual information. Therefore, haptic illusions elicited intramodally or by integrating other senses, such as audition, were not investigated.

Another subset of haptic illusions was discussed in 2017 by Taylor et al. [130]. They reviewed illusions generated via muscle vibration, for example, creating the illusion of a limb movement by applying vibrations to one muscle of an agonist-antagonist muscle pair. They investigated local (e.g., actuator placement) and global (i.e., context-related) contributing factors and produced a taxonomy of related illusions and a user's guide on how to elicit them. While they also discussed some illusions targeting other senses induced by muscle vibrations, most of the investigated illusions pertain to proprioception.

There also have been efforts to survey and categorize haptic and tactile illusions more holistically. Hayward [44] conducted a brief taxonomy of tactile illusions in 2008. He surveyed different types of tactile illusions and discussed their creation, stability or robustness, and analogs in other senses. Hayward emphasized the importance of demonstrations of illusion, and thus, he focused the survey on how easily these illusions can be replicated, for instance, whether they can be created using household items or if a specialized setup is required. Hayward's taxonomy purposefully leaves out illusions concerning embodiment, phantom limbs or body pose. In 2011, Lederman and Jones [73] conducted an extensive survey on haptic and tactile illusions relevant to information presentation in haptic displays. They categorized the researched illusions and built a framework based on the haptic percept an illusion is altering. They split the illusions into two groups, based on which of the two subsystems of the somatosensory system [75] they are targeting: object properties (like its material, weight, or geometry) and haptic space perception (both, external space and the body itself). Overall, they built a comprehensive catalog of numerous illusions, describing how they are generated as well as their robustness and strength if these could be ascertained from the investigated literature.

## 2.4 Summary

In summary, haptic illusions have been addressed in several reviews over the last decades. Most of these regard a subset of haptic illusions, such as pseudo-haptics or proprioceptive illusions. Efforts have been made to collect and catalog a broad spectrum of haptic illusions found in literature and explain how these are elicited. However, the latest of these comprehensive reviews ([73]) was published around a decade ago. With technologies, such as Mixed Reality systems and high-fidelity rendering techniques, getting more advanced and prevalent in research, many novel or enhanced methods of generating haptic illusions have become feasible, which could not have been considered in the existing reviews.

Additionally, while this topic has been studied in both perception research and HCI, so far, there has not been a systematic review with an interdisciplinary approach. Lastly, the reviews we investigated did not include a detailed report of methods to ensure replicability and understanding. We aim to remedy this with our systematic literature review, providing an updated, structured overview of haptic feedback through sensory illusions, as well as analyzing and discussing these illusions on several dimensions beyond their affiliation to a particular category.

## 3 METHOD

The goal of this review is to present an overview of existing work regarding haptic feedback induced by sensory illusions in the research field of HCI. This section explains our research method. We present the research questions we defined for this work (3.1) and our search strategy (3.2). We describe the eligibility criteria for papers to be included in our work (3.3) and explain our screening (3.4) and subsequent coding process (3.5).

### 3.1 Research Questions

We define our main research questions as follows:

- How can haptic illusions known to occur in perception be adopted and adapted to introduce haptic feedback in computing systems?

To answer this adequately, we must address the following questions:

- RQ1: Which haptic illusions known to occur in perception from prior literature are explored for haptic feedback in computing systems, and which are underrepresented? (see Section 4)
- RQ2: What are the reasons for this prevalence and underrepresentation of different illusions? (see Section 5.1)
- RQ3: What general considerations must be taken into account when generating feedback through illusions? (see Sections 5.2 and 5.3)
- RQ4: Which future research directions could consequently be of interest to this field? (see Section 5.5)

To achieve this, we conduct a systematic literature review and follow the PRISMA 2020 [99] guidelines for reporting systematic reviews, an updated version of the PRISMA [90] guidelines published in 2009. Our PRISMA flow diagram is shown in Figure 1.

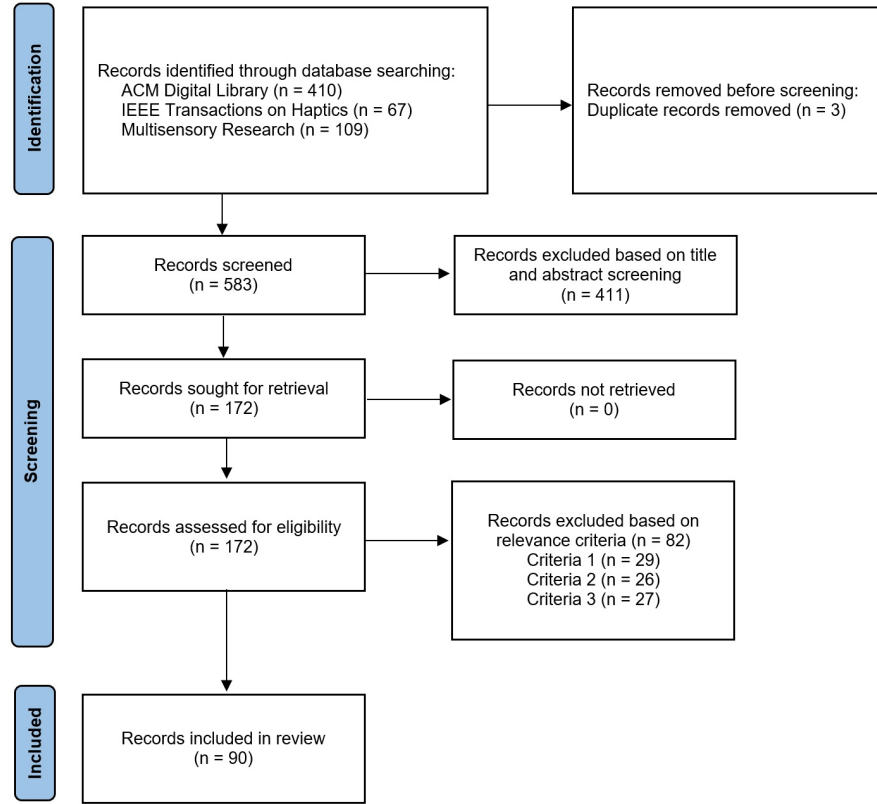


Fig. 1. PRISMA flow diagram showing the stages of identification, screening, and inclusion of our systematic search. A description and explanation of exclusion criteria can be found in section 3.3.

### 3.2 Search Strategy

The ACM Digital Library<sup>1</sup> was chosen as our primary database for HCI. According to the h-index from the past five years found on Google Scholar Metrics<sup>2</sup> (last accessed: July 3rd, 2023), this database contains seven out of the top ten publications in the field of HCI.

In addition to the broad search in the field of HCI, we aimed to cover the advancements relevant to this topic in the fields of engineering and perception research over the past decade. Preliminary searches with our search strategy showed IEEE Transactions On Haptics<sup>3</sup> to yield the most results in the engineering field. In perception research, the journal Multisensory Research<sup>4</sup> showed to yield the most results for this topic.

As this work focuses on haptic illusions, the terms *haptic* and *illusion* are considered important components within the search query. However, using these keywords on their own showed to provide a high number of publications (*haptic*

<sup>1</sup><https://dl.acm.org/>

<sup>2</sup>[https://scholar.google.de/citations?view\\_op=top\\_venues&vq=eng\\_humancomputerinteraction](https://scholar.google.de/citations?view_op=top_venues&vq=eng_humancomputerinteraction)

<sup>3</sup><https://ieeexplore.ieee.org/xpl/RecentIssue.jsp?punumber=4543165>

<sup>4</sup><https://brill.com/view/journals/msr/msr-overview.xml>

over 9000 results and *illusion* over 8000 results), where a majority did not fit our research questions. Therefore, we used these terms only in conjunction and subsequently added subcategories of haptic illusions we found in related work and preliminary screenings. To ensure no fitting work is missed, we added different spellings (e.g., singular and plural). To ensure the query works on all databases equally, we did not use any special operators for wildcards, like asterisks or question marks. The final search query consisted of the following terms:

```
"haptic illusion" OR "tactile illusion" OR "multisensory illusion" OR "proprioceptive
illusion" OR "temperature illusion" OR "haptic illusions" OR "tactile illusions" OR
"multisensory illusions" OR "proprioceptive illusions" OR "temperature illusions" OR
intersensory OR "pseudo-haptic" OR pseudohaptic OR "pseudo haptic" OR "pseudo-haptics"
OR pseudohaptics OR "pseudo haptics"
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These terms were allowed to appear anywhere in the full text of a paper for all three databases used. We did not set any filters or limitations for the results. The searches were conducted multiple times in 2021, 2022, and 2023. The last search and final cut-off were done on June 5th, 2023. This resulted in 586 records across all three libraries, composed of 410 items from the ACM Digital Library, 67 items from IEEE Transactions On Haptics, and 109 items from Multisensory Research.

### 3.3 Eligibility

**3.3.1 Formal criteria.** We included work that was peer-reviewed and archival. This covers papers categorized as a *journal article*, *full- and short-paper*, *book*, *book chapter*, *poster*, and *work in progress/late-breaking work*. We excluded other forms of publications, for example, workshop introductions and summaries.

**3.3.2 Relevance criteria.** Our relevance criteria for the decision, if a work should be included as relevant in the survey, were the following:

- (1) The perception of a haptic sensation has to be investigated.
- (2) The haptic sensation has to be generated or altered by a sensory illusion.
- (3) The effect of this illusion has to be proven.

Criteria (1) requires the found works to be concerned with a perceived haptic sensation. This first excludes publications not trying to generate any kind of haptic experience, for instance, research investigating audiovisual illusions (e.g., [5]). Furthermore, this excludes publications where illusions may occur, but the haptic sensation is not actively investigated, for example, research concerning interface navigation (e.g., [83]) or visuo-haptic perception of people on the autism spectrum (e.g., [107]).

Criteria (2) requires works to contain at least one sensory illusion that generates and/or alters the investigated haptic sensation as an experimental condition. This illusion can be intersensory (a discrepancy between the haptic and another sense) or intrasensory (real haptic stimulation differs from the perceived sensation). This excludes publications concerned with haptic feedback or haptic perception without any discrepancy in sensed and actual stimuli (e.g., [142]).

Criteria (3) requires works to show that an illusion and the resulting haptic feedback actually occur. This excludes works without an evaluation conducted on a human subject (e.g., [68]), as the effect of an illusion relies on the perception of a person. Furthermore, this excludes secondary studies, such as surveys and reviews (which are discussed in the related work), meta-analyses, or follow-up papers on a previously reported study.



### 3.4 Screening Process

Before the screening, three duplicate records from the ACM Digital Library were removed. Screening of the records was then conducted in two phases. First, the titles and abstracts of all remaining 583 records were reviewed based on the eligibility criteria presented in section 3.3. All records were assessed by two researchers independently and manually. Records deemed unfit or duplicates by both researchers were removed, while records considered fitting our inclusion criteria or cases with no consensus between the researchers were kept for the subsequent phase. In total, 411 records were excluded in this step. The remaining 172 records were then reviewed again in the second phase, this time using the full text. Again, both researchers evaluated all full texts independently and labeled them as fitting, not fitting, or unsure based on the presented criteria. These results were then compared and discussed and consequently merged into a final list of qualified publications. In this phase, another 82 records were excluded, leaving 90 records in our final corpus. These consist of 58 records from the ACM Digital Library, 27 records from IEEE Transactions On Haptics, and 5 records from Multisensory Research.

### 3.5 Coding Process

The 90 publications were coded independently by the same two researchers using an open coding approach to reduce possible bias. Every code was only used once per paper and relates to the research questions. Two iterations were made by both researchers independently, and after each iteration, the results were discussed. At the end of the second iteration, a congruent set of codes was assembled, which then served as the structure for a final coding iteration, resulting in the dimensions and categorizations presented in our results section.

## 4 RESULTS

In this section, we report the results of our SLR on haptic feedback induced by sensory illusions. These results represent the codes that arose during the coding process. We structure our results into different sections: First, we categorize the investigated illusions based on the haptic properties that they aim to alter (4.1). Next, we show the senses addressed to induce the illusions (4.2) and the technologies that are utilized (4.3). Subsequently, we provide an overview of the relationships between the targeted property, addressed sense, and technologies (4.4) and describe the goals and motivation of the works we investigated (4.5). Lastly, we describe how the investigated works evaluated the success of the illusions (4.6). These subsections were chosen as they constitute topics discussed by all included publications, making them comparable. The number of retrieved papers, included in our SLR and broken down by publication date, is presented in Figure 2. Overall, the rising numbers in publications indicate an increased interest in this topic. The drop in the number of included works in 2022 is likely due to a general decrease in conducted user studies during the pandemic.

### 4.1 Haptic Illusions

This section presents the types of illusions explored in the investigated publications. The decisive factor for our categorization in this respect is the haptic property the illusion targets. The resulting groups are not intended to represent a complete hierarchical structure necessarily but originate from clusters found in our coded data. An overview of these groups and their distribution is given in Table 1.

**4.1.1 Proprioception and Body Schema Illusions.** The first group of illusions we found does not involve altering the haptic properties of an object but rather altering the perception of proprioception or one's body schema. First



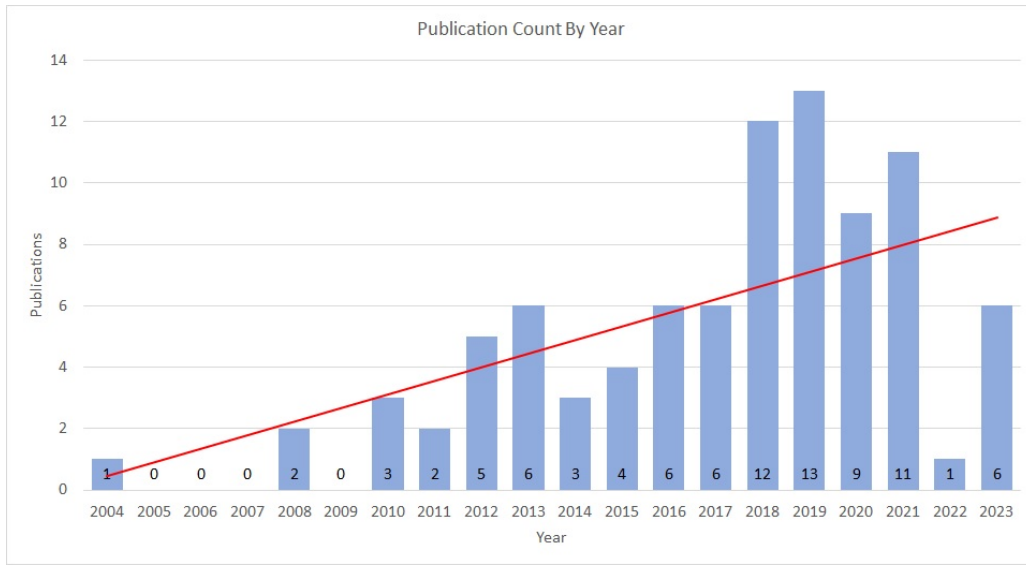


Fig. 2. Number of publications included in our review by publication year. The linear trend line (red) shows the increased interest in this topic. The earliest publication fitting our criteria was published in 2004. Note that 2023 could only contain publications published before our final search date ( June 5th, 2023 ).

demonstrated by Botvinick and Cohen [13] in 1998, the Rubber Hand Illusion (RHI) is now one of the most widely known sensory illusions concerning body ownership. It refers to the adoption of an alien limb (a rubber hand) into one's own body perception, resulting in tactile sensations applied to a participant's real hidden hand being misperceived to stem from the visible rubber hand. The studied works showed that this illusion can be adapted effectively by substituting parts of this process. The three publications exploring the RHI replaced the rubber hand with a drawn, two-dimensional one [100], used pleasant stimuli instead of hurting the artificial limb [26], or synchronized the index finger's pose through tracking and a motorized hand to allow active tapping of the finger [3] instead of stroking with a brush, as done in the original research.

A more recent advancement, the Virtual Hand Illusion (VHI), originates from the Rubber Hand Illusion, but it replaces the rubber hand with a completely virtual hand rendered in immersive Virtual Reality (VR) by a head-mounted display. Visual occlusion of the real hand is, therefore, easy to achieve. The main improvement is the ability to actively track the participants' real hands, allowing the virtual hand to mimic the pose and motion of the real hand. This also enables the identical spatial placement of real and virtual hand [80, 117] but still allows for visual displacements to be generated artificially [105]. The tactile stimulus received can also deviate widely from the original brush stroking of the RHI. Tactile stimuli might be applied in mid-air using ultrasound [105], might originate from physical surfaces the participant is actively touching [117], or might not be presented at all [80]. Both Lin and Jörg [80] and Schwind et al. [117] demonstrated that appearance does have a major impact on the effect of the VHI. They showed that a realistic human hand model generates the best results.

Misperceptions of proprioception can also be generated and used in other ways. Okabe et al. [94] showed that a perceived motion of a finger could be induced using a moving electrotactile pattern on the fingertip. Alternatively, Strandholt et al. [124] explored the ability to alter the virtual positioning of tracked, hand-held props in a virtual

	Number of Publications	Included Publications
<b>Proprioception and Body Schema Illusions</b>	<b>8 (8.89%)</b>	
- Rubber Hand Illusion	3 (3.33%)	[3, 26, 100]
- Virtual Hand Illusion	3 (3.33%)	[80, 105, 117]
- Other	2 (2.22%)	[94, 124]
<b>Phantom Sensations</b>	<b>24 (26.67%)</b>	
- On-Body	11 (12.22%)	[22, 25, 31, 52, 56, 61, 79, 81, 93, 103, 119]
- Out-of-body in external object	4 (4.44%)	[41, 65, 118, 151]
- Out-of-body in mid-air	9 (10.00%)	[10, 39, 40, 54, 77, 78, 102, 104, 106]
<b>Altered Perception of Tactile Stimuli</b>	<b>4 (4.44%)</b>	[19, 121, 139, 145]
<b>Geometry Illusions</b>	<b>9 (10.00%)</b>	
- Shape Illusion	5 (5.56%)	[7, 8, 12, 21, 133]
- Size Illusion	4 (4.44%)	[6, 11, 132, 147]
<b>Weight Illusions</b>	<b>17 (18.89%)</b>	
- Size-Weight Illusion	3 (3.33%)	[43, 82, 116]
- Visual simulation of moving objects inside	2 (2.22%)	[55, 146]
- Asymmetric oscillation	2 (2.22%)	[1, 128]
- Control-display ratio	5 (5.56%)	[58, 92, 108, 112, 115]
- Other	5 (5.56%)	[2, 59, 85, 96, 120]
<b>Stiffness Illusions</b>	<b>13 (14.44%)</b>	
- Visual texture deformation	4 (4.44%)	[4, 57, 67, 144]
- Control-display ratio	2 (2.22%)	[20, 141]
- Simulated deformation sounds	2 (2.22%)	[69, 134]
- Friction grain model	4 (4.44%)	[46, 47, 60, 63]
- Restricting Deformation	1 (1.11%)	[129]
<b>Surface Texture Illusions</b>	<b>13 (14.44%)</b>	
- Cursor representation	3 (3.33%)	[71, 72, 87]
- Control-display ratio of scrolling screen	2 (2.22%)	[62, 136]
- Superimposed visual/auditory textures	5 (5.56%)	[14, 23, 33, 34, 149]
- Velvet Hand Illusion	2 (2.22%)	[101, 148]
- Manipulating Velocity	1 (1.11%)	[64]
<b>Multiple Object-based Illusions</b>	<b>1 (1.11%)</b>	[113]
<b>Ambient Illusions</b>	<b>1 (1.11%)</b>	[16]

Table 1. Distribution of the haptic illusions found in the investigated publications, first categorized by the main haptic property they target. These groups do not constitute a comprehensive taxonomy but are derived from clusters found in our coded data.

environment. They manipulated the sense of proprioception for the holding arm to redirect and synchronize interaction spatially and temporally between the physical object and its virtual representation.

**4.1.2 Phantom Sensations.** A plurality of the investigated publications concern the creation of phantom sensations. Such a sensation can be perceived between multiple spatially separated cutaneous stimulations, for instance, between two vibrotactile actuators placed on a subject's skin. Phantom sensations can be stationary or moving in between the real stimuli and can be generated in a number of ways, including through funneling and the saltation or cutaneous rabbit illusion. In funneling, the relative difference in intensity between stimuli determines the location of the illusionary sensation [137]. For saltation (or "cutaneous rabbit"), the skin receives rapid sequential stimulations at differing locations with a certain time interval between stimuli, resulting in the tactile sensation being perceived at intermediate points as

if it is "hopping" from one location to the other in multiple steps [36]. Furthermore, the perception of a single tactile sensation moving smoothly between end-points (Tactile Apparent Motion) can be generated using multiple stimuli induced with an optimized asynchrony (Stimulus-Onset-Asynchrony) and distance between actuators [17]. The types of illusions generated in the works we investigated can be categorized by the location of the perceived sensation.

Most research investigated illusionary sensations felt directly on the subject's body. These include stationary sensations generated by vibrotactile actuators using funneling [52] and saltation [56] as well as tactile apparent motion on the skin [22, 25, 31, 52, 93, 119]. Liu et al. [81] use these moving sensations in combination with nearby thermal stimuli to create an apparent thermal motion. Additionally, apparent motion penetrating the body (e.g., a sensation flowing through the body generated by actuators on each side of a body part) has also been investigated both with tactile [61] and thermal [103] stimuli. Furthermore, Lezkan et al. [79] show the funneling illusion to work in active exploration with multiple fingers by proving that the sensation of bumps and holes felt on two fingers sliding along a surface elicit the feeling of a single bump or hole in between the two.

However, phantom sensations do not necessarily have to be confined to the body itself. Miyazaki et al. [89] first showed in 2010 that phantom sensations can be extended to the outside of the body onto an external physical object held between a subject's hands. They placed a stick onto the index fingers of both hands participants and stimulated these fingers to elicit a cutaneous rabbit illusion between them. This produces a sensation seemingly originating from somewhere within the held stick. Subsequently, different phantom sensations inside external physical objects have been investigated. Seo and Choi [118] apply apparent tactile motion to an external object grasped in one hand, Kim et al. [65] and Zhao et al. [151] produce a sensation inside an object held in both hands, and Hachisu and Suzuki [41] create apparent motion between two hands of different people during a handshake.

Furthermore, phantom sensations can occur without any physical connection (neither body nor an external object) between the stimulus locations. Instead, the physical object can be substituted by a virtual (visual) object [10, 40, 77, 78] or the illusion can even be generated with nothing held or shown between the stimulus locations [10, 39, 54, 77, 102, 104, 106].

**4.1.3 Altered Perception of Tactile Stimuli.** While phantom sensations and apparent tactile motion are primarily induced intramodally by vibrotactile or thermal stimuli, other works investigated the effects of visual and auditory cues on the perception of tactile sensations. These works show the possibility of visual representations manipulating the sensed location [19] and the characteristics [121], i.e., tapping versus stroking, of a stimulus on the body. Further, they show auditory cues altering the perceived intensity [145] and duration [139] of tactile sensations.

**4.1.4 Geometry Illusions.** For distinguishing or recognizing physical objects during active exploration, the perception of their geometry (i.e., shape and size) is essential. Haptically, this usually involves enclosing the object fully or partially within a hand or continuously moving across its contour with fingers [74]. The investigated works present illusions altering the perceived geometry during these explorations, thus creating a shape illusion where the perceived form of an object differs from an actual physical prop. For instance, sensed corners, edges, or slopes diverge from their actual placement. This is achieved by visually distorting the object and displacing the exploring hand accordingly [7, 8]. Turchet et al. [133] use an analogous approach to change the perception of the floor to contain bumps and holes. They distort the floor visually and displace the whole body in the virtual environment, additionally changing the camera orientation and adding footstep sounds in intervals determined by the illusory slope. Chen et al. [21] instead evaluated how devices able to produce lateral forces may be used to elicit the illusion of normal displacements to convey shapes. Lastly, Bickmann et al. [12] also show that a number of different shapes can be perceived to be held in a virtual

environment without grasping any physical prop. Instead, when the hand closes to a fist, a combination of the palm's own resistance, visual distortion of the hand pose, and the addition of a visually rendered object can create the illusion of different hand-held items.

In addition to changing the perceived shape, size illusions have been investigated, which solely alter the perceived size of an object from its physical counterpart. The illusion can be generated similarly to shape illusions by distorting the visual size of the object [132] or additionally distorting the subject's hand positions [6] or pose [11] (visually spreading its fingers apart). This illusion can also be achieved when the hand is extended with a grabbing tool. Yang et al. [147] showed the possibility of creating feedback for objects of different sizes based on a grabbing tool similar to chopsticks by visually displacing their closing angles to fit different-sized virtually rendered objects.

**4.1.5 Weight Illusions.** Weight Illusions are sensory illusions changing the perceived weight of a physical object. While weight is often judged vertically (e.g., by lifting an object), we also include illusions changing the perceived resistance force when an object is pushed or pulled horizontally since this depends on an object's weight, and the used illusions are generated similarly. A physical object's mass is determined by its density and volume and, thus, dependent on its material and size. Many illusions, therefore, manipulate one of these factors.

The size-weight illusion [43, 82, 116] is based on altering the visual size of the handled object, resulting in a misinterpretation of the object's weight to be heavier if the visual representation is smaller and vice versa. Maehigashi et al. [82] additionally compares this effect with brightness-weight and material-weight illusions. They report that contrary to previous findings in real-life situations, in VR, darker and heavier-looking materials cause the objects to be judged heavier.

Other changes in the visual presentation also achieve an altered perception of weight, namely visually superimposing a movable object inside the physical prop, like a rolling ball [146] or a liquid [55].

Asymmetric oscillations, meaning an object oscillating with asymmetric acceleration toward one direction, alter the perceived force in a targeted direction. [1, 128]. They can introduce an altered sense of weight when applied in the direction of gravitational forces.

Another method is to adjust the control-display ratio of a subject's arm while in contact with (holding or pushing) an object [58, 92, 108, 112, 115]. To generate this illusion, the visual representation of the subject's arm is altered while moving to gain less or more distance than the real arm. This creates the feeling of the arm (and consequently the held or moved object) being lighter or heavier.

A similar concept was used by Aoyama et al. [2], who altered the felt resistance while pushing a physical device using a moving pattern projected onto the hand. Based on the speed of this pattern, the arm seemed to move more or less, resulting in the resistance feeling lighter or heavier. Osato et al. [96] altered the perceived direction of force by letting a visually animated character push or pull an object equipped with a vibrotactile actuator. Similarly, Matsuyama et al. [85] investigated the change in perceived force resulting from different facial expressions of an animated character while it's pulling against the movement of the mouse cursor on a desktop screen. Shitara et al. [120] laterally stretch the skin on a fingertip, which results in a perception of illusionary forces pulling on the finger. Keller et al. [59] instead relied on an indirect solution using the received input. Subjects could only move objects on the provided tabletop display if they exerted enough pressure on it, thus suggesting a force required to lift and move items.

**4.1.6 Stiffness Illusions.** The subjective perception of stiffness depends on the perception of force and displacement. While force is typically sensed haptically, displacement can additionally be perceived visually [66]. Therefore, many illusions target the displacement component to alter perceived stiffness, for instance, by deforming the visual texture

on an object's surface when it is being touched. The level of abstraction varies widely between the investigated methods: Argelaguet et al. [4] generate this illusion using a cursor on a screen, animating the deformation when clicking. Kawabe [57] also uses an indirect approach, deforming a surface on a screen behind two hands tracked in mid-air based on their distance, creating the illusion of the material stretching. Kokubun et al. [67] try to evoke a more direct sensation by using a rear touchscreen and deforming the texture on a screen based on the direct contact point of the fingers. Wolf and Bäder [144] present the texture using a projector and add electrotactile feedback to elicit the illusion while touching a flat, rigid surface.

Instead of visually deforming, studies show the possibility of suggesting the sensation of different amounts of stiffness based on sounds simulating different materials being pressed [69] or walked on [134].

Analogously to the alteration of perceived weight, the control-display ratio, i.e., the ratio between actual and displayed movement, is used to modulate the perceived stiffness of objects by adjusting the motion of a user's hand [141] or foot [20] during the pressing of an object in VR. These works show that a gain in the movement results in the objects being perceived as softer while restricting the movement while pressing increases the perceived stiffness.

Instead of using vision or audition, the friction grain model elicits an altered perception of stiffness using vibrotactile stimuli. It was first introduced by Kildal [60] in 2010, who demonstrated it using a stylus. It elicits the illusion of a compliant material by releasing grains of vibrotactile feedback at predefined force thresholds. This means that vibrations can be felt while a subject changes the applied pressure with the stylus (e.g., trying to press it further down) onto the underlying surface. While the pressure remains static, no feedback is applied. This generates the illusion of an underlying material with a lower stiffness, controllable by the amount and spacing of the vibrotactile grains. Kim and Lee [63] adapted this technique to simulate the perceived force feedback of a button click. Heo and Lee [46] used this approach to induce the illusion of both nominal (material stiffness) and tangential (surface friction) forces. Lastly, Heo et al. [47] implemented the friction grain approach into a hand-held object to elicit the illusion when stretching, bending, and twisting it.

Tao et al. [129] instead used a finger-worn device to restrict fingerpad deformation, which resulted in objects feeling softer when pressed.

**4.1.7 Surface Texture Illusions.** Sensing of surface textures of physical objects is done cutaneously and consists of multiple subjective dimensions that can not be separated entirely, including roughness, hardness, stickiness, bumpiness, and temperature [49].

Manipulating the cursor representation in a classical mouse and desktop scenario allows the creation of pseudo-haptic textures of bumps and holes. These are elicited by adapting the cursors control-display ratio [71], actively displacing the cursor position [87], and changing the cursor's size accordingly [72].

In a scrolling scenario on a touchscreen, sensations of friction can be elicited by adapting the control-display ratio, decelerating the scrolling motion based on the illusory friction being applied [62, 136].

A surface's roughness can be partially inferred through its visual texture and the sound it causes when rubbing over it. Accordingly, superimposing visual or auditory representations can induce the illusion of different surface materials. Visual cues are used in several ways, for instance, showing visual textures of different materials [33], showing or hiding a visual ridge on the surface [149], and utilizing stereoscopy and visual deformations to manipulate the texture roughness perception [14]. Similarly, inserting white noise [34] or the recorded or synthesized sounds of rubbing against materials with one's finger [33] or the sound of a pen or pencil [23] induce an altered perception of surface texture.

Pasqualotto et al. [101] explore the Velvet Hand Illusion. This illusion induces the sensation of a smooth velvet-like material when subjects rub their palms together while a grid of bars is lodged between them. Yokosaka et al. [148] extend on this concept by instead interjecting a rotating cardboard frame between the participants' hand and an object, changing the perceived texture properties of the object's surface.

Lastly, another approach to modifying the perceived roughness of a surface was shown by Kim et al. [64]. They manipulated the velocity of a bumpy surface relative to the exploring hand, which resulted in the participants perceiving more bumps during identical time frames, thus altering the perceived roughness proportionally to the speed gained.

**4.1.8 Multiple Object-based Illusions.** Salazar et al. [113] utilize a wearable device on a finger to generate lateral skin deformations. This elicits the illusion of forces applied nominally onto the fingertips, which is used to modify the perception of stiffness, shape, and friction of objects. These types of illusions are discussed in sections 4.1.6, 4.1.4, and 4.1.7, respectively.

**4.1.9 Ambient Illusions.** Lastly, Brooks et al. [16] show that sensory illusions can modify the perceived ambient temperature of virtual environments based on emitting certain scents stimulating the thermoreceptors of the trigeminal nerve, for instance, using capsaicin to increase and eucalyptol to decrease the perceived environmental temperature.

## 4.2 Senses Used to Induce Haptic Illusions

After providing an overview and categorization of all the illusions used and created across literature, we will now take a look at the senses that were mainly addressed to elicit the illusions for haptic feedback. For the purposes of this review, we split the addressed senses into sight, sound, smell, and haptics (which comprise tactile, temperature, kinesthetic, and vibration sensations).

Across all works, a total instance of 105 codes regarding addressed senses was found. This number is higher than the number of included publications, as some works use more than one sense equally. The distribution of codes and their relation to each other is presented in Figure 3.

The sense of sight is addressed in 44 of the 90 publications (48.89%) to create illusionary haptic feedback. In addition, haptics is addressed 49 times (54.44%), the sense of sound ten times (11.11%), and the sense of smell one time (1.11%). Table 2 provides an overview of all the senses addressed individually or in combination in the investigated works.

Most often, vision is addressed individually, i.e., the change in haptic perception occurs solely through the adaptation of visual stimuli. This is robust and effective for many illusions, including those targeting surface texture [71], weight [115], and shape [8]. Almost as often, other haptic cues are used to alter a haptic percept. The haptic feedback used in the investigated works comprises kinesthetic (one time), thermal (two times), vibrotactile (27 times), electrotactile (two times), and other tactile feedback (seven times). These are mainly used in the context of phantom sensations [56] or tactile apparent motion [93]. Fewer illusions solely build on the sense of sound. The targeted haptic properties differ widely, ranging from the duration of a stimulus [139] to simulated floor materials [134]. And only one work focuses on targeting the sense of smell. Brooks et al. [16] investigate if a temperature illusion can be created by using odors triggering the nose's trigeminal nerve.

Furthermore, the addressed senses are used in several combinations within the included publications. The sense of sight is often combined with haptics (one time with electrotactile, one time with kinesthetic, one time with vibrotactile, and five times with other tactile feedback). For example, these include the rubber hand illusions (e.g., [100]), where tactile sensations together with a visible, artificial hand are used to elicit the illusion. In addition, the sense of sight

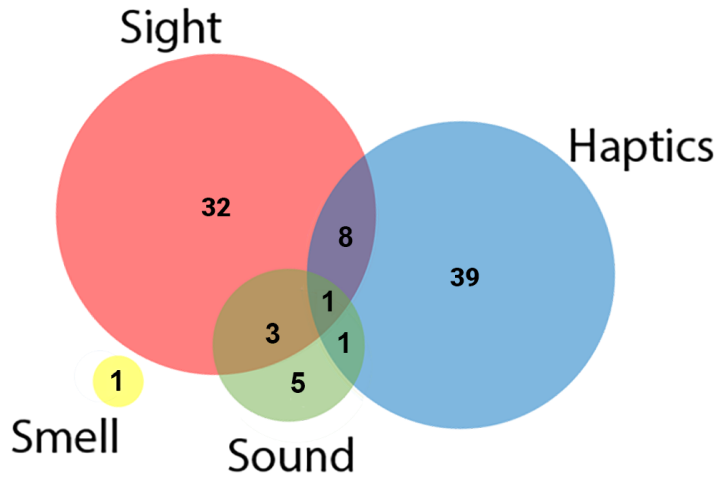


Fig. 3. A graphical representation of the distribution and relation of our codes regarding addressed senses. The sizes of the circles represent the number of instances of the senses. The intersections approximately represent the number of combinations of these senses. The numbers in the specific areas are the total numbers for how often senses were used by themselves or combined.

Addressed Senses	Number of Publications	Included Publications
Visual only	32 (35.56%)	[2, 4, 6–8, 11, 12, 14, 19, 20, 43, 55, 57, 58, 62, 67, 71, 72, 82, 85, 87, 92, 108, 115, 116, 121, 124, 132, 136, 141, 147, 149]
Haptics only	39 (43.33%)	[1, 10, 21, 22, 25, 31, 39–41, 46, 47, 52, 56, 59–61, 63–65, 77–79, 81, 93, 94, 96, 101–104, 106, 113, 118–120, 128, 129, 148, 151]
Auditory Only	5 (5.56%)	[34, 69, 134, 139, 145]
Smell Only	1 (1.11%)	[16]
Visual & Haptics	8 (8.89%)	[3, 26, 80, 100, 105, 112, 117, 144]
Visual & Auditory	3 (3.33%)	[33, 133, 146]
Haptics & Auditory	1 (1.11%)	[23]
Haptics & Visual & Auditory	1 (1.11%)	[54]

Table 2. Overview of how often different senses were addressed individually or in combination in the included works.

and the sense of sound are addressed individually to compare the strength of their resulting illusions [33, 133] or in conjunction to try to create a stronger illusion [146]. The sense of sound and haptics are addressed in conjunction to induce the illusion of different pens or pencils being used during handwriting tasks through vibrotactile feedback and synthesized sounds [23]. Furthermore, Jiang and Chen [54] explore the combination of illusions resulting from the sense of sight, sound, and haptics. They investigate the individual influence these senses have on intermanual tactile apparent motion.



Technology	Number of publications	Included Publications
Desktop Displays	11 (12.22%)	[4, 7, 8, 33, 57, 58, 71, 72, 85, 87, 133]
VR	16 (17.78%)	[6, 11, 12, 19, 20, 80, 82, 104, 112, 115, 117, 124, 132, 141, 146, 147]
AR	5 (5.56%)	[14, 43, 55, 56, 92]
Projectors	2 (2.22%)	[2, 144]
Touchscreens	4 (4.44%)	[62, 65, 67, 136]
Vibrotactile Actuators	27 (30.00%)	[1, 10, 22, 23, 25, 31, 40, 41, 46, 47, 52, 54, 60, 61, 63, 65, 77, 78, 96, 102, 104–106, 118, 119, 128, 151]
Rotating Tractors	1 (1.11%)	[93]
Peltier Module	2 (2.22%)	[39, 103]
Electrodes	2 (2.22%)	[94, 144]
Skin Deformation Devices	4 (4.44%)	[56, 113, 120, 129]
Headphones	7 (7.78%)	[33, 54, 133, 134, 139, 145, 146]
Speakers	3 (3.33%)	[23, 34, 69]
Atomizer	1 (1.11%)	[16]

Table 3. Overview of the technology used to create haptic illusions in the included works. The technologies are split based on the senses they address (from the top: sight, haptic, sound, smell). Note that the sum of these technologies does not reach 100% because custom technologies were used that are not listed here.

### 4.3 Technology

This section presents which devices are actively involved in creating the investigated illusions. This excludes technology that is just used to record data, calculate algorithms, or run background programs. Table 3 provides an overview of the distribution of used technologies across publications.

The majority of technologies used in generating an illusion are visual-related. These comprise classical desktop displays, touchscreens, and projectors, as well as head-mounted displays for Virtual Reality or Augmented Reality. Desktop displays are mainly used to generate a surface texture illusion in combination with a mouse and cursor (e.g., [72]) or to generate shape illusions using hand tracking and image manipulation (e.g., [8]). Touchscreen devices of varying sizes (tablets, smartphones, stationary touchscreens) are mainly used as the held object for out-of-body phantom sensations [65]. Virtual Reality head-mounted displays are utilized the most to elicit an illusion. These devices include the HTC Vive (eight times), Oculus Rift CV1 (four times), Oculus Rift DK2 (two times), Oculus Quest (one time), the Canon HM-A1 (one time), and one which was not named. These VR HMDs are always used in conjunction with tracking technology (held controllers, gloves, or hand tracking) to show a virtual hand. This visual representation is used unaltered for virtual hand illusions (e.g., [117]), changed imperceptibly to redirect (e.g., [124]), or its movement gains modified strongly to elicit weight illusions (e.g., [115]). AR HMDs are included in five different works (three video see-through, two optical see-through), all dealing with different kinds of illusions created by superimposing a visual object or representation [43, 55, 56, 92]. Projectors produce haptic illusions in three works, for example, to generate a stiffness illusion by projecting deforming textures [144].

Another large area we identified within our coding process was the inclusion of tactile feedback-creating technology. This technology was predominantly used for phantom sensations and apparent tactile motion. Most commonly, vibrotactile actuators (small vibrating motors) are used. In addition, a rotating tractor [93] or peltier modules [39, 103] are used for apparent motion illusions. Electrodes are employed to generate tactile sensations [94, 144] and lastly, skin

deformation devices mounted to a finger [113, 120], or arm [56] are used to create the sensation of nominal forces onto the skin.

Furthermore, both headphones and speakers are utilized in the investigated publications to create illusions through sound (e.g., [134]). This does not include publications where headphones were employed to eliminate external noise or cover up sound from a used device (occurred 15 times, e.g., [47]).

Lastly, one publication used an atomizer to nebulize liquids for an olfactory display [16].

#### 4.4 Relationships between Illusions, Senses & Technologies

This section depicts how the illusions (see section 4.1), addressed senses (4.2), and used technologies (4.3) relate to each other. We visualize the distribution and relation of these three aspects in Figure 4. It becomes apparent that, while some illusions can be induced by addressing different senses, most groups targeting the same haptic property primarily rely on one specific modality. Based on which of these senses is addressed, certain particularly suitable technologies are inevitably being used very frequently. A good example of this present phantom sensations. Even if these occur in novel ways, for example, outside of the body, most of the methods to create them (e.g., funneling and saltation) are still entirely intrasensory. This leads most publications exploring these sensations to simply use common vibrotactile actuators, as these have been proven to elicit very robust illusions [52, 102]. Furthermore, weight illusions are mostly induced visually through VR technology. Many of these are created by adapting the visual representation of a held object or changing the control-display ratio of a participant's arm, which both can be achieved easily in VR [55, 115]. On the other hand, surface texture illusions are elicited through various different senses, often also in combination (i.e., multimodal). For instance, Cho et al. [23] simulated different surfaces using haptic (vibrotactile actuators) and auditory (speakers) technologies simultaneously. Etzi et al. [33] instead used visual and auditory cues individually.

#### 4.5 Research Goals, Motivations

We identified the primary research goal stated by the study authors to understand better the motivation driving research on haptic illusions. Resulting secondary benefits or positive side effects that may occur are not considered unless they are clearly stated as the main objective. The most frequently mentioned goal across all studies was to evaluate or present a new illusion technique/concept (47 times, e.g., [71, 78, 94]). Other mentioned goals were to gain a better understanding about the principles of an illusion (13 times, e.g., [117, 120, 133]), to reaffirm findings or extend them by the use of new technologies (10 times, e.g., [10, 43, 65]), or enhance the general experience of users (7 times, e.g., [23, 63, 112]). Furthermore, the exploration of new frameworks or basic principles (3 times [102, 118]) and the improvement of user performance (2 times [56, 92]) were named as the main motivation less commonly.

#### 4.6 Evaluation Methods

Based on the primary motivation of the research, the evaluation method utilized may vary greatly between different works on haptic illusions. This section presents the evaluation method and resulting metrics used in the investigated works.

Most commonly, the effectiveness of the haptic illusion is verified using single-item questions rating perceived haptic stimuli (37 times), such as Likert scales (e.g., [93]) or magnitude estimation procedures (e.g., [43]). These methods target the effectiveness of the illusion to elicit a certain haptic sensation directly. Also common is using a two-alternative forced choice (2AFC) task (35 times), often following the psychometric method of constant stimuli (e.g., [141]), method of limits (e.g. [47]), or a staircase approach (e.g. [39]). These psychometric methods are then mostly used to identify

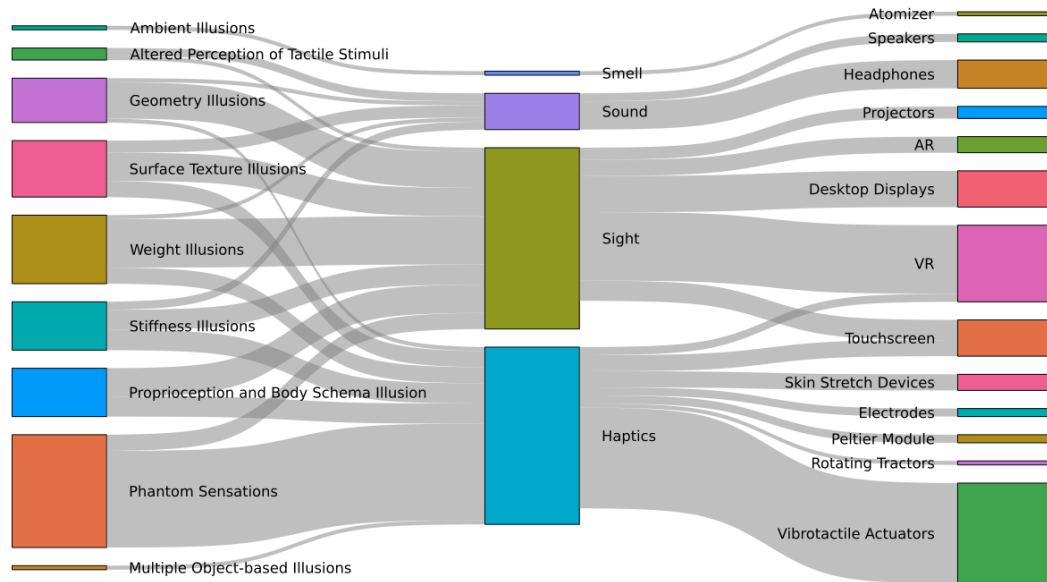


Fig. 4. This alluvial diagram highlights the distribution and relationships between illusions, addressed senses and used technologies we found in 90 included publications. The **left** side shows all investigated illusions categorized by the haptic property they are targeting. The **center** presents the senses which were utilized to elicit these illusions. On the **right**, the technologies used in their generation are listed.

detection thresholds (e.g., see [141]), points of subjective equality (e.g., see [11]), or just-noticeable differences (e.g., see [4]). Instead of using one single-item or 2AFC question, many works evaluated their illusion through a self-created multi-item questionnaire (twelve times, e.g. [115]) targeting different related aspects from which they then infer the efficacy of the haptic illusions. For both phantom sensations and proprioceptive illusions, studies often let participants indicate the position of the perceived stimuli or perceived proprioceptive drift by pointing at it (seven times, e.g. see [10] for phantom sensation location and [3] for proprioceptive drift). A few works rely on qualitative analysis of interviews as their primary evaluation method (five times, e.g. [60]). Lastly, many works employed self-built evaluation methods to fit their specific use case or research question, which cannot be grouped into the abovementioned methods.

The vast majority of the investigated works employ a within-subject experiment design for their studies (82 times), while the remainder utilizes a between-groups design (eight times, e.g., [80]). The number of participants in the user studies conducted within the investigated works averages 14.95 persons (SD = 8.63) and ranges from four participants (see [95]) to 60 participants (see [80]).

## 5 DISCUSSION

In this section, we discuss how the knowledge about haptic illusions from cognitive science is applied to the field of HCI, based on our results and overviews of established illusions in previous works [44, 73]. We identify and explain common trends and gaps in research of haptic illusions and their connections to dominant senses in perception and technological advancements. We provide reasoning for the under-representation of some illusions as well as general opportunities

and challenges when building interfaces based on haptic illusions. Furthermore, we discuss the similarities of elicitation methods of haptic illusions used in HCI independent of the targeted property and use this to classify illusion based on four independent dimensions: target property, elicitation method, used technology, and addressed sense. Consequently, we stipulate possible future directions of interest for research.

## 5.1 Research Trends & Gaps

This section will discuss research trends and gaps based on our findings and put them into the context of the previously established works of Hayward [44] and Lederman and Jones [73], which both cataloged haptic illusions known from cognitive sciences. First, we examine the prevalence of visually elicited illusions (5.1.1) and phantom sensations (5.1.2), which together make up the majority of the illusions employed for haptic feedback. Further, we discuss how haptic illusions have evolved with recent advancements in computing (5.1.3) and the increasing use of other senses in elicitation (5.1.4). Lastly, we analyze why many illusions found in prior literature (5.1.5) are underrepresented in HCI and discuss the lack of multimodal approaches to generate haptic illusions (5.1.6).

*5.1.1 Visual dominance.* Visual dominance in sensing has been well established [122]. Therefore, easier and more extensive access to our vision greatly influences the control we have over subjects' perceptions of reality and the environment. So, it is not surprising that the rise of VR affected the number and types of haptic illusions being produced. As we have previously shown in Figure 2, we can observe a continuous increase in the total number of illusions being researched over the years, spiking around 2018 and 2019. Figure 5 shows the distribution of illusions and used technologies in publications over the same period of time. This shows a similar trend for the use of VR technology, which now makes up the majority of used visual technologies from 2018 onward. This increase is likely caused by the emergence of consumer-ready VR systems. While VR and HMDs have been around since the 1960s [38, 126], robust off-the-shelf VR hardware has become prevalent with the releases of the HTC Vive and the consumer version of the Oculus Rift in 2016 [29, 131], which might have resulted in an increase in studies and subsequent publications manifesting the years after.

This increase in the use of VR shapes the type of illusions being investigated. In the classical, two-dimensional desktop scenarios, illusions are generally created by adjusting the cursor representation, and their focus lies on the perception of surface textures. With the jump to immersive environments and the ability to fully control them, as well as the visual representation of the user's body, other (novel) types of illusions have become prevalent. Weight illusions have increased analogously to VR usage, as these are mainly generated by visual-kinesthetic discrepancies, which can easily be introduced in immersive VR by manipulating the control-display ratio of a virtual hand (e.g., [115]). Changes in control-display ratio had been applied in many desktop scenarios before to simulate frictions or textures (e.g., [71]), but these could only apply indirectly to a cursor or other form of representation. The manipulation of the hand's representation allows the direct alteration of the weight sensation of a held object. The same trend towards virtually represented hands and bodies also shows a change in proprioception and body schema illusions. The classical Rubber Hand Illusion [13] is gradually replaced or rather enhanced by the Virtual Hand Illusion (e.g., [117]), which can be produced with less setup and has the added benefit of interactivity and opportunity for active exploration using touch. Proprioception illusions also take advantage of altering control-display ratios, but as opposed to the strong adjustments used in weight illusions, these visual alterations should be undetectable and gradual to create a proprioceptive drift (e.g., [124]).

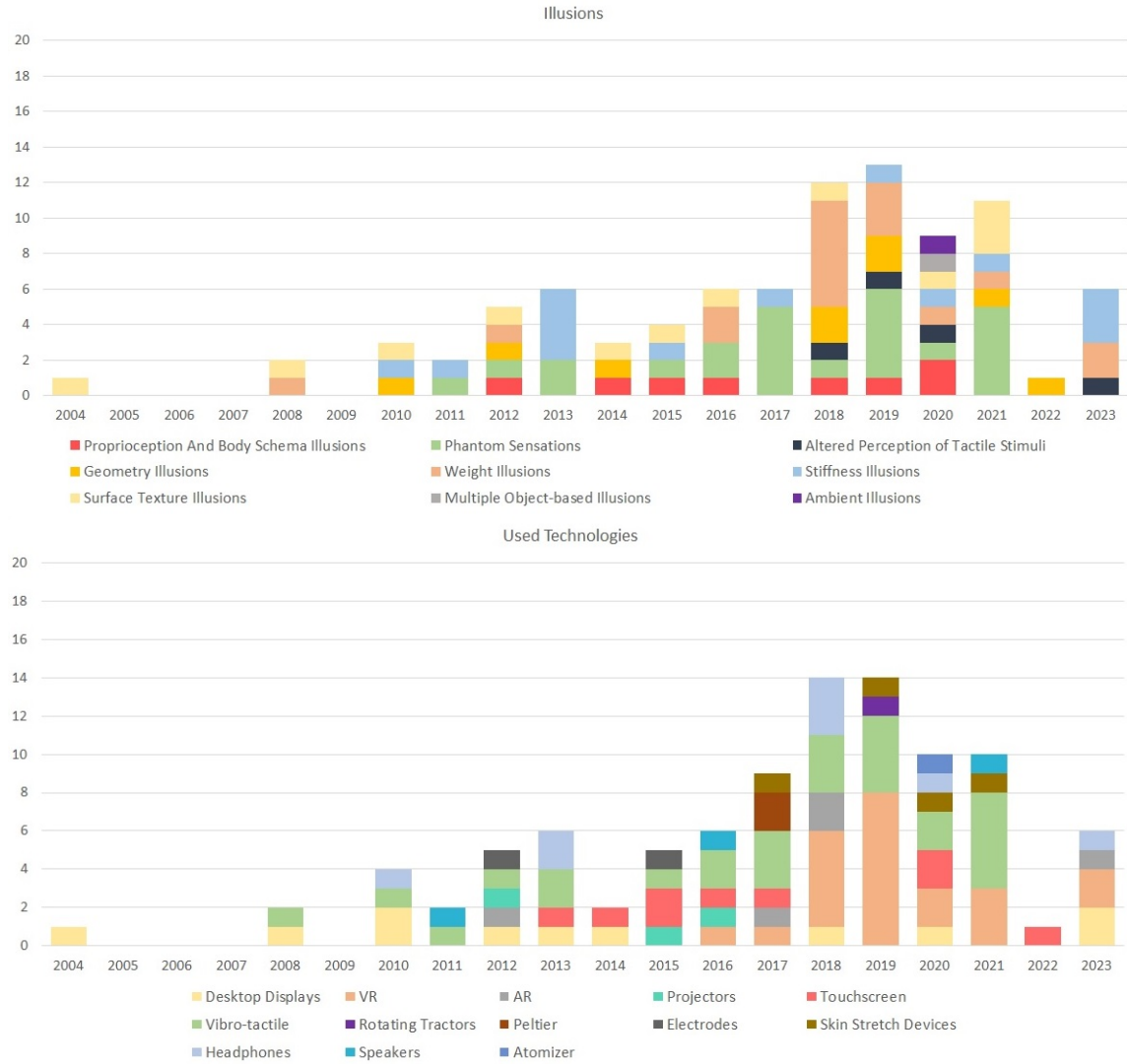


Fig. 5. The number of haptic illusions explored and the technologies used in their creation, broken down by publication year, shows how the research interest in different illusions and the used technologies have evolved over this period and how these factors may have influenced each other. Note that the colors in the upper and the lower bar charts are not directly related to each other. **Top** shows the distribution of illusions categorized by the haptic property they are targeting. Phantom Sensations comprise the biggest portion of researched illusions during the whole period. From 2018 onward, we see the proportion of investigated weight illusions increase. **Bottom** shows the distribution of technologies used to generate these illusions. The total number of technologies ( 97 ) exceeds the publication count ( 90 ) because more than one can be used simultaneously. Analogously to the research interest in phantom sensations, vibrotactile actuators were commonly used throughout the time period. Starting from 2016 and spiking in 2018/2019, we see a big increase in the use of VR technology to elicit illusions.

**5.1.2 Phantom Sensations.** Phantom sensations and tactile apparent motion have been prevalent for a large portion of the studied time period but have experienced an upswing in recent years (see Figure 5). In our investigation, they

turned out to be the most widely used and researched types of illusions. These illusions can be elicited in a number of ways, for instance, funneling (e.g., [52]) or saltation (e.g., [65]), all of which have been studied extensively and shown to be very robust to create sensations on a body part. This widespread use of these techniques might be related to the high amount of illusions and effects they can produce without a complex setup. Vibrating actuators are cheap and easy to implement and use or might already be integrated into devices that can be held (e.g., in VR controllers [10]). Therefore, prototypes can be set up and adapted more easily for a wide range of different explorations. While the creation of phantom sensations on the skin is still being explored, an increasing amount of publications investigate the extension of these sensations out of the body. However, these illusions seem to be robust enough for the overall setup to barely have to change. Phantom sensations have been shown to be present (albeit with different strengths) between two actual actuators, no matter if the actuation points are next to one another on the body (e.g., [52]), connected with a physical object (e.g., [65]), or not connected at all (e.g., [102]). All these factors make phantom sensations and tactile apparent motion very flexible. This already led to the creation of advanced prototypes, such as a tactile display using two-dimensional arrays of actuators on the body [52] or a smartphone [65], and might affect the future developments in tactile displays, as these struggle with the possible density of actuators [42].

*5.1.3 Evolution of Illusions.* In Table 4, we identify and compare illusions used in HCI to those that are well known in perception research and have already been presented in the surveys of Hayward [44] in 2008 and Lederman and Jones [73] in 2011. The frequency of illusions employed for haptic feedback in HCI varies independent of their popularity in perception research. For instance, phantom sensations and weight illusions appear much more frequently than other commonly known illusions, such as the RHI. While the targeted haptic property of these illusions remains the same, the methods of inducing these illusions have adapted or changed. Advancements in technology create new possibilities to use existing methods in novel ways, combine them, or create new methods to generate more robust or scalable illusions. For instance, illusions of geometry in HCI evolved a lot from the classical size misjudgments adapted from optical illusions (e.g., the Müller-Lyer illusion [127]): through powerful computer vision and display techniques, illusions of sizes and shapes can be elicited by displacing [8] or even distorting [11] visible hands when exploring three-dimensional objects. Furthermore, a moving VHI can be used in substantially more applications than the classical RHI and is strengthened by the increased sense of embodiment and agency that interactivity and immersion in VR entail.

*5.1.4 Senses.* One thing that does not appear to have changed is the predominant use of visual and haptic stimuli in attempts to create illusions, as we have seen and discussed previously (see sections 5.1.1 and 5.1.2).

In contrast, illusions induced by auditory stimulations have only been used sporadically over the last decade. While they are quite underrepresented, the effect on the haptic perception of this modality has been researched both independently (e.g., [69]) and in conjunction with other senses, such as sight (e.g., [146]) and haptic (e.g., [23]). Overall, audio-induced illusions are able to target a broad range of material properties of objects, such as weight [146], stiffness [69, 134], and roughness [23, 33]. The preference for visual and haptic cues over sound seems to be based on the lower strength of audio-haptic illusions. The sense of sound can still have a non-negligible influence on haptic perception. This is evidenced by the fact that when addressing other senses, experimenters often deliberately try to exclude the sense of sound by using noise-canceling headphones and/or drowning it out with white noise. Nevertheless, due to the few publications researching this area, the strength of audition to induce different illusions and the interplay of it and other senses is still not fully explored.

Researchers have recently started exploring the sense of smell as a possible modality to generate haptic illusions. Brooks et al. [16] induce the illusion of temperature sensations using an olfactory display. While some gustatory displays have also been explored in HCI [138], to the best of our knowledge, no haptic illusion using these interfaces has been proposed yet. However, illusions similar to the one investigated by Brooks et al. could be feasible. The sense of smell and the sense of taste share some common challenges: The current technology targeting these senses is still in its infancy, and the apparatus needed for stimulation is still very complex. Additionally, as Brooks et al. noted, due to the stimulation only acting directly on the sensing organ, the resulting illusion is not spatially localized correctly, i.e., when touching a simulated hot surface, the temperature sensation would not change on one's hand but in the nasal pathway.

*5.1.5 Underrepresented Illusions.* Comparing the illusions used in the included publications with the overview of existing illusions (see Table 4) shows that most of the main categories of properties targeted by illusions (illusions of material, illusions of geometry, illusions of body space) have been explored to generate haptic feedback in computing systems. However, when we look at individual illusions, we can observe that most have not been considered. We specify four likely reasons for the underrepresentation of these illusions in HCI.

- (1) The illusion imposes impractical requirements on how the sensing organ or body part has to interact to create the illusion. A good example is the popular Aristotle's Illusion, which requires subjects to feel an object between the fingertips of two crossed fingers to generate the illusion of two separate objects. While this illusion is robust, the demands on the user disqualify it for many applications.
- (2) The illusion and the haptic property it targets are very narrowly focused and specific. These illusions generally require very specific set-ups for niche outcomes, which cannot be scaled or adapted for a broader use easily. Most of the shape illusions fall under this category. For example, the elongated rotating disk illusion creates the illusion of a disk increasing in length when it is held between the thumb and index finger and rotated orthogonally with the other hand. The possible applications of this illusion for interfaces are slim, and while it possibly could be implemented (and to an extent dynamically adjusted) with current technology, the intended outcome (an object feeling longer) can just be more easily accomplished directly.
- (3) Better or easier methods to create illusions targeting the same haptic property have been shown. For instance, except for the size-weight illusion, none of the illusions from our compiled list targeting the alteration of a weight sensation have seen considerable use in HCI. Instead, we have mostly seen a novel method of changing the control-display ratio of a virtual hand while it is holding the target object. The other properties that have been shown to have an effect on weight perception might be more difficult to achieve and adapt dynamically (e.g., texture or temperature) or simply have less of an effect (e.g., visual material cues [73]) than the methods we have seen in HCI.
- (4) Lastly, some individual illusions simply might not be robust enough to rely on them to provide feedback. As Gentaz and Hatwell [37] discussed, many geometrical haptic illusions that originate from visual analogs have had discrepant outcomes in different studies (e.g., the Ponzo and Poggendorff illusions).

*5.1.6 Multimodality.* Multimodal illusions form another group, which are underrepresented in the works we investigated, yet they have great future potential to deliver more robust and effective haptic feedback. The effectiveness of illusions addressed to the visual, haptic, and, to an extent, auditory modality has been shown in many of the investigated publications and the established related works. Furthermore, the use of multiple illusions addressing different modalities has been explored. However, the interaction of modalities for different illusions is still unclear. Reported



Targeted Property	Illusion	Included Publications
<b>Material</b> - Texture - Stiffness - Temperature - Weight	Thermal grill illusion  Size-weight illusion Density- or material-weight illusion Force by acceleration asymmetry Shape-weight Illusion, Weight after-effect, Surface texture-weight illusions, Temperature-weight illusion	[23, 33, 34, 62, 64, 71, 72, 87, 101, 113, 136, 148, 149] [4, 46, 47, 57, 60, 63, 67, 69, 113, 129, 134, 144] [16] None [2, 55, 59, 92, 96, 108, 112, 115, 120, 146] [43, 82, 116] [82] [1, 128] None
<b>Geometry</b> - Size  - Shape	Müller-Lyer illusion, Horizontal-vertical illusion, Bisection illusion, Radial-tangential illusion, Ponzo illusion, Filled Space (Oppel-Kundt/Helmholtz) illusion, Delboeuf illusion  Elongated rotating disk illusion, Rotating hourglass illusion, Ridge illusion, Computer paper illusion, Bump illusion, Fish-bone illusion, Comb illusion, Haptic curvature aftereffect, Haptic simultaneous contrast effect for curvature, Contour enhancement illusion, Curved-plate illusion, Aristotle's illusion (Tactile diplopia), Tactile barber pole	[6, 11, 132, 147] None  [7, 8, 12, 21, 113, 133] None
<b>Body Space</b> - On Skin         - Body Schema	Movement: Tactile apparent motion  Errors of localization: Sensory funneling illusion Errors of localization: Sensory saltation illusion Thermal spatiotemporal illusions Thermal referral Numerosity of taps from beeps, Change numbness, Temporal ordering, Tactile Motion after-effect, Distance: Tau and kappa effects, Weber's illusion, Effect of stimulus orientation  Rubber hand illusion Vibration illusion	[19, 139, 145] [22, 25, 41, 52, 54, 61, 93, 104, 106, 118, 119, 151] [10, 52, 65, 77–79, 102] [10, 31, 40, 56, 65, 78] [39, 103] [81] None  [80, 94, 105, 117, 124] [3, 26, 100] None
<b>External Haptic Space</b> - Parallelism  - Oblique Effect	Zöllner illusion, Poggendorff illusion, Bourdon illusion	None None None

Table 4. This table gives an overview of established illusions compiled from the surveys of Hayward [44] and Lederman and Jones [73]. Additionally, our surveyed publications are included and categorized according to the illusions they explored.

results concerning multimodal illusions producing haptic feedback vary from a seemingly additive effect (e.g., in visual and haptic [56]) to small or no improvement when two modalities are combined compared to the use of a single one by itself (e.g., visual and electrotactile [144] or visual and audio [134]). The exact cross-modal interaction between senses has also been shown to vary based on the context. Researchers investigated the interplay of visual and audio cues

and found that both senses could be dominating over the other in perception, dependent on the exploration task and scenario [133]. The senses of smell and taste have generally been underexplored, probably due to lower reliance on them during the exploration of environments. However, the sense of smell was shown to be able to alter temperature sensations [16]. Therefore, while they might not create a robust or strong enough illusion independently, their inclusion in multimodal illusions could have an added benefit. Additionally, exploring more than two modalities combined would be interesting (and feasible). Just one publication we found investigated the effect of visual, auditory, and tactile stimuli on haptic illusions [54].

**5.1.7 Summary.** To answer our research question regarding the reasons for the prevalence and underrepresentation of different illusions (see RQ2 in section 3.1), we discussed vision’s predominant influence on perception and virtual reality driving novel trends for eliciting sensory illusions. Furthermore, the easy and cheap deployment of vibrotactile actuators elevated the use of phantom sensations and tactile apparent motion illusions. Visual and haptic cues dominate currently, but other senses and the combination of multiple modalities are promising but remain underexplored, while some illusions established in perception research may remain entirely unused due to practical limitations, niche use cases, or lack of robustness.

## 5.2 Interface Building through Illusions

Many works in HCI present methods for realistic haptic feedback, which are difficult to implement with conventional hardware and often rely on specialized set-ups (e.g., encounter-type systems [88] or wearable exoskeletons [97]). Sensory illusions have the potential to provide haptic feedback with less effort and complexity. To address the general consideration that must be taken into account (see RQ3 in section 3.1), this section discusses the key opportunities and challenges that arise from the use of sensory illusions for haptic feedback.

**5.2.1 Opportunities.** Generally, the investigated illusions often target haptic properties, which are difficult to address with conventional haptic interfaces. Adjusting the actual stiffness of a material requires methods (e.g., granular jamming [53]) that are not feasible or desired for every device or application. Altering the weight of an object that can be held freely in one’s hand is even harder to achieve when it cannot be connected to any external, grounded device. Furthermore, the specialized hardware has to be integrated within these devices beforehand, making it less scalable and unsuitable for situations in which everyday objects are augmented or appropriated. As we have shown in section 4.1.6 and section 4.1.5, the perceptions of stiffness and weight can be altered effectively using sensory illusions. For example, both stiffness and weight illusions can be generated solely based on visual cues by texture deformation [144] or a change in control-display ratio [115] respectively. This allows their application to a much wider range of objects and situations, such as tablet and smartphone touchscreens or mixed reality environments.

Even in cases where haptic feedback could be achieved by other means, illusions generally reduce the amount and complexity of required hardware. This can especially be observed for phantom sensations and tactile apparent motion, where many real actuators can be replaced with illusionary ones. Israr and Poupyrev [52] showed that the simulated actuators from the funnel illusion are actually strong enough to elicit a tactile apparent motion illusion, showing that these illusions can scale beyond one additional virtual actuator. As advancements in interactive systems trend towards more mobile devices, the requirements shift. Novel systems and devices need to be smaller and lighter and consume less energy while still being able to produce high-fidelity and high-resolution output. When engineering these new devices, the integration of actuators able to induce sensory illusions therefore can immensely increase the quality and range of haptic feedback they can produce in a small space with low cost and energy demand.

Another interesting opportunity emerges from wearables, devices embedded in our clothing, and human augmentation. Having direct access to a user's sensory organs, body parts, and skin allows for a wide and effective use of sensory illusions, such as phantom sensations [52, 56] and apparent tactile motion [61, 93, 103]. Instead of integrating more hardware into every object, combining on-body devices and sensory illusions can enable quality haptic feedback in many everyday life scenarios. Thus, developing novel on-body devices should consider the benefits of the lightweight and low-cost implementation of sensory illusions.

Additionally, as we have discussed before, many of these illusions result from stimuli addressed to different senses, meaning they could be used in conjunction with each other or added to interfaces with existing haptic feedback output. Combining different haptic interface systems is often difficult or creates redundancies. For instance, using both a haptic glove (e.g., [51]) and mid-air ultrasonic feedback (see [111]) would lead to a conflict, as the glove covers the palm's skin, which the ultrasonic feedback is targeting. Furthermore, adding more capabilities for additional sensations, such as temperature or surface texture, to existing haptic interfaces adds complexity and is limited by the device's available space. Haptic illusions are able to cover multiple sensations in parallel without the same disadvantages, as physical restrictions do not limit them. To get closer to the vision of an ultimate display [125] that, among other things, creates flawless haptic experiences, the use of sensory illusions may be required when conventional hardware approaches cannot precisely address all haptic properties.

**5.2.2 Challenges.** The effect of an illusion is generally lower than what can be achieved with actual hardware. Therefore, in the publications we investigated, haptic illusions are mainly used to alter the perception of haptic properties on an existing physical object. The strength of sensory illusions does not suffice to create haptic sensations in mid-air on its own. So, it must be coupled with an actual haptic sensation (e.g., a resisting force) to produce realistic virtual objects. The publications exploring the creation of virtual objects relied on existing forces and only adapted how they were interpreted. For example, Bickmann et al. [12] relied on the force created by your own palm when closing your hand and adapted the visual representation to add a virtual object and distort the hand, resulting in the forces to be perceived to originate from a held object. Physical props or active devices are still necessary to create realistic sensations. The development of novel devices that can elicit illusions without overly restricting the natural interactions of the user remains an open challenge for future research.

In addition, efficacy can vary widely between users. Researchers should look for illusions that have been shown to be robust, or they could evaluate new methods that could lead to more robust perceptions. In addition, as novel devices are developed, designers and engineers could aim to develop methods to more accurately track and measure users' perceptions, such as through physiological measurements, and to adapt systems to inter- and intrapersonal differences. Advances in these areas will contribute to more accurate and precise haptic illusions for all users.

Furthermore, since illusions rely on perception, environmental noise can easily disturb them. This explains the frequent use of noise-canceling headphones, as sounds from the environment or the active device can alter the perceived illusion. Similarly, immersive virtual environments were built for many of the investigated illusions to ensure less visual noise influencing the results.

Lastly, similar to the field of active haptics, the work studied often relied on custom-built devices to create the illusion as effectively as possible. These approaches would need to be generalized to enable replication and integration into future systems. The development of off-the-shelf devices or easily replicable hardware to create specific haptic illusions is essential for future advancements.

### 5.3 Classification of Haptic Illusions in HCI

As shown in Table 4, most illusions investigated in HCI cannot easily be categorized into illusions known from previous works. Moreover, as we showed in section 5.1.5, many of these known illusions might not be feasible for use in HCI. Therefore, to properly consider every aspect introduced by the use of sensory illusions for building haptic interfaces (see RQ3 in section 3.1), this section discusses a new additional dimension needed to categorize haptic illusions used within HCI.

So far, the classification of illusions solely relied on the haptic property an illusion was targeting. However, how we perceive the haptic properties of objects and space can be variable depending on the interaction. For instance, forces applied to our hands can be interpreted differently. We might perceive the force as the object's weight if we are currently lifting an object vertically. If we press against an object horizontally, we might feel the object's resistance or stiffness. Consequently, a single method used to elicit an illusion can target different haptic properties, as Salazar et al. [113] showed by changing the perceived shape, texture, and stiffness of objects through a single method. Therefore, we propose the elicitation method as a new independent dimension relevant to discuss and ultimately classify haptic illusions in HCI.

Table 5 gives an overview of the methods used in HCI to elicit illusions based on the works we reviewed. The illusions used in these works are classified by the target property and elicitation method.

This shows that target and method are not linked rigidly, i.e., many methods can target one property, and one method can target different properties. In particular, different material and geometry properties of objects can easily be altered using the same methods, such as control-display ratio or lateral skin stretch. This might greatly increase the usefulness of these methods, as it allows for designing a broad spectrum of haptic properties using a single method and setup. However, illusions targeting the body and skin are not easily transferred toward another property. However, due to the number of publications found in HCI using the corresponding methods, such as Funneling, Saltation, and Stimulus-Onset-Asynchrony (SOA), these methods might be very relevant to target the respective properties. In addition to providing insights into the relevance and versatility of the different methods used in HCI, this overview also suggests potential opportunities for currently unused combinations of methods and targeted properties.

Adding the elicitation method, illusions can now be uniquely classified by four characteristics: The haptic property the illusion is targeting, the method used to elicit the illusion, the technology used to create it, and the sense addressed by this technology.

Figure 6 shows all illusions we reviewed in this work, characterized by these four dimensions in an alluvial flow diagram. It can be observed that some illusions are represented as straight lines across all characteristics in this diagram. This is mostly true for skin sensations generally induced by funneling, saltation, and SOA methods using vibrotactile actuators. Although they are used less frequently, other technologies (such as peltier elements) can induce similar illusions using analogous methods. Similarly, illusions related to RHI appear to be straightforward, although they are separated into their visual and haptic components, whereas the visual part, in turn, is induced either through the classical rubber hand ("Custom") or through a virtual hand in an immersive virtual environment ("VR"). On the contrary, used methods, technologies, and senses to target object properties are much more diverse and interconnected. Solely visual methods, such as adapting the control-display ratio, can target many haptic properties, partially depending on the technology used to create the discrepancy. For example, while Lécuyer et al. [71] were able to alter the perception of texture by manipulating the ratio of mouse to cursor movement on a Desktop PC, Samad et al. [115] could adapt the perceived weight of objects using this method on participants' whole hands in immersive VR. However, the methods

used are not limited to a specific sense but can sometimes be applied by addressing different senses. For example, simulating an object inside a held passive prop to elicit a perceived change in weight has been achieved by visual [55, 146] and by auditory [146] cues. This flow also highlights that, as we previously discussed in section 5.1.4, the sense of sound is addressed much fewer but is able to target a wide range of object properties. The strong interconnectedness also shows that the combination of different methods, senses, and technology is feasible and could greatly increase the efficacy of these illusions. We can easily target the same properties by addressing different senses with different technologies, but we can also combine methods using the same modalities. For instance, we can change the stiffness perception through speakers producing deformation sounds and a projector displaying a visual texture deformation. Or it is possible to change the perception of surface textures by superimposing a visual texture and simultaneously adapting the control-display ratio. The interconnected flow further suggests potential new combinations of targeted properties, used methods, addressed senses, and technologies we have yet to find and investigate in HCI.

#### 5.4 Detailed Description of the Classification, Table and Alluvial

In this section, we provide a comprehensive description of the dimensions and classifications found in Table 5 and Figure 6.

Table 5 categorizes the surveyed publications by their targeted haptic property as well as the methods used to elicit the illusion. Some publications appeared more than once as multiple methods or target properties were explored. The targeted haptic properties are derived from the classifications used in the survey by Lederman and Jones [73]. Their original hierarchical division is shown in the left column of Table 4.

The methods describe the interactions and procedures used to elicit haptic illusions, irrespective of the targeted property (and technology or addressed sense). These classifications are derived from clusters found in the publications we surveyed. Some methods, such as funneling and saltation, have already been defined in existing publications. Others have specific procedures that can be easily recognized, such as the RHI and VHI. Lastly, some specific methods used in the publications we surveyed have not been categorized yet. We contextualize these methods to provide a comprehensive overview.

- **RHI:** This refers to the procedures used in the RHI and VHI experiments. VHI is included as it uses a similar method to the classical RHI, changing only the utilized technologies (VR). A more detailed explanation of these methods can be found in section 4.1.1.
- **C/D Ratio:** An alteration of the control-display ratio, i.e., a discrepancy of real to virtual movement gains of an interactor. This has been applied to mouse cursors (e.g., [71]), fingers (e.g., [136]), and arms (e.g., [115]) to elicit different illusions.
- **Moving Pattern:** Displaying a pattern moving across a body part. This simulation is not limited to a specific modality. For instance, it was displayed visually [2] and tactually [94] in our surveyed publications.
- **Funneling, Saltation, and Stimulus-Onset-Asynchrony:** Funneling, Saltation, and SOA are common methods used to elicit phantom sensations and tactile apparent motion. These methods are explained in section 4.1.2 and discussed in section 5.1.2.
- **Incongruent Distractor:** This describes the use of an incongruent stimulus (e.g., asynchronous, mislocated, or misdirected) to alter the perception of an existing haptic stimulus. Examples of these are shown in section 4.1.3.
- **3D Deformation:** The deformation of a virtual (3-dimensional) object occurs during the interaction or procedure.

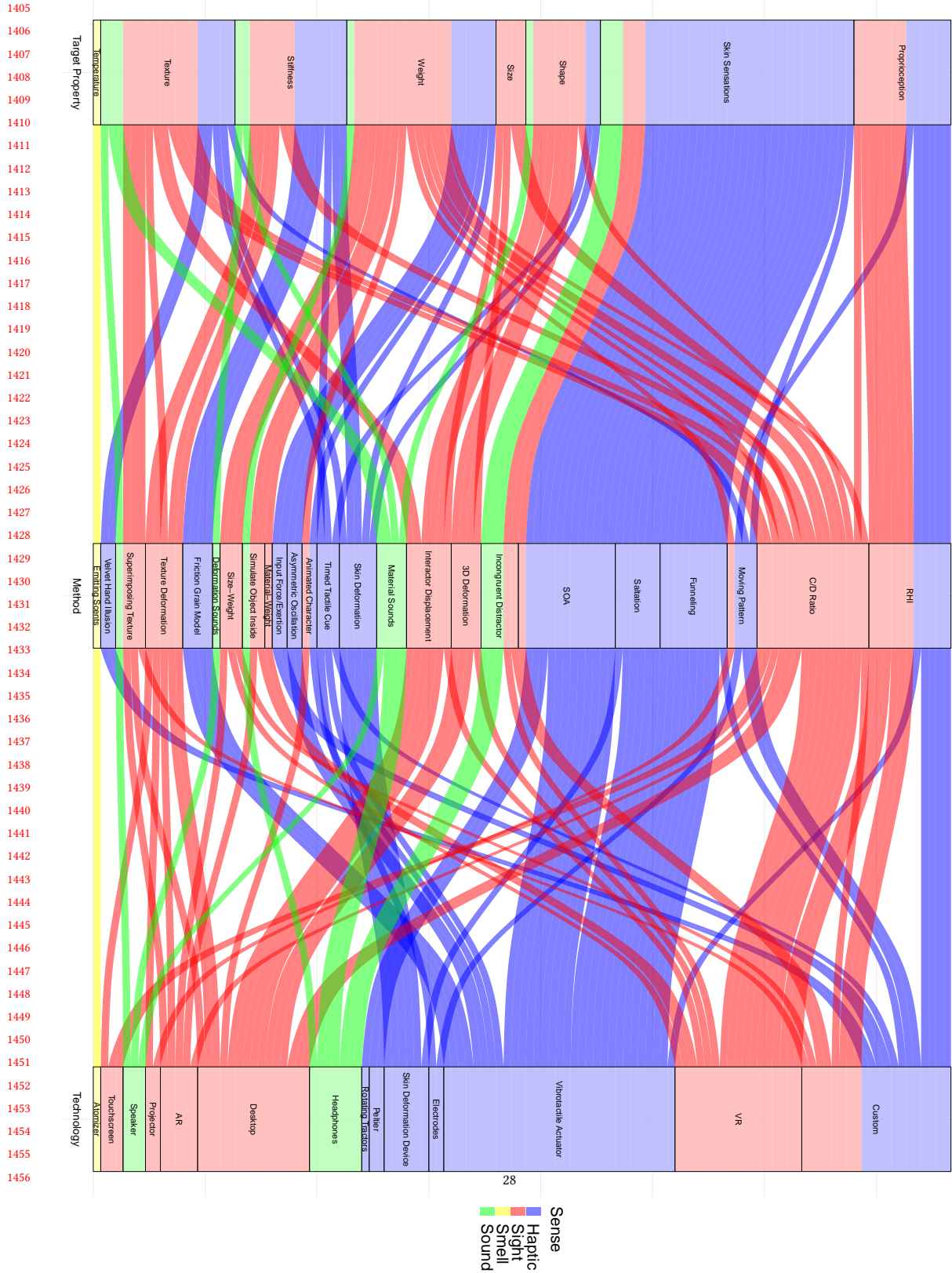


Fig. 6. Alluvial diagram showing every illusion investigated in our surveyed publications characterized by four dimensions: Target Property, Method, Technology, and Sense. For a full explanation of this diagram, refer to section 5.4.

	Weight	Size	Shape	Texture	Stiffness	Temperature	Proprioception	Skin Sensations
RHI							[3, 26, 80, 100, 105, 117]	
C/D Ratio	[58, 92, 108, 112, 115]	[11, 147]	[12]	[62, 71, 72, 136]	[20, 141]		[124]	
Moving Pattern	[2]			[64]			[94]	[81]
Funneling								[10, 52, 61, 65, 77–79, 102, 118]
Saltation								[10, 31, 40, 56, 65, 78]
SOA								[22, 25, 39, 41, 52, 54, 93, 103, 104, 106, 119, 151]
Incongruent Distractor								[19, 54, 121, 139, 145]
3D Deformation		[132]	[7, 8, 133]					
Interactor Displacement		[6]	[7, 8, 133]	[72, 87]				
Material Sounds			[133]	[23, 33]	[134]			
Skin Deformation	[120]		[113]	[113]	[113, 129]			
Timed Tactile Cue			[21]	[23]	[144]			
Animated Character	[85, 96]							
Asymmetric Oscillation	[1, 128]							
Input Force/Exertion	[59, 112]							
Material-Weight	[82]							
Simulate Object Inside	[55, 146]							
Size-Weight	[43, 82, 116]							
Deformation Sounds					[69]			
Friction Grain Model					[46, 47, 60, 63]			
Texture Deformation				[14]	[4, 57, 67, 144]			
Superimposing Texture				[14, 33, 34, 149]				
Velvet Hand Illusion				[101, 148]				
Emitting Scents						[16]		

Table 5. This table provides an overview of the haptic properties targeted and methods used in our surveyed publications. Publications may appear in more than one cell if they use multiple methods or target different properties. For a full explanation of this table, refer to section 5.4.

- **Interactor Displacement:** Actively displacing the representation of the interactor. As opposed to C/D Ratio, this does not solely adapt the movement gains of the interactor but can also apply displacements during moments without any movement or in a different direction from the movement trajectory.
- **Material Sounds:** Replicating the sounds of materials occurring during contact and applying them to interactions with another (virtual) object.
- **Skin Deformation:** This refers to cutaneous deformations, such as stretching the skin laterally or restricting the skin's deformation.
- **Timed Tactile Cue:** This refers to a tactile cue, e.g., vibrations, being displayed synchronously to an interaction with an object.



- **Animated Character:** Most of the presented methods rely on very simple cues to elicit an illusion. Conversely, this method employs elaborate animations of virtual characters and thus relies on more complex concepts, including social cues like changes in facial expressions [85].
- **Asymmetric Oscillation:** An object vibrating with asymmetric acceleration patterns.
- **Input Force/Exertion:** In this method, users are required to exert a force, either onto a rigid object (e.g., [59]) or in mid-air by flexing their muscles (e.g., [112]), to be able to interact with a virtual object, which suggests a resistance.
- **Material-Weight:** This method utilizes the material-weight effect of an object feeling lighter when its material seems to be denser. For example, an object that is visually presented to be made of metal is perceived to be lighter than an equally weighted object presented to be made of light wood.
- **Simulate Object Inside:** Simulating a mobile object (e.g., a rolling ball [146] or a fluid [55]) inside the object being augmented to change the perception of its properties.
- **Size-Weight:** This method utilizes the size-weight effect of a bigger object feeling lighter than an equally weighted smaller object when held.
- **Deformation Sounds:** Replicating the sound of a material being indented or deformed during interaction with another (virtual) object.
- **Friction Grain Model:** This refers to a specific technique of small vibration grains being produced at set intervals during changes in input pressure. A more detailed explanation is given in section 4.1.6.
- **Texture Deformation:** A 2-dimensional deformation of the surface texture of an object occurring synchronously to an interaction.
- **Superimposing Texture:** Superimposing a virtual texture onto an existing surface.
- **Velvet Hand Illusion:** This refers to the specific procedure in the Velvet Hand Illusion, where subjects rub the palms of their hands together with a grid of bars lodged between them.
- **Emitting Scents:** Emitting scents into the air or directly into the nose, e.g., by nebulizing fluids [16].

Figure 6 shows an alluvial diagram of all illusions we found in the investigated publications. Each illusion, defined as a combination of the target property, method, technology, and addressed sense, is represented as a string flowing from column to column. Note that each string is continuous throughout the whole diagram. Overall, we found 108 illusions in the investigated works. The columns and color code represent four dimensions an illusion can be characterized by. The Target Property (left) and Method (center) are identical to the definitions given above. The Technology column (right) shows the technologies actively involved in the respective method to elicit the illusion (see section 4.3 for a more detailed explanation). The columns are separated vertically into categories. The height of these categories along the vertical axis is based on the respective number of illusions. The sense addressed to create an illusion is represented by colors and separated into Haptic, Sight, Smell, and Sound (see section 4.2 for a more detailed explanation).

## 5.5 Research Directions

This section discusses which future research directions could interest this field based on the insights gained from underrepresented and well-established haptic illusions (see RQ4 in section 3.1).

We found that many established illusions have been adapted and enhanced with new technologies and methods, making them more robust or easier to produce. Simultaneously, novel haptic illusions have been reported, addressing senses less frequently used within the works we investigated (e.g., sound and smell). However, the effect on haptic

feedback of illusions using these senses or multiple modalities combined has not been widely researched. The overviews we provided underline the opportunities to extend existing methods to different contexts using new technologies and multimodal approaches.

As seen from the reported motivations and goals, most publications try to present novel illusion techniques, understand existing ones, or extend them by using new technologies. All of these require proving that an illusion can be produced, which is usually done in a controlled setting. One important future research direction may be how these studied haptic illusions might fare in more realistic scenarios with more natural conditions. Over the investigated time period, we could observe a development from the use of abstract desktop scenarios and geometric primitives to more natural interactions and realistic environments created by virtual realities, which still remain completely controllable [16, 112, 124]. The next step would be to adapt these illusions to the real world and allow them to augment everyday life objects. As many factors and multiple modalities influence the perception of haptic properties of real, physical objects, exploring haptic illusions on real or realistic (e.g., high-fidelity visuals and sounds) materials and objects would be necessary to understand how these methods might fair were they to be widely adopted and employed over long time frames. How prolonged exposure, learning effects, and familiarity may alter the efficacy and robustness of haptic illusions long-term still remains to be researched.

Furthermore, Augmented Reality provides the possibility to bring haptic illusions into the real environment without the need for complex set-ups. At the same time, AR does not allow the same amount of control over the surroundings. While superimposing virtual objects over existing ones is now trivial, making real objects disappear requires more effort (e.g., using diminished reality [43]). As video-seethrough Augmented Reality headsets become more powerful and ubiquitous, more manipulation of visual and auditory cues becomes available to employ.

In addition, we can see that investigated illusions and used methods often rely on the evolution and availability of hardware and existing technology. In the future, research could be investigated more in opportunities to reduce the needed amount of hardware. Especially as we explore haptic illusions, more research on methods that rely nearly solely on the human senses and cognition could be made. Getting more independent of technology could also be a way to have more research on the so far underrepresented illusions. Future research might aim to develop better methods to solve these issues to allow novel and established techniques to be used for promising haptic illusions in new areas. However, as we have seen from trends in the last decade, we should never limit the ideas for possible illusions on current technologies.

## 5.6 Limitations

While this literature survey paper strives to provide a comprehensive overview of the existing research in the realm of haptic feedback for computing systems created by sensory illusions, it is essential to acknowledge the inherent limitations stemming from the vastness and multidisciplinary nature of haptics research. Haptic feedback spans a wide spectrum of applications, ranging from virtual and augmented reality to robotics and medical simulations, each with unique challenges and solutions. As a result, relevant works employing sensory illusion for haptic feedback might have been missed due to our set restrictions on databases or keywords.

Furthermore, due to the widely different methods used to evaluate and report the successfulness of haptic illusions in the works we investigated (see 4.6), we cannot create precise comparisons regarding the robustness and efficacy of illusions. While research on haptic devices can usually rely on objective metrics that can be measured and reported, such as force output or absolute temperature, haptic illusions rely on subjective experiences that are affected by intra- and outer-personal circumstances. We require more standardized processes, such as psychometric methods, to reliably

compare the outcomes. For now, we are limited to the reporting in the individual works and frequency analysis of used techniques to infer illusions' potential.

## 6 CONCLUSION

Sensory illusions, which have been explored in perception research, now play an increasing role in generating haptic feedback for computing systems. We conducted a systematic literature review to provide an overview and understanding of how these illusions are adopted or adapted to enhance haptic feedback in computing systems. We investigated which haptic illusions known to occur in perception from prior literature are explored for haptic feedback and which remain underrepresented and established possible origins for the prevalence and underrepresentation of certain methods for eliciting illusions. We identified current trends and gaps and specified possible future directions of interest for research. In particular, we discussed that illusions used to create haptic feedback have remained mostly the same, while the underlying methods used to create them have changed due to ever-increasing knowledge and novel technologies. Multimodal illusions, or those addressing senses other than sight and touch, have generally been underexplored but could hide great potential for future advancements. In addition, various haptic illusions have not been widely explored to create haptic feedback in computing systems because they are impractical to generate or surpassed by better methods targeting the same properties. This highlighted the need for a new classification of haptic illusions tailored to HCI, comprising the target property, elicitation method, used technology, and addressed sense of each illusion. Using this classification, we provided a comprehensive overview and discussion of how sensory illusions can create haptic feedback.

Conclusively, constant technological advancements have allowed the adaptation and enhancement of methods for stronger, more robust haptic illusions and provide completely novel ones. Nevertheless, our haptic perception and the haptic properties these illusions may target remain the same. So, instead of limiting ourselves by constantly changing technologies, future research may focus on exploring illusions under more natural conditions to understand better how these illusions could enhance our everyday lives long-term.

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