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Augmenting the feel of real objects: An analysis of haptic augmented reality

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ABSTRACT

Advances in haptic technologies can alter how real objects feel to our touch and create the experience of haptic augmented reality (AR). However, the definition, use cases, and value to end users of such haptic AR remain unclear. Existing work is concerned with technological implementation and lacks a user-centered perspective. To address these limitations, we analyze haptic AR systems in the literature to understand what constitutes haptic AR, why we would want to alter our sense of touch, and how haptic AR interactions take place. To demonstrate the value of studying haptic AR in the context of real-world tasks and user impressions of the concept itself, we also conducted a small exploratory study with five prototypical applications of different haptic AR systems. Our analysis highlights unexplored areas for haptics and HCI researchers and the need to conduct user evaluations of the overall concept rather than just point examples.

1. Introduction

Our senses allow the perception of the world around us; altering them creates an illusion of being in a different reality than we really are. Similar to how visual augmented reality (AR) experiences such as Pokemon GO[1] and IKEA Place[2] change what we *see* in our surroundings, modern haptic technologies can change how we *feel* our surroundings. *Haptic augmented reality* systems can change our sense of touch in multiple interesting ways. For instance, a plain surface can be made to feel like wood (Romano and Kuchenbecker, 2012), a regular pen to feel like a hammer (Preechayasomboon and Rombokas, 2021), or a screw to feel like a button (Tao et al., 2021).

Haptic augmented reality was first discussed as a research area in a 2009 paper by Jeon and Choi (2009). They extended the Reality-Virtuality Continuum of Milgram et al. (1994) to include degrees of virtuality in touch. This extension introduced a visuo-haptic continuum consisting of nine categories with the degrees of virtuality in touch being classified as “haptic reality”, “haptic mixed reality”, and “haptic virtuality”. They defined haptic augmented reality as one category of haptic mixed reality that “enables the user to feel a real environment augmented with synthetic haptic stimuli”. This focus on the real environment differentiates haptic augmented reality from previous research in haptics for augmented reality (Vallino and Brown, 1999) which is termed as *haptic virtual reality* by Jeon and Choi (2009) as it is focused on touching things that do not exist.

Despite over a decade of research on haptic AR, work in this domain has almost exclusively been technical and efforts have been focused on building systems for bringing about changes in tactile perception. A few surveys (Basdogan et al., 2020; Pacchierotti et al., 2017) exist about haptic technology and how it can convey touch stimuli about remote and virtual environments (Jeon et al., 2015), but they do not focus on the interactions and experience of haptic AR. The technical focus behind haptic AR research has led to many exciting and impressive systems. However, due to this strong focus on building technology, discussions on how it will be experienced and used have been limited. We identified the following gaps with existing haptic AR literature:

- *Unclear distinction between Haptic AR and Haptics for AR* - The original definition of haptic AR fits a broad range of haptic developments. For example, are devices that can provide different kinds of haptic properties examples of haptic AR systems, or are they just excellent haptic devices? With haptic technology for AR/VR environments, the user can feel synthetic haptic feedback in the environment, but no real touch events occur in these interactions. These interactions should then be classified as haptic virtual reality instead of haptic augmented reality, but the use of these terms is inconsistent.
- *Missing purposes* - Papers mainly focus on altering the haptic properties of objects and rarely mention reasons why a user would wish to do so or which tasks a change would suit.

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[1] https://pokemongolive.com/en/.
[2] https://apps.apple.com/us/app/ikea-place/id1279244498.

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- *Unclear interaction space* - The literature lacks a discussion on how haptic AR interactions take place and what kinds of touches can be altered. In particular, an overview of existing haptic AR interactions in relation to human touch with unaltered objects is missing.
- *Evaluations not in context* - Most literature on haptic AR describes point designs that detail how to achieve a certain kind of augmentation. The user evaluations primarily focus on how successful the system is at changing haptic sensations rather than on evaluating them in the context of user goals and tasks with the augmentation.

This work aims to address these gaps by providing an overview of haptic AR from a user-centered perspective rather than a technical perspective. After presenting differing views and criteria for haptic AR systems in the literature, we build on Jeon and Choi's work to propose a refined definition for *what* constitutes haptic AR. In our revised definition, a haptic AR system is a technology that can change the feel of other real-world objects and surfaces during touch events. We discuss how this definition helps delineate haptic AR systems with clear criteria. Then, we outline the reasons *why* a person would be interested in changing how objects feel. We show that these reasons and user tasks are rarely discussed in creating and evaluating haptic AR systems. Also, we explore the interaction space of haptic AR by categorizing the different haptic AR displays and kinds of touch events altered (*how*). With haptic AR literature having little to no evaluations of user experience, we conduct an exploratory study on the concept of haptic AR to support our overall review, helping us identify further gaps and future directions specific to the experience of haptic AR. Our overview of the what, why, and how of haptic AR systems helps haptic device creators, interaction designers, and novice researchers who wish to pursue research in haptic AR to describe existing work, informs the development of evaluation criteria for haptic AR systems, and highlights unexplored areas of haptic augmentation. The paper is organized into three parts, we first present our review of existing literature (Sections 2–6), followed by a small-scale study on haptic AR user experience (Section 7), and then finally, discuss gaps and future directions (Section 8).

2. Related work

Below, we outline prior work on the broader topic of haptic devices, including the purposes behind their use and existing categorizations. Then, we present relevant literature on the human haptic perception of real-world objects and the recent progress in designing for the haptic experience.

2.1. Haptic systems for mixed realities

Haptic devices have been used in a variety of ways for virtual and augmented reality applications. One group of systems provide haptic feedback for visual AR/VR environments. Such systems usually provide haptic stimuli corresponding to the additional virtual elements that a user sees. Tasbi (Pezent et al., 2019) is a wristband supporting squeeze and vibrotactile feedback that enables wearers to feel virtual user interfaces and objects in mid-air. Tsui and Morimoto (2021) created a hand-worn display consisting of 3×3 pin array that can be used to feel contact with virtual objects on the palm in mid-air. W-FYD (Fani et al., 2018) is a finger-worn haptic device that provides softness cues for mid-air objects by stretching a piece of fabric upon contact with the wearer's fingertip. Similarly, several other devices have been proposed for interacting with virtual objects (Chossat et al., 2019; Leonardis et al., 2017; Young et al., 2019). These devices provide synthetic haptic feedback for interactions with virtual rather than real objects. Thus, they do not fit our definition of haptic AR.

In the literature, a single device with multiple kinds of haptic feedback is sometimes called haptic AR. Park et al. (2020) presented a button that is augmented with a vibrotactile actuator that can provide different responses when pressed, according to the vibration played. In "A pneu shape display", Russomanno et al. (2017) created a shape display that sits on top of a touchscreen and provides programmable haptic feedback through pneumatic actuators. Devices for surface haptics, such as those that use electrotactile stimulation (Yoshimoto et al., 2014) or lateral vibrations (Saga and Raskar, 2013), can also fit the original definition of haptic AR by Jeon and Choi. These devices can only change the feel of the haptic system itself. Thus, they fall within the larger haptic device category rather than haptic AR systems.

Another group of work has focused on devices that can provide haptic feedback to the user when a real surface is touched. For example, one can create the sensation of a different texture than the natural texture of the surface. Ando et al. (2007) created a device attached to the nail that gave vibrotactile feedback for texture augmentation. Manipulating the deformation of the fingertip when an object is grabbed can alter perceived hardness and weight. Minamizawa et al. (2008) created a finger-worn device that, when used to grab real objects, deforms the fingertip to create a sensation of virtual objects inside the grabbed object. Grounded force-feedback (GFF) devices have also been used to alter the perceived stiffness of real-world objects when touched through a tool held in the user's hand (Jeon and Choi, 2010). Our work focuses on these systems focused on touching real surfaces.

2.2. Categorizations and taxonomies of haptic devices

Several categorization schemes have been proposed for haptic devices, providing complementary perspectives on haptic systems in relation to the human sensory system and engineering considerations. The most common categorization divides haptic hardware into tactile devices that primarily target receptors in the skin (e.g., pressure, shear, and vibration-based) vs. kinesthetic devices that can render force and torque to muscles and joints (e.g., force-feedback, exoskeletons) (Culbertson et al., 2018). This categorization reflects the neural mechanisms underlying human touch perception (Lederman and Klatzky, 2009). Culbertson et al. (2018) have further divided the tactile devices into skin deformation devices, vibration, and haptic surfaces. Others have focused on the design and engineering principles for building the systems as the basis for categorizing haptic devices (Hayward and MacLean, 2007; Kuchenbecker, 2018). For example, Kuchenbecker (2018) divided haptic devices into grounded, ungrounded, and surface devices. Other haptic taxonomies and review papers have focused on a specific category of devices (e.g., grounded Seifi et al., 2019 or wearables Pacchierotti et al., 2017) to detail their mechanical properties, design considerations, and evaluation criteria. For example, device weight is a key consideration for wearable devices, whereas workspace size is more important for grounded devices. Recent reviews of haptics in immersive environments (Wang et al., 2019; Dangxiao et al., 2019; Bermejo and Hui, 2021) have similarly synthesized haptic devices based on their technical design considerations. For example, Wang et al. (2019) divide haptic devices for VR applications into grounded, wearable, and handheld devices. Two categorizations specific to haptic AR have been described by Jeon et al. (2015) based on the purpose of the augmentation as artificial recreation or augmented perception, and how the physical properties are changed by the haptic AR system as within or between property augmentation. This categorization is relevant for device designers as it focuses on how the technology works, but it does not provide any information on how these systems are used. Our categorization of haptic AR devices is instead focused on interaction. Since haptic AR is about augmenting the feel of real objects, we later categorize the devices according to the interface they provide between the user's touch and existing objects. Our grouping provides a complementary view to prior categorizations that is tailored toward haptic AR.

2.3. Human haptic perception and experience

A large body of literature exists on how people interact with objects in the real world (see Lederman and Klatzky (2009) for a review). Past studies have outlined object properties primarily sensed through touch (e.g., compliance, weight) and stereotypical hand movements, also known as exploratory procedures, that people use to sense object properties (Lederman and Klatzky, 1987). Prior work has also identified human sensory thresholds for various haptic stimuli, providing perceptual metrics for evaluating haptic AR interactions (Lederman and Klatzky, 2009; Samur, 2012). For instance, they argued that haptic augmentation should be perceivable by the human sensory system. We use this literature to analyze "how" haptic AR interactions take place by analyzing the hand movements in our sample and highlighting the current interaction gaps.

Haptic experience design is a growing research area in haptics and human–computer interaction (HCI). Recent studies have detailed novice and expert designers' processes, challenges, and design tools in creating haptic interactions (MacLean et al., 2017; Schneider et al., 2017; Seifi et al., 2020). To evaluate haptic experiences, Kim and Schneider (2020) have proposed a model with various dimensions such as saliency, harmony, and realism. Previous work has also outlined several application areas where haptic feedback can add value to an interaction (Maclean and Hayward, 2008; MacLean, 2008; MacLean et al., 2017; Huisman, 2017). Our work builds on these efforts by analyzing the haptic AR literature through a user-centered and experiential lens. We outline the "why" for haptic AR (i.e., the added value) based on our literature sample discussing application areas focused on the added context of changing the sensations of real objects. In addition, we reflect on our study results in light of the haptic experience model by Kim and Schneider (2020) and highlight the need for further guidelines for the evaluation of haptic AR systems.

3. Methods

To gain insights into the concept of haptic AR, we analyzed a set of papers that alter our sense of touch. With the definition of haptic AR being unclear and the literature fragmented across venues in different domains (such as haptics, HCI, and virtual reality), a broad keyword-based search would be ineffective for collecting relevant papers. Instead, we decided to begin our search with a small set of *seed papers* that constitute haptic AR.

We searched three primary haptics venues: the *IEEE Transactions on Haptics*, the *IEEE World Haptics Conference*, and the *IEEE Haptics Symposium*. We began our search from the haptics venues rather than HCI venues as most developments in haptic AR are published in haptics venues. We use the query `(Haptic* OR Tactile) AND (AR OR Augment*)` to search for the title, abstract, and author keywords of every publication in the selected venues. This query resulted in a set of 142 papers that we screened using the original definition of haptic AR with the added constraint that a real touch event must take place. We also excluded any papers that are only texture modeling techniques or algorithms instead of a complete haptic AR system. This initial screening resulted in 24 seed papers.

Using the seed papers, we created a revised definition and clear criteria for what constitutes a haptic AR interaction (Section 4). Then, we used forward and backward chaining on the seed papers to gather relevant papers from other domains (e.g., HCI, VR, manufacturing), papers not published at IEEE venues, and papers that augmented human touch but did not explicitly mention the previous keywords. Our final sample consisted of 72 papers. For analysis, we focused on addressing the issues of missing purposes and unclear interaction space that we identified. Thus, we coded this final set of papers by extracting free-form text about the haptic AR interactions in terms of purposes and applications, interaction characteristics, and augmentation type.

4. What is haptic augmented reality?

The first definition of haptic AR by Jeon and Choi (2009), as well as how subsequent work describes the concept, usually refers to haptic AR as combining real and synthetic haptic stimuli. While useful, this definition of haptic AR also encompasses systems that are confined to a single object by embedding the haptic system inside the object. For example, a button with a vibration motor inside it can change how it feels by combining the natural click feedback of the button with synthetic vibrations. However, such a button becomes a specific kind of haptic device rather than augmenting the world around us. The term haptic AR is also often misused by referring to haptics for visual AR (e.g., virtual objects) as haptic AR, a fact that has also been noted by Jeon and Choi in a subsequent work (Jeon et al., 2015). Due to these issues, we thus decided to further refine the definition of haptic augmented reality by Jeon and Choi and provide an updated survey of the field.

To revise the definition of haptic AR, the lead author went through the 142 papers that resulted from our search query in the haptics venues. While going through this list, the lead author noted the different ways in which papers referred to haptic AR and selected examples of systems where it was unclear whether it was haptic AR or not (e.g., the above-mentioned button example). This list of ways prior work described or referred to haptic AR and the list of unclear examples was then discussed in a meeting with all the authors. In the meeting, the authors discussed why each example was or was not an instance of haptic AR according to the definition by Jeon and Choi and sometimes compared the examples to variations in visual AR. The lead author wrote notes of the discussion and criteria, which he then used to draft a revised definition of haptic AR. The other authors provided feedback on the draft definition for further refinement. Based on our analysis of the literature and discussion, we propose that:

> A haptic AR system is a technology that can control the existing haptic feedback of other real-world objects and surfaces during touch events.

This definition is a more specific version of the original definition of haptic AR by Jeon and Choi (2009) and focuses on the *augmentation* aspect of haptic AR. We use the word "control" to reflect the fact that a haptic AR system may not always change haptic properties and could also allow the sensing of natural haptic feedback when required. In other words, a haptic AR system controls or adjusts the degree of feel-through when touching a physical object. Our mention of real touch events is in line with how recent work refers to haptic AR as an interaction where "a user experiences real haptic stimuli to which artificial haptic signals are added" (Park et al., 2020) and "real touch sensation is augmented by virtual stimuli, allowing us to alter the haptic properties of real objects" (Yim et al., 2021). Furthermore, we define a haptic AR interaction to have the following criteria (see Fig. 1):

1. a touch interaction or exchange of forces takes place between the user and a real object/surface.
2. the user perceives the thing being touched as feeling different from what it feels when unaugmented.
3. the feedback is provided using physical stimuli through an external haptic AR system, and the haptic AR system is not permanently attached to or integrated in the object/surface with the aim of changing how the object feels.

4.1. Implications

This definition allows haptics researchers to clearly identify and describe haptic AR systems in the literature. Criterion one's mention of a real object/surface ensures that reality is actually being augmented and it is not just virtual content that is felt, for example, haptic devices

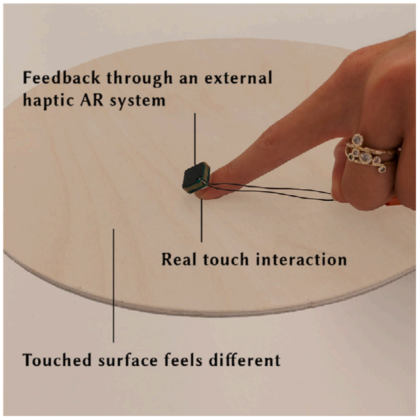

Fig. 1. Three characteristics of a haptic AR interaction: a real touch event, feedback through a haptic AR system, and change in tactile perception. In this example, a user experiences a haptic AR system that makes a smooth plastic table seem like it has a wooden surface. The visual overlay is used to convey the change in the object's feel in the paper and is not displayed to the user.

for interacting with purely visual AR objects (Pezent et al., 2019) (Haptics for AR) do not match this criterion. Criterion three ensures that reality is actually being augmented and not permanently altered into something new just to change how it feels. For example, single devices that provide different haptic sensations (Park et al., 2020) or pseudo-haptics (Lecuyer et al., 2000) systems do not match the last criterion. While user interactions may cause permanent changes to the object/surface being touched, such as cutting an apple, the object should still be a regular object and not one specifically created for the interaction.

The definition can also fit systems that can act as both haptic AR and haptic VR. For example, in the case of remote teleoperation through a robot, the physical signals that are exchanged between the user and the object being touched can be altered by the systems for haptic AR. The system can also just record signals from an object and play them back to the user, which is not a direct exchange of forces, making it act as an indirect touch-through system. The visual analog of such a system is a video see-through headset that can display both AR and VR content.

Furthermore, one can describe a haptic AR system by specifying the touch interactions and types of real objects or surfaces that are augmented (criterion 1) as well as how the augmentation was applied (criterion 3). Finally, user evaluation of a haptic AR system needs to include a comparison to the unaltered object (criterion 2) to ensure that the user perception actually changes.

5. Why haptic AR?

We posit five reasons behind using haptic AR (Fig. 2): leveraging real haptic feedback; hedonic or affective purposes; supernatural touch sensing and accessibility; enhancing dexterous tasks; and subtle and private interactions. The purposes of haptic augmented reality have been previously described by Jeon et al. (2015) as either artificial recreation or augmenting perception. This description of purpose is useful for feedback designers but does not answer the question of why a user would want to recreate other physical feedback or change their perception when touching an object. Thus, we complement this work by further listing reasons and ways haptic AR can benefit users.

Most papers do not explicitly mention a reason for using haptic AR, and hence, these purposes are identified by analyzing the abstract, introduction, or conclusion sections. These purposes are reasons why someone would like to modulate the haptic feedback of the real world rather than a fixed orthogonal categorization of haptic AR systems. i.e., the papers we analyzed in our review can have multiple reasons for a specific augmentation. These purposes are also inspired by papers on the general advantages of using haptic feedback (Jacko, 2012; Maclean and Hayward, 2008; MacLean, 2008; MacLean et al., 2017; Huisman, 2017), which we discuss in the context of haptic AR while the others are drawn from earlier work in haptic AR.

5.1. Leveraging real haptic feedback

Artificial feedback produced by various haptic technologies is considered inadequate (Jeon, 2011) when compared to the natural haptic sensations of real objects, which are higher fidelity, crisp, and distinctive (McMahan and Kuchenbecker, 2009a). Haptic AR combines this artificial feedback with a much richer real feedback to diversify the feel of props in a VR scene (de Tinguy et al., 2018; Ye et al., 2003; Borst and Volz, 2005; Choi et al., 2021; Jeon et al., 2011; Jeon and Harders, 2012), to change the prop's feel as a result of user interactions (Minamizawa et al., 2008) (e.g. virtual water falling from a bottle changes its weight), or to enable interactions that are impossible in the real world (Abtahi et al., 2022).

In medical training, haptic AR is used for simulating physical feedback during tasks such as palpation (Condino et al., 2016; Parkes et al., 2009; Solanki and Raja, 2010; Jeon et al., 2012; Jeon and Harders, 2014) and bone drilling (Ha-Van et al., 2020; Van and Harders, 2017) on mannequins (Salazar et al., 2020) or real people (de Tinguy et al., 2018) without any disease. Using haptic AR over real patients allows practice on different variations of a disease for extensive training and helps deal with availability, time constraints, ethics, and safety when working with real patients.

Haptic AR can also facilitate the in-situ design of object properties such as textures (Yoshimoto et al., 2014) and provide physical augmentation over touchscreens (Deng et al., 2016) as well as large-scale and projected displays (Lee et al., 2004).

5.2. Hedonic purposes

A very common purpose behind touch is affect and pleasure (MacLean, 2008), such as in the case of a massage or sexual touch (Huisman, 2017). Some haptic AR work tries to make touch events more exciting. Tactile Echoes (Kawazoe et al., 2021) is a finger-worn device that records and replays vibrations from contact with the environment similar to auditory echoes, to "enliven" tactile experiences. Another example is bARefoot (Strohmeier et al., 2020), a shoe that changes the texture perceived on the wearer's foot to make running on artificial terrain more enjoyable. Haptic AR may also make objects feel better. Manipulation of the textures of 3D printed objects can increase the fidelity of these prototypes, making them feel more premium (Yoshimoto et al., 2015).

While the hedonic use of haptic AR is attractive, earlier work has not evaluated the efficacy of haptic AR for affect. Also, several other hedonic applications, such as making touch more comfortable or amusing are not explored in literature. The opposite of hedonics can also be explored, where things are made to intentionally feel worse, such as to repel people.

5.3. Supernatural touch sensing and accessibility

Enhanced senses are a common superpower in science fiction and fantasy media. Such abilities can be achieved using haptic AR by providing information that one cannot perceive normally. SmartTouch (Kajimoto et al., 2003) is a fingertip-worn electrocutaneous display with an optical sensor that recognizes the surface being touched. The extra data from the sensor allows it to convey temporal information about previous touches to the surface. Haptic AR combined with content on touchscreens allows users to perceive information that is difficult to visualize, such as textures, complex topography, and shapes (Evreinova et al., 2013). Using haptic AR, we can achieve effects such as texture

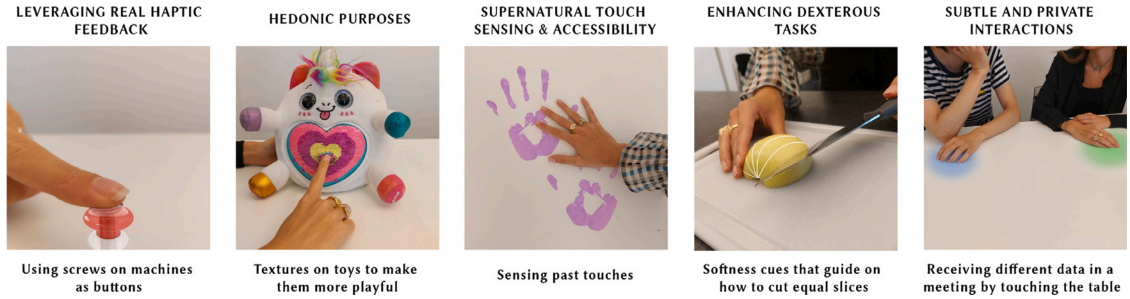

Fig. 2. The five purposes of haptic AR (in columns) illustrated through an example of each (in rows). Leveraging real haptic feedback; Supernatural touch sensing and accessibility; and enhancing dexterous tasks have examples present in existing literature, whereas systems for hedonic purposes and subtle and private interactions are underexplored.

augmentation, click sensations, and tactile cues (Kyung and Lee, 2009; Fukumoto and Sugimura, 2001; Kildal, 2010) on flat surfaces. Haptic AR can also add such haptic capabilities to old devices that lack such feedback (Fukumoto and Sugimura, 2001) or to provide individual feedback for multi-user systems.

Haptic AR systems can additionally act as accessibility devices to restore a loss of haptic ability such as due to age, injury, or medical conditions. An example is using a skin vibration sensor to sense haptic information about touched objects and amplify the signals for the wearer (Maeda et al., 2016). Additional tactile information can also supplement other lost senses. The previous SmartTouch (Kajimoto et al., 2003) example can be a Braille display. A possible use case for REVEL (Bau and Poupyrev, 2012) to help visually impaired users, such as by adding directions to walls or changing how a button feels to convey its state.

5.4. Enhancing dexterous tasks

Haptic technology is often employed to provide physical guidance, and reduce cognitive overload (MacLean, 2008; Maclean and Hayward, 2008). Similarly, haptic AR can enhance tasks involving physical entities.

Tasks that require manual dexterity can greatly benefit from extra forces from a haptic AR system. SmartTool (Nojima et al., 2002) combines sensors and a haptic display to provide appropriate kinesthetic cues while using a physical tool. For example, to cut a hard-boiled egg with a knife, SmartTool can make the yolk feel harder than the rest of the egg, allowing the user to precisely separate the two parts of the egg.

Haptic AR systems can help manipulate objects that are occluded from the user's view or cannot be accurately perceived visually. For example, dental technicians can be provided with guidance and corrective feedback on tool angles during tooth carving tasks (Yoshimoto et al., 2016). Converting visual information to haptic feedback can also reduce demands on our visual and auditory perception. Other examples of using haptic AR to provide tactile guidance for medical tasks include producing additional cues such as for perceiving ideal grip force (Yoshimoto et al., 2013, 2011) and magnifying natural haptic feedback felt (Doria et al., 2021; yun Yao et al., 2005).

5.5. Subtle and private interactions

Manipulating the sense of touch through haptic AR can create completely different experiences for two users who touch the same object. Touch also does not require a person to change their gaze to look at a specific object. Thus, haptic AR can be useful for security applications or for subtle communication. Objects can be changed while being held to convey instructions discreetly.

While prior work denotes a reason to use haptic feedback is its subtle and private nature (e.g., phones vibrating) (MacLean et al., 2017), this purpose is rarely used to develop haptic AR systems, nor do any of the studies in our review evaluate their proposed augmentations for subtly or privacy of the feedback.

5.6. Implications

This list of five reasons allows application developers to describe the goals of their haptic AR systems and evaluate them accordingly. As mentioned before, prior work mainly focuses on implementing augmentations and knowing the purposes behind augmenting our sense of touch can be used to put existing systems to work. Out of the five haptic AR purposes we outline, Hedonic Purposes and Subtle and Private Interactions have gaps in the literature as haptic AR systems that are based on these user goals have not been built in the past.

6. How do haptic AR interactions take place?

In this section, we describe two categorizations for interactions in haptic AR. The first categorization is based on how systems act as interfaces during touch events to change a user's haptic perception. The second is based on the kinds of touch events that take place during a haptic AR interaction. We are interested in the interactions between the user and the object/surface altered. Thus, we do not discuss the technical details of the hardware setup or how successful previous haptic AR systems have been in altering user perception .

6.1. Types of interfaces

We categorize haptic AR systems based on the interface they provide between the human touch and the altered objects or surfaces (Fig. 3). This categorization is inspired by types of visual AR systems (Azuma et al., 2001), and we discuss the analogs between visual and haptic spaces.

1. **Direct touch** systems do not cover or obstruct parts of the body, thus preserving the user's natural haptic abilities. Finger-worn vibrotactile devices are a common example of such systems. Haplets (Preechayasomboon and Rombokas, 2021) are nail-worn vibrotactile actuators for AR/VR applications. As an example, the authors present changing how a pen feels by providing haptic

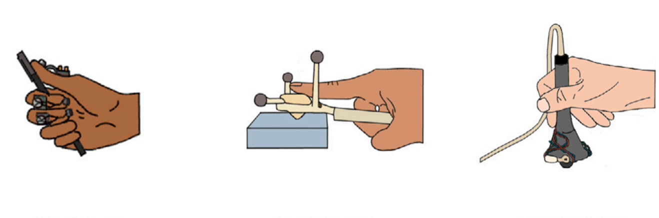

Fig. 3. Three ways in which haptic AR systems act as interfaces between users and real objects: Allowing direct contact between the object and the user's skin (Preechayasomboon and Rombokas, 2021); indirectly touching the object through a medium but making it seem like the object is being touched (Choi et al., 2021); Touching objects through a tool (Kianzad and MacLean, 2018).

feedback at specific fingers to make the user feel they are holding a hammer or a spraying can. Ishimaru and Saga (2020) use electrical muscle stimulation (EMS) on a user's forearm to make them feel bumps on flat touchscreens. These systems are akin to optical see-through AR displays as they help retain our natural senses while augmenting them as required.

2. **Touch-through** systems allow the user to touch a real object but through an interface. The user interacts as if they are touching the object directly. An example of such a system is the handheld haptic device by Choi et al. (2021). It can vary the perceived softness of real objects at the fingertip using active transient vibrations. Another approach to change perceived softness (Tao et al., 2021) uses a hollow frame and a motor to restrict fingerpad deformation. An example of a touch-through system for texture augmentation is a data glove by Junput et al. (2020) with a vibration motor on the fingertip. These systems change how we perceive the real world at all times, they are analogous to video see-through AR displays, which change the properties of our sense of sight (e.g., our depth of field).
3. **Tool-mediated** systems involve touching objects and surfaces not using the body but through a tool such as a pen held in the user's hand. This tool is untethered and provides the required feedback to change the user's haptic perception. Culbertson et al. (2014) created a system for recording the haptic textures of surfaces that could then be played back on a flat surface. To play the haptic texture, the authors attached a voice coil actuator to a pen, which vibrated according to the recorded data as the user moved the pen on a flat surface. Later, Culbertson and Kuchenbecker (2017) created a haptic stylus with a ball on its tip that performed better at rendering the recorded haptic textures than a GFF device. These tools change the haptic feedback of things they touch, just like how handheld or phone-based AR systems act as a medium to change the way the environment looks.

The categories of touch-through and tool-mediated systems, which can be thought of as indirect touch, may be implemented in the same way but differ from the interaction point of view on which our categorization is based. In tool-mediated systems, the user is supposed to be using the tool as part of the interaction, similar to using a tool in real-world (e.g., using a pen to write on a whiteboard or to scratch a surface). In contrast, in the touch-through systems, the interface is because of the technical implementation of the system and the user is supposed to ignore the interface in-between their hand and the physical object.

When comparing visual AR systems, we observe that the category of projected AR systems is missing from haptic AR. Similar to projected AR systems, GFF devices have a spatial limitation in what part of the environment can be augmented. GFF devices can provide a stylus tool to alter haptic properties such as texture (Shin and Choi, 2018, 2020; McMahan and Kuchenbecker, 2009b), hardness (Jeon and Choi, 2008; Kurita et al., 2009), and weight (Jeon et al., 2011) of the touched objects or they can be directly attached to the hand (Solanki and Raja, 2010; Minamizawa et al., 2010). GFF devices are not a separate category similar to how projected AR is in the visual domain as they are not orthogonal to the other categories but can be thought of as the haptic analog if comparing the visual and haptic systems.

6.2. Types of touch events

In this section, we use existing knowledge of ways humans sense objects with their hands to describe what touch types have been augmented in the haptic AR literature. Previous categorizations of haptic systems focus on which haptic properties are changed (Pacchierotti et al., 2017). We take a complementary approach to previous surveys by focusing on how people interact and touch events to examine if it is possible to feel these changed properties in more than one way

In a seminal work, Lederman and Klatzky (1987) identified six exploratory procedures humans use to recognize haptic properties of objects: lateral motion, pressure, static contact, unsupported holding, enclosure, and contour following. Out of these six possible hand movements only the first four have been utilized for haptic AR (marked with an asterisk below). The systems to augment these procedures impose several constraints on how the touches should be executed. Below, we list specific touch events that are possible in haptic AR systems and relate them to the exploratory procedures (Fig. 4). For tool-mediated systems, the fingertips are replaced by the tip of the tool.

1. **Sliding the fingertip***: The "lateral motion" procedure consists of sliding parts of the skin against a surface to perceive texture. Among existing haptic AR systems for the hands, texture augmentation is limited to sliding the fingertips on a surface and not the whole or parts of the hand. Systems that can alter the perception of multiple fingers (Preechayasomboon and Rombokas, 2021; Bau and Poupyrev, 2012; Niwa et al., 2010) are rare (Jeon et al., 2015), and prior work often focus on the index finger.
2. **Pressing the fingertip***: The "pressure" procedure consists of pressing on the surface of an object to perceive its hardness. This touch event is the most common in the haptic AR literature. Similar to the lateral motion procedure, the interaction is constrained to pressing the fingertips and not the whole hand or parts of the hand.
3. **Tapping using the fingertip**: Besides the original pressure procedure which involves applying continuous normal force to a surface, another way to perceive hardness cues in the haptic AR literature involves striking on the surface with a fingertip (Hachisu et al., 2012; Kuchenbecker et al., 2006).
4. **Two-point squeezing**: Another interaction to perceive hardness involves holding and pressing an object using the thumb and fingertips (Yim et al., 2021).
5. **Static contact/hold***: The "static contact" procedure involves keeping a part of the skin stationary against a surface to perceive its temperature. Thermal augmentation is another gap in the haptic AR literature, as no systems attempt to change the perceived temperature of objects. Prior work augments static contact as a way to feel fictitious sensations, such as presenting an object's color via vibrations or (Hulin et al., 2020) or illusory movement on a surface (Luo et al., 2022; Hachisu and Suzuki, 2019).
6. **Grasping with the thumb and one finger***: The "unsupported holding" procedure helps people perceive weight and was originally described as "the object is lifted away from any supporting surface and maintained in the hand without any effort to mold the hand to the object" (Lederman and Klatzky, 1987). However, haptic AR systems render weight through vertical and shear forces on the fingerpads (Minamizawa et al., 2007b,a; Scheggi et al., 2010) or via kinesthetic feedback on the wrist (Minamizawa et al., 2010). Hence, instead of holding objects in the palm of the hand, the haptic AR interaction for perceiving weight involves gripping an object using the thumb and index finger.

The enclosure and contour following procedures are used to sense the geometric properties of objects, and their absence suggests the challenges in augmenting shape information. Some papers do talk about altering the shape of touched objects (Hirai et al., 2021; Scheggi et al., 2010), but in the context of surface features rather than global shape.

The small set of possible interactions exposes the constraints on existing haptic AR experiences. Users need to follow instructions for interacting with objects rather than touching them in ways that seem natural, reducing user immersion. Building haptic AR systems that support multiple touch types can enable users to interact with objects more freely.

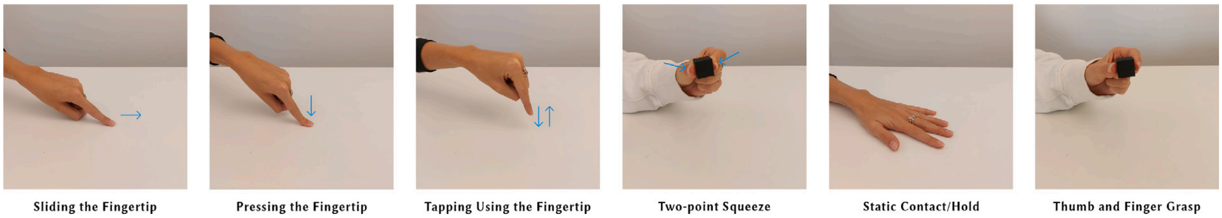

Fig. 4. Out of six known ways humans touch objects to perceive their haptic properties (Lederman and Klatzky, 1987), current haptic AR systems only augment four: lateral motion, pressure, static contact, and unsupported holding. Out of these four, several constraints are imposed on which parts of the hand can touch the objects. This leads to primarily six touch events in existing haptic AR literature.

Beyond Hands - Some systems target the feet to alter ground texture while standing (Iijima et al., 2019; Sakai et al., 2018) or augment ground surface features and texture while walking (Son et al., 2019; Strohmeier et al., 2020). Augmentation of touch events involving other body parts is absent in the haptic AR literature. Besides the limbs, other areas of high tactile sensitivity, such as the lips and tongue, are prime locations for haptic augmentation in future systems (Corniani and Saal, 2020).

6.3. Implications

The categories of haptic AR interfaces allow us to discuss the progress and pros and cons of haptic AR systems in relation to what is known for visual AR systems. Understanding constraints such as being limited in space helps application developers to choose appropriate haptic AR systems for applications. The types of touch events help haptics researchers who aim to develop devices to assess the limitations of existing systems and expose gaps in the literature, such as not being able to manipulate geometric properties of objects or to augment touch involving body parts other than the limbs.

7. User impressions

The haptic AR literature lacks data on what users think of the overall idea of altering their sense of touch. Few papers evaluate the experience of touch augmentation with a single device, while most papers focus their evaluation on how successful a system is in producing the desired haptic sensations. Papers that evaluate haptic AR in the context of tasks do so for only domain-specific instances (e.g., surgery training). We complement these past efforts by conducting a user study where we asked participants to try example applications with haptic augmentation and reflect on those examples. Our aim is to provide an example study focusing on user experience to show what kind of studies researchers should consider conducting when evaluating a haptic AR system and to identify future directions for haptic AR based on user impressions besides the gaps in the literature. This study is a preliminary first step in studying haptic AR user experience and is not meant to provide generalizable results.

7.1. Example applications

The five example applications (see Fig. 5) we present are meant to act as a representative set of haptic AR technology. We intend to cover a breadth of applications that capture the different purposes of haptic AR and a variety of augmentations, along with filling some gaps in the literature. Our focus with these prototypes is not technical complexity, and hence we Wizard of Oz (WoZ) the sensing where required.

Haptic Spell Check

We alter the hardness of the buttons on a keyboard to augment the typing experience. When the user first presses an incorrect key, the keystroke is not registered. Instead, the key feels harder to press than a regular key. This interaction can alert the user of a possible error and they can fix their mistake or press the key a second time to register the keystroke.

This augmentation is achieved by attaching a voice coil actuator (Haptuator Planar by Tactile Labs) to the user's fingernails. On pressing a wrong key, a 50 ms 250 Hz rectangular sinusoidal waveform is played. The pattern is from the 40 waveforms for button augmentation by Park et al. (2020). Similar to their work, we use the physical switch of the button for sensing. The vibrotactile feedback combined with the button's kinesthetic sensation creates the compliance illusion that the button is harder to press than usual. Since this example uses the natural feedback of a button and alters it using haptic AR, it captures *leveraging real haptic feedback* for haptic AR and the *hardness augmentation*.

Textures on Ice Pops

We augment a regular ice pop by changing the texture when licking it. This texture adds another layer to the eating experience, which can make it more exciting for the user.

A voice coil actuator (Haptuator Mark II by Tactile Labs) is attached to the finger holding the ice pop. When the user licks the ice pop, a signal from the VibViz library (Seifi et al., 2015) with the "Pulsing" metaphor is played, which feels as a texture on the tongue. Lick events are sensed using capacitive sensing by attaching a piece of aluminium foil on the ice cream stick in contact with the frozen ice cream.

This application captures the *hedonic purpose* of haptic AR and the *roughness* texture augmentation. We also use this example to explore tongue texture augmentation as an unexplored body part in the haptic AR literature.

Haptic Messages

At a social event, sometimes drinking glasses get mixed. We alter the wetness of the surface of the glass to help identify which glass belongs to the user. On touching any glass other than their own, the glass feels wet to the user, which repulses them and conveys that this glass is not theirs.

This wetness augmentation is achieved with a ring worn on the fingertip, which releases a drop of rubbing alcohol that comes in contact with the finger. Rubbing alcohol is colorless and volatile, making the surface feel wet just for a few seconds, after which the liquid vaporizes. The system consists of a luer needle at the end of a pipe attached to a syringe holding the alcohol, which is pushed with a small amount of force to release a drop of liquid through a WoZ setup.

We change how the same glass feels to different users and hence showcase the *subtle and private interactions* purpose of haptic AR along with the *moisture (friction)* augmentation, which is an unexplored area in the haptic AR literature.

Hot and Cold Game

The hot and cold game is a children's game where a player has to find a hidden object by only receiving hints that they are getting closer (hot) or farther (cold) from their goal. Inspired by this game, we created a haptic AR version where a player has to navigate through a simple maze by choosing the path that feels hot to touch.

We create the maze on a metal table with splitting paths leading to eight exits. Only one of the exits corresponds to the correct one. The player can detect the correct direction by touching each fork in the path

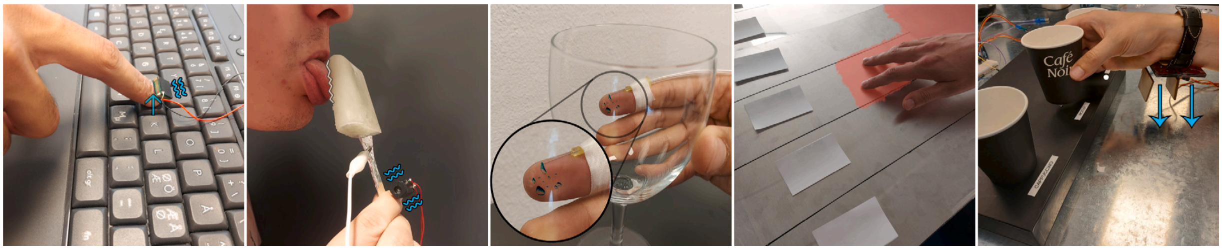

Fig. 5. Haptic AR applications (left to right): Altering the hardness of pressed keys; Feeling texture on an ice pop; Feeling wetness on a wine glass; Heat-based guidance; Altering the weight of coffee mugs.

and choosing the warm one. The correct path is heated by a clothing steamer (Steam & Go GC361 by Philips) underneath the table in a WoZ setup.

This example captures the *enhancing dexterous tasks* purpose of haptic AR along with the *thermal* augmentation, which is an unexplored area in haptic AR literature. This example also captures spatial limited haptic AR similar to systems involving GFF devices.

Data Haptization

We represent information about the number of calories in three different kinds of coffee: Espresso, Cappuccino, and Mocha by altering the perceived weight of their cups.

We prototype a wristband consisting of an array of 14 strong magnets (each holds approx. 940 g) parts of which are covered by a thin layer of wood. The coffee cups are placed on top of a platform on a metal table. When lifted, a number of magnets in the array are exposed, which pull the wearer's hand toward the metal table, creating the illusion of weight. Which mug is being lifted is sensed through photoresistors embedded in the platform the cups are placed on.

Feeling extra information about the object than its physical properties is an example of using haptic AR for *supernatural touch sensing and accessibility* and the *weight* augmentation.

7.2. Participants

We recruited 12 participants (4 female, 8 male) between the ages of 21 and 39 (mean: 27.53, std: 4.21) for our study. None of the participants reported any sensory impairments in their hands or tongue. The participants received a gift worth 15 USD for their time.

7.3. Procedure

At the beginning of the session, the experimenter introduced the participants to the haptic AR concept through a set of illustrations. Next, the participants tried all the example applications one by one. The experimenter explained each application before the participants tried it and had the participants first touch the objects without any change to understand how they felt. For applications involving vibration motors, participants wore noise-canceling headphones. The order of the applications was randomized for each participant.

We followed the relaxed thinking-aloud protocol (Hertzum et al., 2009) for the study. After trying an application, the participants were asked to describe the sensation, what they expected it to feel like, and if they felt like the object had changed. After a participant had finished trying all the applications, we conducted a semi-structured interview with open-ended questions on themes of the utility of the concept, opinions on the example use cases, and settings where such technology could be useful. The study took approximately 30 min for each participant. We took audio recordings of each session, transcribed them with Otter.ai, and analyzed them using thematic analysis (Forbes, 2022).

7.4. Results

Every participant used the word "interesting" to describe the overall idea of haptic AR or one of the demos they tried during the study. When asked about their impression of the concept, all except one participant responded positively. The participants stated that it was "cool" (P3), "fun" (P5), "fascinating" (P7), and "extraordinary" (P2) to be able to change how real objects feel. P7 found it a "natural progression for technology" with how we first are able to change the world through our phones (phone-based AR), then through headsets, and now we can change the real world. Some participants found the idea entertaining, frequently laughed during the study, and described the haptic changes as "weird" and "most unexpected" but in a "quirky" (P3) and "funny" (P5) manner.

In contrast, P10 had a negative reaction to the concept: "scary, I don't know what sensation is coming". They further elaborated that "to actually feel something that is not there, it's like a ghost, scary!". Some participants shared similar comments, even though they were positive about the overall concept. P4 did not like when "things like, act up" and found the ice cream demo "unpleasant because it's unfamiliar". Similarly, P8 described the demos as having a "foreign feeling".

These findings suggest that haptic AR can evoke positive reactions as long as the augmentations align with the user's expectations of the world. The changes may also bring pleasant delightful surprises. However, when haptic AR alters the predictability of the real world, the users can experience losing control of their senses. Thus, for appealing haptic AR experiences, users should be able to anticipate the changes to avoid unpleasant surprises that startle them.

Had the objects really changed?

The perception of augmentation depended on the magnitude of the physical sensation. About half of the participants wanted to feel the weight of the coffee mugs change twofold as the number of calories in Mocha is significantly more than in Espresso. Hence, they did not agree that the mugs had changed because the feedback was too subtle to be noticeable to them. In the case of the wetness examples, the sensation felt just right for certain participants (P3, P8), less wet than expected for some (P10), and too wet for others (P1, P12).

The perceived change also depended on user expectation of the change and interaction task. For the ice pop application, P12 wanted to feel "bubbles" on their tongue, similar to how a carbonated beverage feels, and was disappointed by the vibrotactile feedback, which they did not associate with anything. For the wetness augmentation, P11 expected to feel "condensation" on the glass, and hence, they did not agree that the feeling of the glass had changed.

Users often mentioned hedonic factors even for use cases that had a practical reason. P8 described the wetness as "gentle", and the augmented keyboard buttons were said to be "pleasant" (P3) and "encouraging" (P4). In contrast, P1 found the keyboard buttons to be "unpleasant, similar to an electric shock" and the heat maze "repulsive, like a hot oven".

The above results suggest that the perception of the augmentation depends on the physical sensation but also on the interaction goals and context. Furthermore, hedonics can play a factor in user perception of the augmentation, even if it is not the main reason. Thus, haptic AR systems should be evaluated in relation to the sensation but also user tasks.

Utility

The participants spontaneously identified the different purposes of haptic AR for different prototypes. They liked that "the use case was real" (P3) and not screen-based. Haptic AR was found to be especially useful for training purposes, with P2 mentioning its utility for "guidance stuff, when you're not sure if you are touching the right object".. P4 felt they were being "conditioned to do something". P8 noted that the haptic changes "will leave a lasting impression" and could be very useful for changing habits.

Participants compared the usefulness of the haptic change to visual feedback, saying that they would "not like to have a new more cumbersome interaction for something that can be found out by looking at the internet" (P5) but would welcome extra information if they were already supposed to touch something. P9 commented on the saliency of the haptic augmentation: "if I were drunk, I would not be able to feel the difference"; in that case, visual feedback could be superior. Some participants wanted to change certain objects in specific locations, such as their office or home, and did not want to experience haptic changes everywhere in everyday life. Just like how existing work is domain-specific, P4 envisioned it as a "niche technology that is tailored to specific purposes".. These reactions reflect the need to make the feedback predictable and customizable by the user to align expectations when manipulating the senses.

Potential Applications

When asked about use cases, participants suggested making everyday textures more useful. P1 wanted to augment the feel of the road textures and bumps during cycling or driving to convey relevant information, such as notifications about approaching the speed limit or being on the wrong side of the road. P4, P6, and P7 related the vibrotactile applications to their electric toothbrush and suggested altering the texture felt on teeth to communicate how dirty the teeth are.

The idea of using haptic AR with food captivated some participants. P1 wanted to eat less junk food and thought of making buttons on the microwave or coffee machine to "make much, much more effort to press" when preparing unhealthy food. P2 was inspired by the ice pops application and suggested applying texture augmentation on more food items to avoid overeating.

Another category of use cases was to skip extra steps required to obtain information about objects. P5 wanted to "know if a VR headset is discharged by touching it instead of having to put it on".. P8 wanted to feel the expiry date of items in their fridge by touching them once and not having to look for the date on the package.

8. Discussion

Haptic AR research has focused on building devices to change our haptic perception. With this paper, we hope to shift the discussion from devices and mechanisms to the users of these systems. We do so by examining the existing body of work from the non-technical lens of user-centered design; and supplementing this analysis with an exploration of user impressions by asking people to experience a variety of example applications. This resulted in a refined definition for *what* haptic AR means, a list of reasons *why* a person would want to change their tactile perception (user goals), an understanding of *how* interactions with haptic augmentation take place (interaction characteristics), and initial data on *how* do people use and think about using haptic AR systems (tasks and impressions). We now discuss additional questions that arose during our investigation.

8.1. Future directions for user-centered haptic AR research

Our analysis reveals the existing strengths and gaps in designing and studying haptic AR systems. Based on this analysis, we outline directions to further the agenda of making haptic AR user-centered.

Building user-centered haptic AR systems: Our review reveals gaps that require building haptic AR systems to support multiple interactions and purposes along with evaluating them better. Designing such systems can widen the interaction possibilities of haptic AR in interesting and novel ways. Furthermore, the need for specialized equipment is likely a reason why haptic AR has almost no examples of consumer-level applications. There is a need to develop cheap, available, and usable haptic AR systems so that the technology can actually be put into end users' hands. This, in turn, would further accelerate usability-based research in haptic AR. Not having access to a range of hardware for haptic AR was one of the limitations of our study. Thus, we opted to use a Wizard of Oz setup and a qualitative evaluation rather than a controlled experiment. Just as different surveys and tools exist for supporting the development of vibrotactile feedback (Degraen et al., 2021; Schneider et al., 2016) or grounded force feedback (Seifi et al., 2019), technical surveys of the field and specific tools also need to be developed for haptic AR as well.

Studying utility: Our list of purposes and user study has demonstrated that haptic AR can be useful. A related question to this is how well haptic AR performs against other forms of feedback. What are the types of tasks where haptic AR is more suited for than visual AR? Does the user actually need to believe that an object feels different to fulfill the reasons for the AR system? For example, in most visual AR interactions, the users can differentiate the augmented content from the real environment. Yet, they benefit from the added visual information (Pohl et al., 2020). Investigating when and where the haptic augmentation should be discernable from the real object is an interesting question for future work.

Evaluating haptic AR experiences: Our study is an initial step toward evaluating how people experience a change in haptic perception. In line with the model for haptic experience proposed by Kim and Schneider (2020), the participants mentioned saliency and utility of the augmentation, hedonic factors, and realism. While this model is helpful in evaluating the haptic AR experience, it is unclear which specific parameters a haptic AR evaluation should focus on. The best method to evaluate these criteria for haptic AR systems also requires investigation. For instance, our definition and existing studies of haptic AR clarify that the augmented objects should be compared with their unaltered version. But should we also compare the objects to the augmentation target? (e.g., normal button vs. augmented button vs. hard-to-press button)? Future work can establish guidelines and best practices for evaluating haptic augmentations.

Theory Building: Research on visual mixed reality has proposed many definitions (Speicher et al., 2019) along with theoretical discussions of interactions (Abtahi et al., 2022) and extensions of the concept (Simeone et al., 2015; Hettiarachchi and Wigdor, 2016). The field of haptic AR can use the prior work for inspiration on building similar frameworks or new interaction techniques for the sense of touch. For example, haptic AR is currently limited to changing the properties of existing objects. A subset of visual AR focuses on "Diminished Reality" (Cheng et al., 2022), where visual effects are used to remove or conceal objects. Existing work on reducing the sensations felt on touching real objects (Ochiai et al., 2014; Mitchell et al., 2007; Gopal et al., 2013), such as reducing the roughness of a surface, could be extended to create haptic diminished reality for the purpose of concealing the existence of an entire object from the user upon contact.

8.2. Expanding on what can be touched

Our list of possible touch events suggests multiple limitations in how the human body can feel the augmented sensations. The touch interaction, however, involves another entity as well: the object or surface being touched. The kinds of surfaces and objects that can be augmented are rarely discussed in the haptic AR literature. For texture augmentation, most studies are constrained to smooth, horizontal, and flat surfaces. Few papers mention altering rough surfaces (Asano et al., 2015) or objects which are not flat (Yoshimoto et al., 2014) or rigid (Yim et al., 2016). What about curved surfaces or those with complex geometries? Also, some systems are limited to specific materials such as conductive objects (Bau and Poupyrev, 2012). We call for future studies to clarify their assumptions or constraints and study their augmentation technique on a wider range of real objects. Development of a set of benchmark objects and materials for haptic augmentation can help advance the field.

Besides objects and surfaces, we also touch our bodies and other human beings. Out of the papers we analyzed, only three augmented human beings and that too for limited purposes such as transferring vibrotactile signals (Hachisu et al., 2020; Luo et al., 2022) or simulating tumors on the skin (de Tinguy et al., 2018). Social touch has a large role in interpersonal communication, but its use is underexplored in haptic AR research. Augmenting human touch has interesting potential in influencing social interactions (Huisman, 2017). For instance, such augmentation may improve the sense of co-presence and intimacy or act as a behavioral intervention. For example, people could be made to appear more confident by making handshakes firmer, emotions could be communicated implicitly and privately, unwanted touches could be made repulsive, and physical contact could become more comfortable or pleasurable. As we saw in our study, augmenting touch is not always seen positively, and augmenting a human being is a sensitive topic. When studying social haptic AR, the experience of both the person being touched and the person initiating the touch action needs to be considered along with social norms and expectations.

8.3. Ethics and safety

Haptic AR is currently limited to research prototypes, and the technology is yet to be available to mainstream users. Considerations of possible misuse, privacy, and safety risks have thus been largely ignored. Can repeated use of certain technology lead to gradual loss of haptic perception? How do people react to sensory conflicts due to changing one property but keeping another correlated property unchanged? How does the interpretation of object usage change when the object does not feel as expected? Can there be a scenario where the user touches a dangerous object under the incorrect assumption that the haptic augmentation will protect them from harm? Should haptic AR systems be limited to modifying objects they have been tested on to prevent unexpected harmful events when the feedback is combined with unknown sensations? On a higher level, changing perception of the real world, especially when the augmentation cannot be easily discerned by the user, raises interesting ethical and interaction questions for haptics. What interaction mechanisms should haptic AR systems devise to ensure user safety and opt-in for these augmentations? Haptic AR research can build on efforts for developing ethical frameworks for other emerging technology (Stilgoe et al., 2020).

9. Conclusion

In this work, we have investigated questions of what, why, and how in relation to haptic augmented reality, an area of research that alters our physical perception of the real world. Answering *what* is haptic AR enables us to better identify and describe systems that augment our sense of touch. Outlining *why* a user would wish to augment their sense of touch helps understand the benefits of haptic AR and evaluate the systems in the context of user goals. Analyzing *how* haptic AR interactions take place exposes current limitations and future directions for haptic AR research. Further, our exploratory study of haptic AR prototypes in the context of real-world tasks demonstrates the value of going beyond just studying single systems to build better haptic AR experiences.

CRediT authorship contribution statement

Arpit Bhatia: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Kasper Hornbæk:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Hasti Seifi:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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