How AI Enables Haptic Virtual Reality in Everyday Environments

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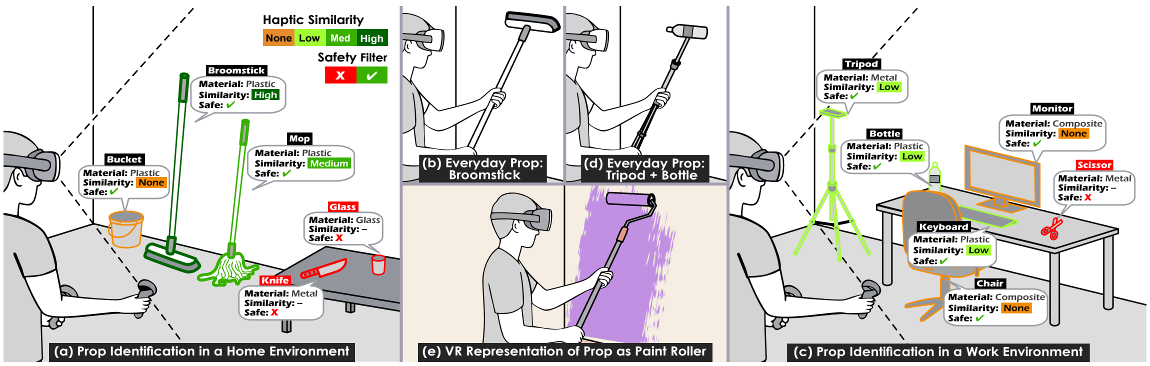

Fig. 1. Concept of a VR system enabling users in home and work environments to make use of everyday objects to enhance the haptic fidelity of an immersive training application in which users learn how to paint. **(a)** An AR interface highlights detected objects in a user's home environment alongside evaluated perceptual, affordance, and semantic properties, and determines whether they are safe for use and haptically similar to a virtual paint roller. **(b)** The prop mapping system recommends the user to pick up the broomstick as it provides a highly realistic feedback for the virtual paint roller. **(c)** When used in a different environment, e. g., at work, where no single prop sufficiently matches the haptics of a paint roller, **(d)** the system recommends to combine two available objects, e. g., a tripod and a plastic bottle, to better approximate the haptics of **(e)** a virtual paint roller interacted with in VR.

When using immersive virtual reality technology in everyday environments at home or at work, the majority of users do not have access to convincing haptic feedback. We argue that through the usage of artificial intelligence, the user's physical environment and the objects therein can be taken advantage of to achieve multimodal haptic sensations without the need for specialized haptic hardware. For this, we transfer the concept of passive haptic feedback to everyday environments. We outline how immersive systems employing the proposed concept of *everyday props* can leverage artificial intelligence to enable the (1) identification of, (2) mapping of, and (3) interaction with everyday objects serving as haptic props in immersive environments.

Additional Key Words and Phrases: virtual reality, artificial intelligence, passive haptic feedback, computer vision, perceptual illusions

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1 Introduction

Immersive virtual reality (VR) technology is becoming increasingly popular in everyday contexts, with consumer-grade head-mounted displays (HMDs) now commonly used at home and at work [14]. Despite this growing adoption, current consumer systems provide little to no convincing haptic feedback during interaction [35]. When users rely solely on hand tracking, as supported by many modern HMDs, they typically receive no physical feedback at all. Even standard VR controllers provide only limited vibrotactile cues and only fixed kinesthetic properties (i. e., a fixed shape, weight, texture, etc.). In addition, controllers generally hinder users from leveraging the dexterity of their hands. As a consequence, this diminishes interaction fidelity and immersion in everyday VR scenarios, potentially preventing VR from unfolding its full potential as a medium for rich, embodied interaction [27].

Users in everyday environments, such as living rooms, kitchens, offices, or workshops, are typically surrounded by a wide variety of physical objects that differ in shape, size, material, temperature, compliance, and affordances. From warm mugs and textured tools to flexible household items, such objects inherently offer diverse haptic cues that can support multimodal interaction. Leveraging these objects for VR interaction, without requiring users to purchase specialized haptic hardware, reflects the core idea of passive haptic feedback (also referred to as prop-based or proxy-based haptic feedback) [12, 13, 36, 37]. When employing passive haptics, physical objects act as tangible stand-ins for virtual objects, enabling users to experience haptic sensations grounded in the real world [25]. For example, a warm cup could represent an overheated component in a VR training simulation, or a broomstick might serve as a convincing haptic proxy for a paint roller in a VR tutorial. Figure 1 illustrates this concept using a virtual paint roller example. The system first detects objects in the user's environment and filters out unsafe ones. It then evaluates the perceptual, affordance, and semantic properties of the remaining objects to determine their haptic similarity to a virtual paint roller and recommends suitable props or combinations of objects to approximate the haptics of the virtual tool.

We refer to the use of such everyday objects for haptics in VR as *everyday props*, a concept previously introduced and discussed with the human-computer interaction (HCI), VR, and haptics research communities at our 2021 CHI workshop[1] on *Everyday Proxy Objects for Virtual Reality* (EPO4VR) [7]. In this position paper, we argue that recent advances in artificial intelligence (AI) can help realize this concept for readily available, affordable, and multisensory VR haptics. We outline how AI-driven scene understanding and reasoning can enable VR systems to (1) identify, (2) map, and (3) support interaction with everyday objects serving as haptic props, thus advancing the vision of accessible, everyday haptic feedback for immersive experiences.

2 AI for Everyday Prop-based Haptic Feedback

While the potential of leveraging everyday objects as props for haptic feedback in VR is promising, effectively realizing this vision at scale requires overcoming key challenges. First, the immersive system needs to identify suitable physical objects in everyday environments (often featuring clutter and uncontrolled lighting). Next, the system needs to determine which physical object best represents which virtual object according to perceptual and interaction-related metrics. Finally, interaction techniques need to be employed to ensure intuitive and safe interaction with these objects during

[1] https://epo4vr.dfki.de/

immersive experiences. At each of these three stages, AI will be a key component to enable and facilitate corresponding solutions.

2.1 AI for Everyday Prop Identification

In many VR and MR pipelines, object understanding remains at the level of category recognition, such as identifying a chair or a mug. However, enabling everyday objects to function as haptic props requires assessing whether a detected chair is both accessible and sufficiently stable to support the user's weight, or whether a mug is empty to grasp safely. Unlike controlled laboratory settings, home and office environments are cluttered, visually complex, and constantly changing. Objects may be partially occluded, poorly lit, or embedded within larger structures such as shelves, making reliable context-aware assessment challenging. We frame prop identification as a two-stage problem: (i) detecting and localizing everyday objects in the user environment, and (ii) characterizing them along three dimensions: perceptual (e. g., shape), affordance (e. g., grasping), and semantic (e. g., possible uses) attributes.

AI can enable this richer form of scene understanding and object characterization by combining perception with reasoning. VLMs can support robust open-vocabulary object detection [29], providing structured representations of physical objects in the user's environment. LLMs can operate on these representations to reason about the perceptual, affordance, and semantic attributes of detected objects, producing interaction-relevant characterizations. In addition to enabling downstream prop–virtual object mapping, these AI-derived characterizations support a safety filter that screens out sharp, fragile, or hazardous objects before they are proposed as haptic props. To improve reliability, LLM reasoning about interaction-relevant attributes can be strengthened through systematic knowledge injection [4], incorporating structured domain knowledge, such as findings from haptic perception research, directly into the model's decision-making process.

Analyzing MR passthrough feeds introduces privacy risks, as personal environments are continuously captured and processed. To reduce this risk, AI-based privacy screening can be performed locally, for example on a connected PC, using lightweight vision models to automatically detect and mask sensitive regions before any data is transmitted to the cloud. Additionally, users should be able to explicitly define regions to exclude from the analysis, retaining direct control over which parts of their environment are processed.

2.2 AI for Everyday Prop Mapping

To determine which physical object best represents which virtual object, we propose optimizing prop mapping for *haptic similarity*. This concept of similarity covers three main factors: (i) *perceptual*, (ii) *affordance*, and (iii) *semantic similarity*. Perceptual similarity refers to the alignment of perceived sensory characteristics (e.g., shape), while affordance similarity refers to the ability of the physical object to support the same action possibilities (e.g., grasping) as the virtual object. Finally, semantic similarity relates to the association users have with an object, such as the purpose. In this context, AI can help us in several ways: First, AI can assist in advancing similarity models that combine perceptual, affordance, and semantic similarity factors. Second, AI can enable us to optimize the prop–object mappings based on the haptic similarity scores. Third, AI can help to suggest possible prop combinations when a single one is not sufficient. An example of prop combination is illustrated in Figure 1 (d): when no individual physical object adequately matches the haptics of a virtual paint roller, the system recommends combining a tripod and a plastic bottle to better approximate its characteristics (e. g., perceived weight and mass distribution) and increase overall haptic similarity. Lastly, AI can aid users in achieving spatial colocation between virtual and physical object pairs through alignment cues (e. g., visual indicators [22]).

2.3 AI for Everyday Prop Interaction

To enable intuitive and safe interaction with everyday props in VR, an initial mapping between a haptic prop and its virtual counterpart is not sufficient. Although perceptual and spatial differences are minimized during the prop mapping stage, small mismatches often still remain. These perceptual mismatches might disrupt immersion and lead to breaks in presence [34].

Perceptual mismatches between haptic props and virtual objects can be conceptualized as challenges of similarity and colocation [28]. We propose to address these challenges through two corresponding classes of perceptual illusions: (i) *similarity-focused illusions*, and (ii) *colocation-focused illusions*. We conceptualize these perceptual illusions as interaction techniques as they directly shape how users perceive and manipulate virtual objects through haptic props. Similarity-focused illusions aim to compensate for haptic and functional differences, such as small mismatches in weight, texture, or shape, for example through techniques which modulate visual feedback such as pseudo-haptics [26]. Colocation-focused illusions mitigate small positional or orientational misalignments between the haptic prop and its virtual representation using techniques such as hand redirection or haptic retargeting [3, 47].

AI can advance prop interaction by enabling adaptive, context-aware management of perceptual illusions, which are typically manual design decisions. It can assist in deciding when and how to apply perceptual illusions such as pseudo-haptics or haptic retargeting by selecting strategies that best compensate for detected similarity or colocation mismatches. This also includes determining how strongly an illusion should be applied and when it should be reduced or disabled. AI-based systems can further enable the dynamic adjustment of illusion parameters based on real-time tracking data. By continuously monitoring hand trajectories, interaction speed, and spatial relationships, such systems can incrementally adapt parameters such as gains, offsets, or retargeting targets to keep manipulations plausible and below perceptual detection thresholds [47]. In addition, AI systems with contextual reasoning capabilities, such as LLMs and VLMs, can better understand the broader context of interaction. This includes recognizing hazards, obstacles, or nearby bystanders and adapting illusion strategies to avoid unsafe or socially inappropriate interactions, for example, by redirecting actions away from restricted areas or nearby bystanders.

3 Conclusion & Outlook

AI will play a key enabling role in the realization of ubiquitous haptic feedback that allows users of immersive applications to feel their virtual surroundings while being physically located in their homes or at work. To achieve this vision, in our upcoming research we plan to explore the concept of everyday props and AI-based solutions for the entailed challenges relating to similarity and colocation [40]. With this paper, we aim to encourage colleagues in the domains of VR, haptics, HCI, and computer vision to turn their attention towards the challenges posed by everyday proxy usage and to collaborate with us on related research questions.

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Dr. André Zenner is a postdoctoral researcher at Saarland University and at the German Research Center for Artificial Intelligence (DFKI) in Saarbrücken, Germany. He has studied computer science and obtained his PhD from Saarland University in 2022 under the supervision of Prof. Dr. Antonio Krüger. His research focuses on HCI and VR, with a specific focus on haptics for VR and perceptual illusion techniques. He was awarded the prestigious IEEE VGTC Virtual Reality Best Dissertation Award in 2024 for his doctoral thesis on proxy-based haptic feedback in VR [40].

Examples of his research contributions include the two handheld haptic VR controllers *Shifty* [45] and *Drag:on* [41, 46]. André Zenner has also worked in the field of perceptual illusion techniques for VR and contributed several novel hand redirection algorithms [43, 49] and psychophysical investigations [42, 43, 47, 49] that inform about the detectability of such techniques. Furthermore, his research has covered the combination of hard- and software-based approaches to VR haptics [2, 8, 9, 38, 40, 48, 51].

Following an open-science approach, André Zenner has released several open-source repositories that allow others to build upon the software and physical prototypes developed in his research. These include, e. g., building instructions for *Shifty*[2] [45] and *Drag:on*[3] [46], the *Virtual Reality Hand Redirection Toolkit*[4] [44], and the *Unity Staircase Procedure Toolkit*[5] [50].

Muhammad Moiz Sakha

Muhammad Moiz Sakha is a PhD student at Saarland University, Germany, supervised by Prof. Dr. Antonio Krüger, where he previously earned his MSc in Visual Computing. His research focuses on VR, 3D user interfaces, and HCI, with a recent emphasis on AI-enhanced haptic feedback in immersive environments. He previously developed and evaluated a VR application that provides detailed 3D visualizations of plants based on real-world data captured by robots, allowing plant breeders to remotely analyze plant traits in VR [31]. This work was recognized with the Best Demo Award at the ACM Symposium on Spatial User Interaction in 2024 [32]. He also investigates safe human-machine

[2]https://github.com/AndreZenner/shifty
[3]https://github.com/AndreZenner/dragon
[4]https://github.com/AndreZenner/hand-redirection-toolkit
[5]https://github.com/AndreZenner/staircase-procedure

interaction for drones, focusing on handover strategies and critical alert design to support operators monitoring drones in control rooms [23].

Sukran Karaosmanoglu

Dr. Sukran Karaosmanoglu is a postdoctoral researcher in the Human-Computer Interaction Group at the Department of Informatics, Universität Hamburg, Germany. She received her PhD [15] in Computer Science from Universität Hamburg in 2025 under the supervision of Prof. Dr. Frank Steinicke. Her research centers on understanding, designing, and developing technology-based interactive experiences, particularly immersive VR games, that create a positive societal impact for individuals of all ages and conditions. Her focus areas include promoting physical activity [6, 10, 16, 22], active aging [17–19, 33], and social interaction [20, 21, 30, 39]. Building on this foundation, she is interested in investigating how everyday objects in immersive environments can be utilized to support users, particularly in addressing pressing societal challenges.

Florian Daiber

Dr. Florian Daiber is a senior researcher at the German Research Center for Artificial Intelligence (DFKI) in Saarbrücken, Germany, where he leads research activities at the intersection of HCI, 3D user interfaces, and extended reality (XR). He studied Geoinformatics at the University of Münster and obtained his PhD from Saarland University in 2015 under the supervision of Prof. Dr. Antonio Krüger. His research centers on the design, implementation, and evaluation of 3D interaction techniques for VR and AR, with a particular emphasis on haptics, mid-air interaction, and multimodal feedback. Florian Daiber has contributed to the development of gesture-based and tangible interaction techniques for XR, exploring how spatial input, wearable sensing, and haptic feedback can be combined to create more expressive and precise 3D user interfaces. He works on fundamental and applied research in domains including training, sports, and industrial scenarios. More recently, his research also investigates the integration of AI-driven adaptive systems into XR, enabling context-aware and personalized interaction.

Frank Steinicke

Dr. Frank Steinicke is a Professor of Human-Computer Interaction at the Department of Informatics at the Universität Hamburg, Germany. His research focuses primarily on integrating natural and artificial intelligence with digital realities to enhance interactions and experiences within computer-mediated environments.

He studied Mathematics with a Minor in Computer Science at the University of Münster, earning both his PhD and Venia Legendi in Computer Science from there. He worked on perceptually-inspired user interfaces, e.g., using redirection techniques with passive haptics [5, 11]. Recognized for his contributions, Frank Steinicke received the IEEE VGTC Virtual Reality Technical Achievement Award in 2023 and was inducted into the IEEE VR Academy. In 2024, he was inaugurated into the Academy of Sciences and Humanities in Hamburg, and in 2025, he was inducted into the XR Hall of Fame.

His group has released several open-source repositories for AI development and haptic interactions. These include, e. g., building instructions for *Intelligent Virtual Humans SDK*[6] [24] or building instructions for a vibrotactile fingercap for wireless 3D interactions *HapFinger*[7] [1].

[6]https://github.com/uhhhci/intelligent-virtual-agent-sdk
[7]https://github.com/uhhhci/HapFinger