Smooth as Steel Wool: Effects of Visual Stimuli on the Haptic Perception of Roughness in Virtual Reality

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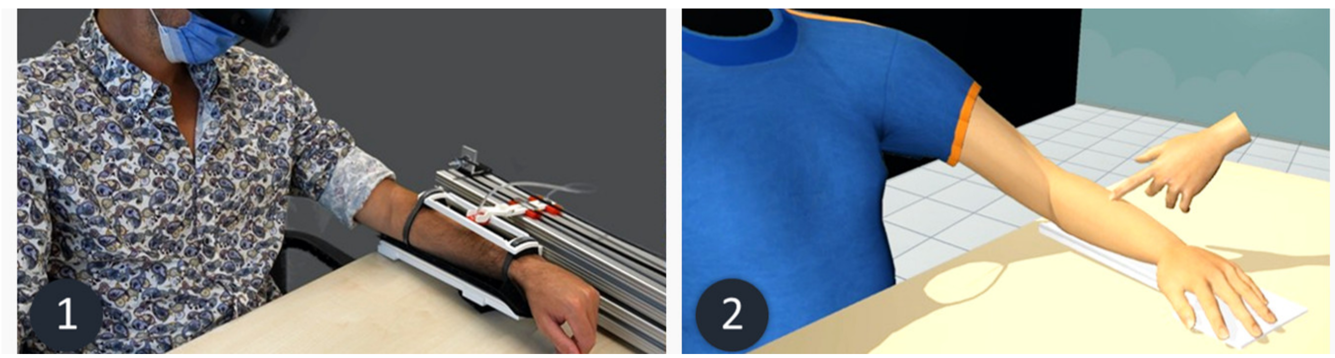

Figure 1: A participant during the experiment showing (1) the real-world setup and apparatus for haptic stroke movements, and (2) the virtual scene as it appears in VR.

ABSTRACT

Haptic Feedback is essential for lifelike Virtual Reality (VR) experiences. To provide a wide range of matching sensations of being touched or stroked, current approaches typically need large numbers of different physical textures. However, even advanced devices can only accommodate a limited number of textures to remain wearable. Therefore, a better understanding is necessary of how expectations elicited by different visualizations affect haptic perception, to achieve a balance between physical constraints and great variety of matching physical textures.

In this work, we conducted an experiment (N=31) assessing how the perception of roughness is affected within VR. We designed a prototype for arm stroking and compared the effects of different visualizations on the perception of physical textures with distinct roughnesses. Additionally, we used the visualizations' real-world materials, no-haptics and vibrotactile feedback as baselines. As one result, we found that two levels of roughness can be sufficient to convey a realistic illusion.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

KEYWORDS

perception, roughness, caress, touch, haptic feedback, stroke, virtual reality

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1 INTRODUCTION

Virtual Reality (VR) has never been more realistic, thanks to ever-improving visual and auditory qualities. However, in terms of haptics, the current state of virtual environments is still far from Sutherland's vision of the ultimate display [93]. To add an additional sense of touch and being touched to virtual environments and, therefore, to enrich the user's perception, researchers investigated haptic devices that are capable of providing force feedback [20, 60, 62, 98], a sense of touch [40, 86], or representing stroking [11, 75, 77]. Often, this is achieved through vibrotactile feedback [9, 18, 52, 53, 62, 84], which is limited in terms of realism [28, 67]. Other approaches addressed this by providing physical textures [3, 7, 67, 106]. However, those mostly focus on *active touch* (touching something) rather than *passive touch* (being touched) which is essential for the perception of the environment and how people interact with it and others. Further, these approaches are usually focusing on specific use cases, as they can only carry a limited number of physical textures, and, thus, can only support a limited set of visualizations in VR appropriately.

Therefore, in order to facilitate the design of novel devices that convey a realistic illusion with a minimal set of physical textures due to physical limitations, a deep understanding of how visuals in VR affect haptic perception is necessary. Previous research has shown that visual perception is one of the most dominant human senses and contributes to haptic expectations before and upon contact [25, 65, 92, 111]. In terms of roughness, for example, if persons *see* something rough, they also expect to *feel* something rough. However, what would happen if the visual expectation and a haptic stimulus do not match? And to which extend are visual expectations overwriting haptic perception and vice-versa so that users still perceive a matching sensation?

In this work, we hypothesize that a physical actuation while being in VR only needs to be close enough to its real-world counterpart, and not necessarily identical, for conveying a realistic sensation. Therefore, we investigated how users *discriminatively* perceive haptic and visual stimuli during *passive touch* on the example of texture roughness. In a first step, we explored the roughness expectations of 50 items through an online pre-study (N=40) and clustered them into five levels ranging from *very smooth* to *very rough*. In a second step, we investigated the perception of five physical textures with different levels of roughness combined with ten visualizations derived from the pre-study in a controlled lab experiment (N=31). For this, we designed a physical prototype that facilitates haptic stroke sensations along the arm and presents varying visualizations in a VR environment. Further, we compared the physical textures to the visualizations' real-world materials, a silicone cushion, vibrotactile feedback, and no-haptics as baselines. In total, we evaluated 99 combinations of haptic and visual stimuli and assessed their perceived haptic and visual roughness, matching, degree of realism, and pleasantness.

In summary, we advance the state-of-the-art in the haptic perception in correspondence to the visual stimuli in VR environments by providing a systematic investigation of different visual-haptic pairs that allows us to create a clearer picture about real and virtual haptic perception. Therefore, this paper contributes (1) an investigation of the visual expectation of the roughness of 50 items, (2) an empirical evaluation of the interdependency between haptic stimuli and visualizations in VR with regards to perceived roughness, matching, realism, and pleasantness, and (3) a comparison of haptic stroke stimuli with different levels of roughness, vibrotactile phantom sensations, real-world materials, and without haptic feedback.

2 BACKGROUND

In the following, we provide a brief terminology of characteristics for physical materials and two classifications of touch: (1) *Active* and *Passive*, and (2) *Discriminative* and *Affective*.

2.1 Characteristics of Physical Materials

Materials and surfaces have different physical properties essential for tactile perception, such as roughness, hardness, temperature, and friction [44, 78, 79]. Although all characteristics contribute to the full haptic picture, we have to understand each aspect separately. In terms of roughness, which is the focus of this work, Hollins et al. [45] separated roughness further into a coarse and fine roughness. While coarse roughness is often viewed as "voluminous, uneven, lumpy, coarse, and relief" [78] mediated "by spatial cues" [45], fine roughness "is typically described as harsh or rough" [78] mediated "by vibrational cues" [45].

2.2 Classifications of Touch

Touch can be categorized into two classifications: (1) *Active* and *Passive*, and (2) *Discriminative* and *Affective*.

The first classification describes whether a person *actively touches something* or is *passively being touched* [15, 29]. This means *active touch* is an action by the person as the initiator, while *passive touch* is a contact caused to the person by external forces. This also often refers to being touched on body parts not related to the own hands, for example during sensations of caress.

The second classification describes if touch can *discriminate* physical properties and how a touch *affects* emotional responses. This means that *discriminative touch* focuses on how physical contact is perceived physiologically "to detect, discriminate, and identify external stimuli with a view to ultimately making rapid decisions to guide subsequent behavior" [72, 73]. *Affective touch*, however, focuses on what a touch elicits emotionally, conveying "anger, fear, disgust, love, gratitude, and sympathy" [42] or emotional immersion [21, 47].

From a physiological perspective, *discriminative* traits are mainly attributed to the so-called *glabrous skin* [71], which is found on the palm, fingers, or feet. Thereby, research has found that hands have a particularly high sensitivity to changes in the roughness of surfaces (e.g., [59]). In contrast, however, body regions with *hairy skin* [39], such as the arms or upper body, typically respond better to "slow and light" strokes [81] and have weaker discriminative traits [1, 80]. Respectively, most *discriminative touch* research focuses on the discriminative aspects during *active touch*. Research investigating *affective touch*, however, is mostly concentrated around *passive touch*.

However, these combinations are not mutually exclusive and, for example, it is essential to understand how *passive touch* is *discriminatively* perceived in order to provoke affective responses.

3 RELATED WORK

Previous research has proposed a large number of haptic devices that follow the classifications presented in the previous section. In this section, we provide an overview of existing (1) haptic devices in HCI, (2) discuss how to convey haptic textures, and (3) the influences of visual and tactile stimuli on haptic perception.

3.1 Haptic Devices in HCI

Although a large body of research has been proposed to convey passive touch *affectively* and *discriminatively*, most of it focuses on tactile sensations and their effects on emotional factors, caress, force-feedback, guidance, or notifications. Prominent examples include squeezing, twisting, or skin deformation of body parts [37, 61, 75, 89, 90, 113], pneumatic actuation [20, 32, 36, 40, 56, 87], thermal cues [35, 68], mechanical forces [14, 77, 86], and tiny robots for attention guidance [57]. However, the typical state-of-the-art solutions still primarily rely on vibrotactile feedback, which can be easily integrated into small wearable devices [23, 31, 33, 43, 74, 84, 98, 99, 117], full-body suits for enhancing immersion [9, 62], sleeves [48] or even furniture [53]. Thereby, vibrotactile feedback is an effective method to give a lightweight sensation of being touched, affecting the emotional state (e.g., [74, 117]), and stroking through phantom sensations [2, 54]. However, vibrotactile feedback typically suffers from limited realism and is incapable of providing haptic stimuli the same quality as physical textures [28, 67].

3.2 Haptic Textures Representations

Physical textures play an important role to convey haptic feedback both *actively* and *passively*. Previous research has been mostly focusing on the *active touch* aspects and explored methods to provide haptic textures [81, 102, 105] via touchable textures on flat surfaces [6, 19, 76, 94], physical textures on VR controllers [4, 7, 16, 58, 67, 106], vibrotactile arrays placed directly on fingertips [81, 108] or pen devices [18], drones [46, 60], or robotic arms [3, 63, 70].

However, providing textures for *passive touch* has been less explored. While the approaches for *active touch* can be transferred to *passive touch* scenarios and vice-versa, the differences of the respective skin types (*glabrous* and *hairy* skin) that have different discriminative traits require individual investigations. For example, previous work on *passive touch* has employed an array of small tactile motors simulating ants walking on the user's arm [114], vibrotactile arrays [117], a magnet hovering over the arm to stimulate hairs covered in iron powder infused gel [10, 11], or shape memory alloys [75]. Still, while the aforementioned works have primarily focused on the replication of haptic stimuli, it is necessary to understand how visual expectation and perception affect the actual haptic sensation during a *discriminative* contact, especially in VR.

3.3 Visual and Tactile Influences on Haptic Perception

The visual expectation plays a particularly important role in haptic perception (even prior to contact) [25, 92, 111] and the perception of texture is typically multisensory [65]. Lederman and Abbott [64] have discovered that both, visual and tactile perception, can independently classify the grit of a physical texture in almost identical quality, although vision seemed not to be the dominant modality. In their follow-up experiments, Lederman et al. [66] showed that the "multidimensionality of texture perception" is of importance, but visual and haptic perception affect each other depending on the attention. Guest and Spence [30] also observed that the perception of roughness is not improved by combining visual and tactile sensation when users perceived roughness separately. Bergman Tiest and Kappers [8] extended those experiments for a set of various flat materials. Yanagisawa and Takatsuji [111] investigated how the perception of textures is affected by visual expectations before the actual haptic experience and found significant changes in the perception depending on the visual material shown before.

Although these experiments provided significant insights, their focus remains on *active touch*, where participants had to discriminate the roughness of flat surfaces by touching them. As the discriminative traits are, however, largely different for the respective skin types, they can not directly be mapped to *passive touch* scenarios. Moreover, visual and haptic stimuli were the same type of materials (e.g., sandpapers, fabrics, or flat surfaces) and it remains unclear to which degree haptic perception is altered if a physical texture is completely disconnected from an object's visual appearance, which is essential for haptic devices in VR. Focusing on the capabilities of VR environments, it remains unclear to what extent these findings apply to depictions of complex models and objects that provide more visual details that create a certain expectation of their roughness. For example, Degraen et al. [19] created a system based on 3D-printed hairs that can re-create textures with different roughness and hardness. While the authors focused on the replication aspects, the findings also could highlight that the visuals - which are not necessarily matching the haptics - are affecting the haptic perception through the roughness expectations of the participants. However, the paper was limited to the recreation of flat surfaces and textures, such as glass, concrete, or metal, for *active touch*.

As a foundation for various experiments investigating *passive touch* texture perception combined with visual feedback, Botvinick and Cohen have introduced the Rubber Hand Illusion (RHI), in which persons experience a "rubber hand as belonging to themselves" [12]. Using this method, for example, Schütz-Bosbach et al. [88] investigated how congruent and incongruent stimuli of soft cotton and a rough sponge affect the roughness perception. They found that incongruent stimuli did not change the perception of the roughness. However, they observed that when stroking the rubber hand with a smooth fabric, it resulted in a less smooth rating than with the same material on the real hand. Ward et al. [103] further confirmed that although the roughness itself has less influence on the persuasion of the RHI, a mismatch of expected hardness has a negative impact on the body ownership illusion, e.g., when seeing a hard pencil but feeling a soft brush. Additionally, previous research investigated how emotions are affected by visuals and strokes from other persons and found that touch from strangers is perceived more unpleasant [50, 51]. While the aforementioned experiments demonstrated the extent to which visual stimuli can influence haptic perception, further research is necessary to identify how the perception of roughness behaves with more than two distinct gradations. Also, the applicability of these results to different visualizations in a VR environment for *discriminative passive touch* has to be further investigated through adjusted methods, which lies in the focus of this work.

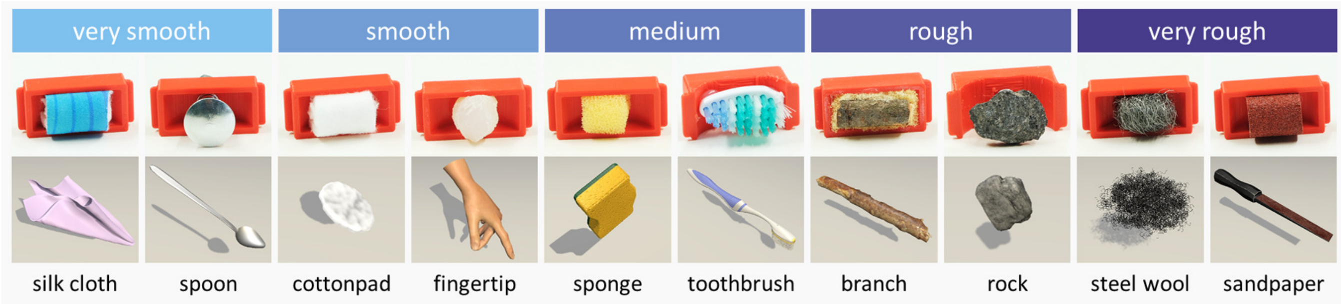

Figure 2: The ten VISUALIZATIONS as they appeared during the main study (bottom) and their real-world counterparts (top) used for the haptic baseline (*real*). All of them are ordered into increasing levels of roughness based on the results of the pre-study. From left to right: *silk*, *spoon*, *cotton*, *finger*, *sponge*, *toothbrush*, *branch*, *rock*, *steel wool*, and *sandpaper*. The *no-visuals* baseline is not depicted.

4 PRE-STUDY: IDENTIFYING VISUALIZATIONS OF DIFFERENT ROUGHNESS EXPECTATION

Before conducting the main study, we had to identify a large variety of possible visualizations that propagate different roughness. As humans often have different conceptions and mental models of how different objects might be perceived, we performed a pre-study in the form of an online questionnaire. Hereby, we focused on the subjective perception of roughness based on the mental models of participants (cf. [88]) to obtain a diverse variation of VISUALIZATIONS with different expectations of roughness. As such, we initially selected 50 items that span a scale from smooth-to-rough which we identified during brainstorming sessions. All of those potential visualizations were carefully chosen to represent a broad variety of items with different roughness and which people should have perceived before.

Then, we asked the participants to rate those items with regard to their expected roughness on a scale from 1 *(very smooth)* to 5 *(very rough)*. To avoid any bias, we did not show any visualizations at this point and had the participants answer the questionnaire just by thinking of the specific items. Thereby, we hypothesized that items with a low deviation of the ratings will be more likely to share a very precise and shared conception of the roughness among all participants, thus, should propagating similar characteristics also in the follow-up study.

4.1 Participants

We advertised the online questionnaire through our institute's network, online discussion groups, and among contacts. In total, 40 individuals participated (20 female, 20 male) with an age range between 23 and 57 years ($M = 30.9, SD = 6.2$). On average, answering the questionnaire took 15 minutes. No compensation was provided.

4.2 Results of Pre-Study

For identifying suitable VISUALIZATIONS that share a similar expected roughness among the participants, we ordered all 50 items by their median ratings. Then, items that showed a high uncertainty ($IQR > 1$) were excluded from the list. For instance, we could observe this when users had too different or no precise conception of the roughness of a specific object. From the remaining items, we selected two VISUALIZATIONS for each of the five levels of roughness with respect to their suitability for VR. Here, we also carefully tried to select items to be as versatile as possible. For example, the silk cloth and bottom of spoon both had the same roughness ($\tilde{x} = 1$) but would be different regarding their hardness.

As result, we identified a total of 10 VISUALIZATIONS, grouped into five ascending levels of expected visual roughness: (1) *very smooth* (Silk Cloth, Bottom of Spoon), (2) *smooth* (Cotton Pad, Fingertip), (3) *medium* (Foam side of Cleaning Sponge, Toothbrush), (4) *rough* (Small Edged Rock, Wooden Branch with Bark), and (5) *very rough* (Steel Wool, coarse Sand Paper).

5 MAIN STUDY

In order to evaluate the influence of HAPTIC STIMULI and VISUALIZATIONS on the perception of roughness, we conducted a controlled experiment investigating the following research questions:

- RQ1. How do different physical textures of HAPTIC STIMULI affect the roughness perception?
- RQ2. How do different VISUALIZATIONS affect the perception of physical textures?
- RQ3. How do different physical textures with varying roughness compare to the VISUALIZATIONS' real-world materials?
- RQ4. How do users perceive haptic strokes compared to vibrotactile phantom sensations?
- RQ5. How do the perception of roughness and the matching of stimuli affect the pleasantness?

5.1 Study Design

We used a within-subjects design with HAPTIC STIMULUS and VISUALIZATION as the independent variable (IV). We varied 11 levels of the VISUALIZATION in VR and 9 levels of the HAPTIC STIMULUS, which resulted in a total of $11 \times 9 = 99$ conditions. We outline both IV in detail in the following.

5.1.1 VISUALIZATION (10+1 levels). We used 10+1 VISUALIZATIONS as identified in the pre-study (Section 4) with the following subjective levels of roughness (in ascending order): (1) *silk*, (2) *spoon*, (3) *finger*,

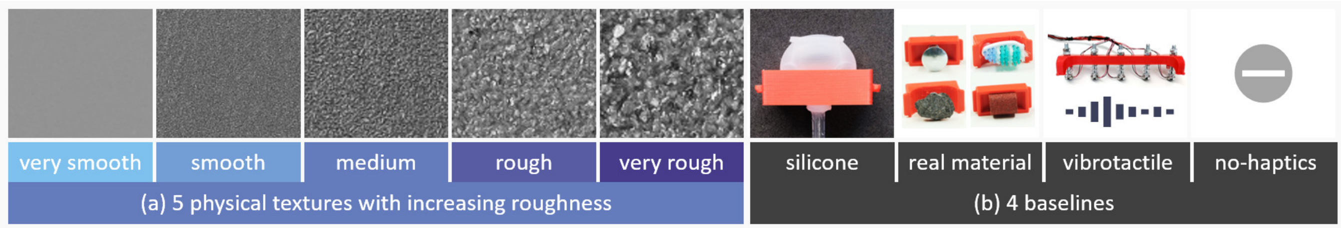

Figure 3: The Haptic Stimuli as used for the main study, showing (a) the five physical textures with increasing roughness (taken as desaturated macro shots for better contrasts and comparison), and (b) the four haptic baselines (from left to right: silicone actuator without texture, the Visualizations' real-world materials, the *Vibration Mount* as used for vibrotactile phantom sensations, and the no-haptics baseline).

(4) *cotton*, (5) *sponge*, (6) *toothbrush*, (7) *branch*, (8) *rock*, (9) *steel wool*, and (10) *sandpaper*. Additionally, we added a neutral *no-visuals* baseline. All visualizations are depicted in Figure 2.

5.1.2 Haptic Stimulus (5+4 levels). We evaluated a total of 9 levels for the haptic sensation. For a uniformly distributed gradation of roughness, we opted for abrasive sandpaper, similar to related work (e.g., [8, 41, 45]). Further, to compare the performance of these five physical textures, we also selected an untextured *Silicone Cushion*, the visualizations' *real-world* materials, state-of-the-art *vibrotactile* phantom sensations, and a *no-haptics* baseline.

In summary, we evaluated the following Haptic Stimuli: (1) *very smooth* (polyethylene), (2) *smooth* (sandpaper 1000), (3) *medium* (sandpaper 400), (4) *rough* (sandpaper 120), (5) *very rough* (sandpaper 80), (6) *silicone*, (7) *vibrotactile* phantom sensation, (8) *real* baseline, and (9) *no-haptics* baseline. An overview of the Haptic Stimuli is provided in Figure 3 and all *real-world* materials for each Visualization are depicted in Figure 2.

5.1.3 Dependent Variables. For each experimental condition, we asked participants to rate the following five aspects: (Q1) *perceived haptic roughness*, (Q2) *perceived visual roughness*, (Q3) *matching* of Haptic Stimuli and Visualizations, (Q4) *real-world expectation and realism* (based on the Witmer-Singer Presence Questionnaire [109]), and (Q5) *pleasantness* of each actuation. All these items were assessed using on a 5-Point scale [55, 101] through the following questions:

Q1. How would you rate the roughness of the Haptic Stimulus? (*very smooth* to *very rough*)
Q2. How would you rate the roughness of the Visualization? (*very smooth* to *very rough*)
Q3. The Haptic Stimulus and Visualization matched. (*did not match* to *did match completely*)
Q4. How much did your experiences in the virtual environment seem consistent with your real-world experiences?[1] (*not consistent* to *very consistent*)
Q5. The actuation felt pleasant. (*not pleasant* to *very pleasant*)

5.2 Apparatus and Study Setup

Before investigating the influences of Visualizations and Haptic Stimuli on the roughness perception, we built a prototype that provided a moving haptic sensation with different levels of roughness on the arm. Therefore, we designed a wearable *Guiding Rail* for the arm that can accommodate various *Actuator Sledge*s, able to move along the arm. The *Actuator Sledge*s are designed to house small objects (i.e., the real-world materials) or an inflatable *Silicone Cushion* for providing the sandpaper-based textures[2] (Figure 4.1, 4.2, and 4.3).

To move an *Actuator Sledge* along the *Guiding Rail*, we used a timing belt driven by a stepper motor[3] on a stationary aluminum rail (Figure 4.5). For the study, we set the movement velocity to 10 cm s^{-1}, which was found to have a high pleasantness rating [1, 96]. A flexible cantilever translates the motion to the *Actuator Sledge* in the wearable *Guiding Rail*. This separation of the motor and actuator made it possible to compensate for slight movements of the user's arms. Additionally, we attached a 3D-printed armrest as a support to keep the arm in place comfortably. To further increase an even actuation, we had to assure the *Guiding Rail* adapts to the individual shapes of arms. Therefore, we first measured the arms of 8 individuals[4] and derived the following convex and concave profiles for the *Guiding Rail*: (1) 0 mm linear, (2) +1.5 mm convex, (3) -1.5 mm concave, and (4) -3 mm concave curved.

5.2.1 Textures with different Roughness and Design of Silicone Cushions. The *Silicone Cushion* design helped to facilitate an even contact surface on the skin for the flexible sandpapers. As such, the *Actuator Sledge*s using a *Silicone Cushion* could convey flexible textures with different levels of roughness through inflation (Figure 4.4). While 3D-printed surfaces would have also been an option [19, 100], we found different grits of abrasive sandpaper more suitable as they could guarantee a normalized scale based on international standards by still providing a versatile flexibility as often used by related work [8, 41, 45]. Similarly, we also investigated to cast textures with different roughness directly into the *Silicone Cushion*, however, this resulted in too subtle differences and did not provide enough rough structures. Vibrotactile [17, 18] and ultrasonic patterns [104] have been shown to create surface roughness as well, however, require sophisticated setups which can only *replicate* the physical roughness property to some degree [104]. Though, as state-of-the-art

[1] based on Q12 of [109]

[2] cast using 2-component silicone EcoFlex 00-30, Smooth-on Inc.
[3] NEMA-17 stepper motor
[4] We measured 8 diverse individuals: 3 female, 5 male, between 26 and 61 years (M=33.5, SD=10.7), between 168 cm and 192 cm tall (M=178, SD=8.2), and between 50 kg and 116 kg weight (M=76.4, SD=18.0)

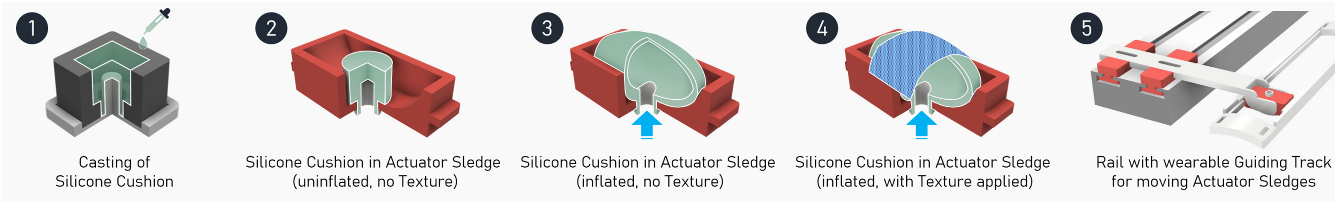

Figure 4: Concept of the actuation: (1) Casting of the *Silicone Cushion*, (2) uninflated *Silicone Cushion* embedded into an *Actuator Sledge*, (3) inflated *Silicone Cushion* without texture, (4) inflated *Silicone Cushion* with an attached texture, and (5) overview of the motion rail for moving the actuator sledges.

approaches use vibrotactile phantom sensations to provide haptic sensation, we added vibrations as a baseline (see Section 5.2.3).

Therefore, we identified that sandpapers were most reliable for our study design. As such, we found grits of 80, 120, 400, and 1000[5] as most suitable during informal pre-tests. For all selected grits, we assured that they did not cause pain, involuntarily trap hairs, and were distinguishable beforehand. However, since even the smoothest sandpaper provides some degree of roughness, we chose a smooth high-gloss strip of polyethylene for the *very smooth* texture. The strips of sandpaper and polyethylene were glued to the center of a *Silicone Cushion* for fixation. Additionally, we used the raw *Silicone Cushion*as another baseline.

The inflation of the *Silicone Cushion* was controlled by an array of two diaphragm pumps and solenoid valves that were connected to an ActuBoard controller [34] (Figure 5.1 and Figure 5.2).

5.2.2 Real-World Materials Baseline. The *real* materials were selected by matching the Visualizations' 3D-models. However, for those mostly rigid real-world materials, an actuation with a *Silicone Cushion* was not possible as these objects had to be fixed in the *Actuator Sledge*. Therefore, we used a spring-loaded design for the *spoon* and *rock*, which limited the maximal extension to avoid too much pressure but were still flexibly adjusting to the arm shape. For the fingertip, we could not guarantee that the actuation would always be performed synchronously when using a real finger (e.g., from the experimenter). Therefore, we cast a silicone finger using a plaster negative and treated it with magnesia chalk commonly used in sports to reduce friction. For the remaining real-world materials, we used soft sponges that had the same purpose as the spring-loaded design but were more suitable for these specific materials, as shown in Figure 2.

5.2.3 Vibrotactile Baseline. In order to provide a state-of-the-art vibrotactile actuation as a baseline, we designed a *Vibration Mount* (Figure 5.3) as a plug-and-play attachment for the *Guiding Rail* that made use of vibrotactile phantom sensations [2, 83]. Hereby, vibrotactile phantom sensations (or sometimes referred as funneling illusion [5]) do not actually provide a physical movement on the arm but the illusion of a continuous motion through changing the intensity of adjacent vibration motors [2, 5]. Since the distance between two adjacent motors has to be in certain ranges depending on the body part to keep up the illusion [1, 24, 95], we designed a support bar for five vibration motors[6] that were equally distributed with a spacing of 31.5 mm [24]. This resulted in a total actuation range of 129 mm, likewise to the length of the physical stroke actuation. Further, as the shapes of the arm varied between participants, we mounted each motor on a spring-loaded screw to provide a uniform contact pressure on the arm. To avoid too much pressure on the arm, we calibrated the maximum extension for each spring-loaded screw by their counter-nut individually for each participant.

For controlling the intensity of the motors to provide the illusion of a continuous movement, we actuated them similarly to existing work by modulating the vibration intensity [5, 33, 52–54, 74] that are using phantom sensations [2, 83]. The actuation always started at one of the outermost motors of the *Vibration Mount* (depending on the direction) and advanced slightly every frame in a single wave-like approach. The leading motor in the direction of sensation was set to full intensity, followed by a short trail of correspondingly less intense vibrations, so that the impression of a continuous motion was conveyed even between two adjacent motors. The timing and velocity of a single vibrotactile actuation from one side to the other was the same as for the physical stroke (10 cm s^{-1}). For driving each motor and controlling it through our VR application, we used the open source ActuBoard platform [34].

5.2.4 Virtual Reality Environment and Visualizations. For the VR environment, we designed a virtual room using the Unity Engine[7]. It had a similar appearance to the physical room and participants were tested at the same setup, which consisted of a wooden table of the same height and measurements in the real and virtual environments.

For all ten Visualizations (excluding the *no-visuals* baseline) we used realistic 3D models from different professional online archives[8]. However, since there were no appropriate 3D models for the steel wool, sandpaper, and cotton pad, a professional digital media artist designed models for those Visualizations. Also, the models featured realistic normal maps and reflections. Given the high-performance requirements for VR, the models could not be rendered entirely photo-realistically, yet have been on the same level as modern VR applications. All Visualizations are depicted

[5]according to the Coated Abrasive Manufacturers Institute (CAMI) notation; the smaller the value, the rougher the texture; non-linear

[6]Vibrating Mini Motor Discs, Pulse-Width Modulation (PWM), 2 V - 5 V

[7]https://unity.com/

[8]CGTrader.com (cgtrader Royalty Free License): Silk Cloth; Turbosquid.com (TurboSquid 3D Model License): Spoon, Toothbrush, Small Edged Rock; Sketchfab.com (CC BY 4.0): Cleaning Sponge, Wooden Branch; Makehumancommunity.org (CC0 1.0): Fingertip

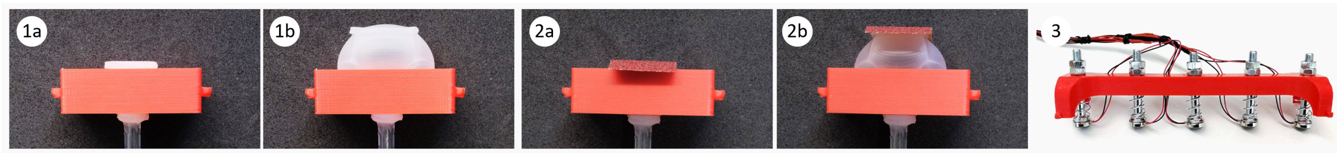

Figure 5: Closeup of the actuators: (1a) uninflated and (1b) inflated *Silicone Cushion* without texture, (2a) uninflated and (2b) inflated actuator with physical texture attached, and (3) *Vibration Mount* for vibrotactile feedback.

in Figure 2 and the complete sources can be found in the supplementary files.

5.2.5 Calibration for Synchronicity of Visualization and Haptic Stimulus. We used an HP Reverb G2 Head-Mounted Display (HMD) for VR. As this HMD uses an inside-out tracking[9], we increased the reliability by placing additional visual markers of different shape, color, and size to the experimentation room until there were no offsets or shifts recognizable.

To ensure spatial consistency between the real and virtual worlds, the scene was always inspected beforehand and, if necessary, recalibrated prior to each participant. Therefore, the virtual and real table edges, as well as the surface of the table, were aligned properly using the VR controllers, i.e., virtual position aligned to physical boundaries, so that both, position and rotation, were identical.

Further, as shown by related work, it was essential that participants could self-identify with their virtual avatar [38, 49, 91, 115]. Therefore, we used a human model[10] that could adapt in size, shape, texture, and color for each participant [49, 97]. Likewise to previous research, we actuated the left forearm (e.g., [1, 49, 88]) and assured that a spatial synchronicity between the virtual and real arm was given to provide an equal actuation across all participants. Additionally, we placed the arm in a provided armrest that was fixed to the table and also recreated in the VR environment.

Most importantly, we assured that physical and virtual objects were time-synchronous [1] by aligning the physical actuation range with the movement in the virtual scene which is essential for a realistic illusion [85]. Therefore, we first measured the distance between the wrist to the *Guiding Rail* and used it as starting point for the VISUALIZATION. As Unity uses a metric system for units, we could then map the physical actuation range of the *Guiding Rail* (129 mm) directly to the virtual scene. Second, based on the physical actuation, we could set the velocity of the virtual actuation to the same (both 10 cm s^{-1}). As a result, we could guarantee a time-synchronous actuation between real and virtual environments which made both, VISUALIZATION and HAPTIC STIMULUS, start and stop at identical positions within the exact time span.

In addition, we used *inverse kinematic* for the upper body and right arm to increase the embodiment [82]. Prior to the experiment, participants familiarized themselves with the VR environment, followed by checking the calibration and the participants' correspondence to their virtual avatar. Figure 1 depicts a participant in the (1) real-world setup as observed from the outside, and (2) the study scene as it appeared in VR.

[9]https://circuitstream.com/blog/hp-reverb-g2/
[10]http://www.makehumancommunity.org/

5.3 Procedure

Before the study: After welcoming the participants, we briefed them on the study procedure. Then, we informed them that all data would be collected anonymously and asked them to sign a consent form. In addition, we assured that participants had no allergies to certain materials before the start of the study. After the introduction, we asked the participants to uncover their left forearm and checked which of the *Guiding Rail* profiles fit best. After helping them to put on a fitting *Guiding Rail*, we ensured that the actuation was comfortable and safe. Therefore, we moved the *Actuator Sledge* along the arm to see if the contact was even and did apply an appropriate amount of pressure with a contact surface of 1-2 cm^2. Similarly, we put on the *Vibration Mount* and adjusted the nuts of the spring-loaded screws for proper contact of each vibrotactile actuator. During this process, participants had to look away and did not see any of the actuators and were also not informed of what will move on their arms. We only informed them that different materials with different roughness will move along the arm but not how many and which exactly, and also gave no information on the *vibrotactile* and *real* baselines. Once ready, participants put on the HMD[11] and rested their left arm in the provided armrest. Once participants agreed that their virtual body felt natural and their own (cf. [91]), we started with the experiment.

During the study: Participants were exposed to VISUALIZATIONS in VR combined with different HAPTIC STIMULI on their arm. The order of the conditions (combination of stimuli) was randomized for each participant respectively to reduce learning and carry-over effects. Each combination of a HAPTIC STIMULUS and VISUALIZATION was presented at least four times, which corresponded to two back-and-forth movements along the length of the arm. However, participants were given the option to repeat an actuation before proceeding to the next. At the end of each condition, we showed the questionnaire on a virtual wall in front of the participants, which they had to answer with the VR controller in their right hand. Additionally, the participants could provide optional verbal feedback, which was noted down by the experimenter. Once a participant was ready, the next condition started.

After the study: After participants finished all 99 conditions, they could take off the HMD and *Guiding Rail*. They were then asked to fill out the final questionnaire and a demographics survey. Additionally, participants were invited to discuss the experiment for supplementary qualitative feedback. Throughout the whole experiment, participants were allowed to pause or stop the experiment at any time. On average, the procedure took 90 minutes per participant.

[11]HP Reverb G2 HMD of current generation

5.3.1 *Hygienic Measures.*
Extended hygienic measures were approved prior to the experiment by the health department of our institution and in line with the latest governmental measures. All individuals had to sanitize their hands at the beginning of the study and wear medical masks throughout the study. All materials, the HMD, and other contact surfaces were sanitized before and after each participant. The study room was ventilated and there was an additional ventilation break of at least 30 minutes between each participant. All experimenters were fully vaccinated and tested regularly for Covid-19[12].

5.4 Participants
We recruited 31 participants (17 female, 14 male) between 18 and 50 years (M=28.7, SD=5.4). 9 of them had no experience with VR while 16 used it a few times before. 4 users stated to be a regular and 2 to be a proficient VR user. 4 participants used the 0 mm, 14 the -1.5 mm, and 13 the -3 mm *Guiding Rail*. Besides snacks and drinks, no compensation was provided.

5.5 Data Analysis
We performed the following statistical analyses:

(1) Aligned Rank Transform (ART): For analyzing the responses of the questionnaires during the study (Q1-Q5), we performed a non-parametric analysis using the Aligned Rank Transform (ART) procedure [22, 110] using mixed-effects models as employed by the *ARTool*[13]. To assess the significance of the fitted model, *ARTool* uses the Kenward-Roger method to approximate the degrees of freedom (*Type III Wald F tests with Kenward-Roger df*). For post-hoc tests, we used the ART-C procedure as proposed by Elkin et al. [22] which was shown to have "more statistical power than a t-test, Mann-Whitney U test, Wilcoxon signed-rank test, and ART" [22]. While Elkin et al. found that "ART-C does not inflate Type I error rates, unlike contrasts based on ART" [22], we acknowledge that there is a debate that a high cell count in ART in general might inflate Type I errors [69]. Therefore, we included an additional Bayesian analysis together with the ART evaluation to the supplementary materials.

(2) Cumulative Link Mixed Models (CLMM): To identify influences of the *perceived haptic roughness* (Q1) and *perceived visual roughness* (Q2) on the *matching* of HAPTIC STIMULI and VISUALIZATIONS (Q3), as well as the influences of the *perceived haptic roughness* (Q1) and *matching* (Q3) on the *pleasantness* (Q5), we fitted a *cumulative link mixed model* (CLMM) using the Laplace approximation. Therefore, we report the results of ANOVA and, as a measure of goodness-of-fit, we calculated the $pseudo{-}R^2$.

(3) Friedman's test and Wilcoxon Rank-Sum tests: For analyzing the post-questionnaires assessing the overall enjoyment and realism, as well as for a comparison of the *matching ratings* (Q3) with the *expected matching*, we performed Friedman's test with Bonferroni-corrected Wilcoxon rank-sum tests for post-hoc comparisons.

[12] *SARS-CoV-2 antigen rapid test*

[13] https://cran.r-project.org/web/packages/ARTool/readme/README.html

6 RESULTS
In the following, we present the analysis of our results from the evaluation per each dependent variable.

6.1 Perceived Haptic Roughness (Q1)
The analysis revealed significant main effects of the HAPTIC STIMULUS on the *perceived haptic roughness* ($F_{8,2941} = 361.68$, $p < .001$). Post-hoc tests confirmed significant effects for almost all HAPTIC STIMULI contrasts (*silicone*-*no-haptics* and *medium*-*rough* p <.01, other p <.001, except *vibrotactile*-*real* and *silicone*-*smooth* p >.05). Although participants showed a good ability to distinguish between different roughness, the data revealed that levels with a higher roughness a similar perceived roughness (*medium*, *rough*, and *very rough* with $\tilde{x} = 4$).

Significant effects of the VISUALIZATION on the *perceived haptic roughness* were found ($F_{10,2941} = 6.71$, $p < .001$). However, post-hoc tests only confirmed significant effects for some contrasts with higher anticipated mismatch regarding this questionnaire item, such as *no-visuals*-*finger*, *cotton*-*finger*, *spoon*-*finger*, *toothbrush*-*rock*, and *toothbrush*-*sandpaper* (all p <.05), as well as *no-visuals*-*rock*, *no-visuals*-*sandpaper*, *silk*-*rock*, *silk*-*sandpaper*, *spoon*-*rock*, *spoon*-*sandpaper*, *cotton*-*rock*, and *cotton*-*sandpaper* (all p <.001).

The analysis also found significant interaction effects between HAPTIC STIMULI and VISUALIZATIONS ($F_{80,2941} = 5.46$, $p < 0.001$). The ratings of the *haptic roughness* are depicted in Figure 6a.

6.2 Perceived Visual Roughness (Q2)
The analysis unveiled that the VISUALIZATIONS had a significant effect on the *perceived visual roughness* ($F_{10,2941} = 733.32$, $p < .001$). Post-hoc tests confirmed significant effects for almost all VISUALIZATIONS except five (*no-visuals*-*sponge* and *toothbrush*-*rock* p <.05, others p <.001, except *silk*-*spoon*, *silk*-*cotton*, *spoon*-*cotton*, *branch*-*rock*, and *steel wool*-*sandpaper* with p >.05). Comparing the medians of each VISUALIZATION, we could observe an almost identical rating of the perceived roughness and the expected roughness from the pre-study. However, we found a shift by one point for the *cotton* towards *very smooth* ($\tilde{x} = 2$ towards $\tilde{x} = 1$) and *sponge* towards *smooth* ($\tilde{x} = 3$ towards $\tilde{x} = 2$). The *no-visuals* baseline was largely rated as neither *smooth* nor *rough* ($\tilde{x} = 3$).

The analysis did not reveal any significant effects for the HAPTIC STIMULUS ($F_{8,2941} = 0.93$, $p > .05$) nor any interaction effects ($F_{80,2941} = 0.46$, $p > .05$). The ratings of the *visual roughness* are depicted in Figure 6b.

6.2.1 *Confirming suitability of selected Visualizations.*
The ratings of the *perceived visual roughness* could show that the selected VISUALIZATIONS were equally distributed and in alignment with the roughness ratings of the same items in the pre-study (as also visible by comparing each column of Figure 6b). Although there was a slightly lower perceived visual roughness for the *cotton* and *sponge*, the results still confirmed that the selection of the ten VISUALIZATIONS covered all five defined levels of roughness, indicating a largely persistent expectation on the roughness.

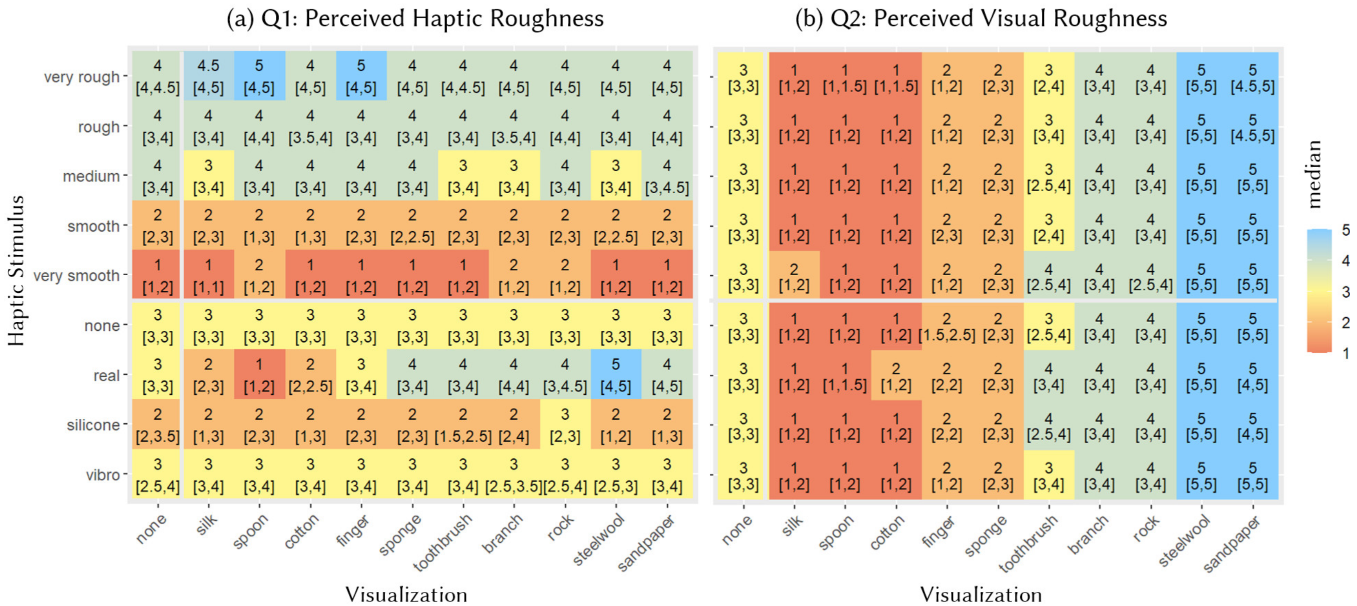

Figure 6: Heatmap representation of the results on (a) the perceived haptic, Q1, and (b) the perceived visual roughness, Q2. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

6.3 Matching of Haptic and Visual Stimuli (Q3)

We found a significant main effect of the HAPTIC STIMULUS on the *matching of both stimuli* ($F_{8,2941} = 148.58$, $p < 0.001$). Post-hoc tests confirmed significant effects for all HAPTIC STIMULI involving the *real* material (p <.001), between *very rough* and *no-haptics*, *vibrotactile*, *smooth* and *real* (all p <.01), as well as between *no-haptics* and *silicone*, *very smooth*, *smooth*, *medium* and *rough* (all p <.001). Significant effects were also found for all *vibrotactile* contrasts except *no-haptics* (p >.05, all others p <.001).

The analysis further revealed significant effects for the VISUALIZATION ($F_{10,2941} = 26.91$, $p < 0.001$) and post-hoc tests revealed significant effects for all *no-visuals* contrasts (all p <.001), except for the *finger* (p >.05).

Moreover, we could identify significant interaction effects ($F_{80,2941} = 19.44$, $p < 0.001$). The ratings of the *matching* are depicted in Figure 7a.

6.3.1 Influence of Haptic and Visual Roughness on Matching. We fitted a *cumulative link mixed model* (CLMM) to predict the *matching* (Q3) with the roughness of HAPTIC STIMULI (Q1) and VISUALIZATIONS (Q2). The model included the participant as random effect ($N = 31, SD = 0.55$). The measures of goodness-of-fit were calculated as $pseudo\text{–}R^2_{McFadden} = 0.209$ and $pseudo\text{–}R^2_{Nagelkerke} = 0.499$. An analysis of variance based on mixed ordinal logistic regression indicated no statistically significant effect of Q1 on Q3 ($\chi^2(4, N = 31) = 0.00, p > .05$) or of Q2 on Q3 ($\chi^2(4, N = 31) = 0.00, p > .05$). However, there was a statistically significant interaction of $Q1 \times Q2$ ($\chi^2(16, N = 31) = 1834, p < .001$).

6.3.2 Comparison to Expected Matching. In order to examine if the matching ratings from the participants in the study are in alignment with our initial expectations of how stimuli should match, we grouped all VISUALIZATION-HAPTIC STIMULUS pairs[14] that had a maximum median deviation of ±1 regarding their visual and haptic roughness and hypothesized that those are *expected matching*. In contrast, pairs with a median deviation > ±1 were marked as *expected non-matching*. All baselines were categorized in individual groups (as introduced in 5.1.2). Friedman's test indicated significant effects ($\chi^2(5) = 125, p < .001$) and Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects between pairs with an *expected matching* and *expected non-matching* confirming our hypothesis (p <.001, $\tilde{x}_{matching} = 4$, $\tilde{x}_{non-matching} = 2$). We further found significant effects for all other groups except for *vibrotactile*-*expected non-matching*, *vibrotactile*-*no-haptics* and *expected matching*-*real* (all three p >.05, all others p <.05; $\tilde{x}_{none} = 1$, $\tilde{x}_{real} = 4$, $\tilde{x}_{silicone} = 3$, $\tilde{x}_{vibro} = 1$).

6.4 Real-World Consistency (Realism, Q4)

The analysis showed significant main effects for the HAPTIC STIMULUS ($F_{8,2941} = 149.85$, $p < .001$). Post-hoc tests showed significant differences for all contrasts involving the *real* material (all p <.001) and for the *no-haptics* contrasts (p <.001), except for *vibrotactile* (p >.05, all other contrasts including *vibrotactile* p <.001). Significant effects were also found for *smooth*-*very rough* (p <.001), *smooth*-*silicone* (p <.01) and *smooth*-*medium* (p <.05).

We also found significant main effects for the VISUALIZATION ($F_{10,2941} = 26.36$, $p < .001$). Post-hoc tests revealed significant

[14] including only the five level of roughness; the baselines were treated as individual groups

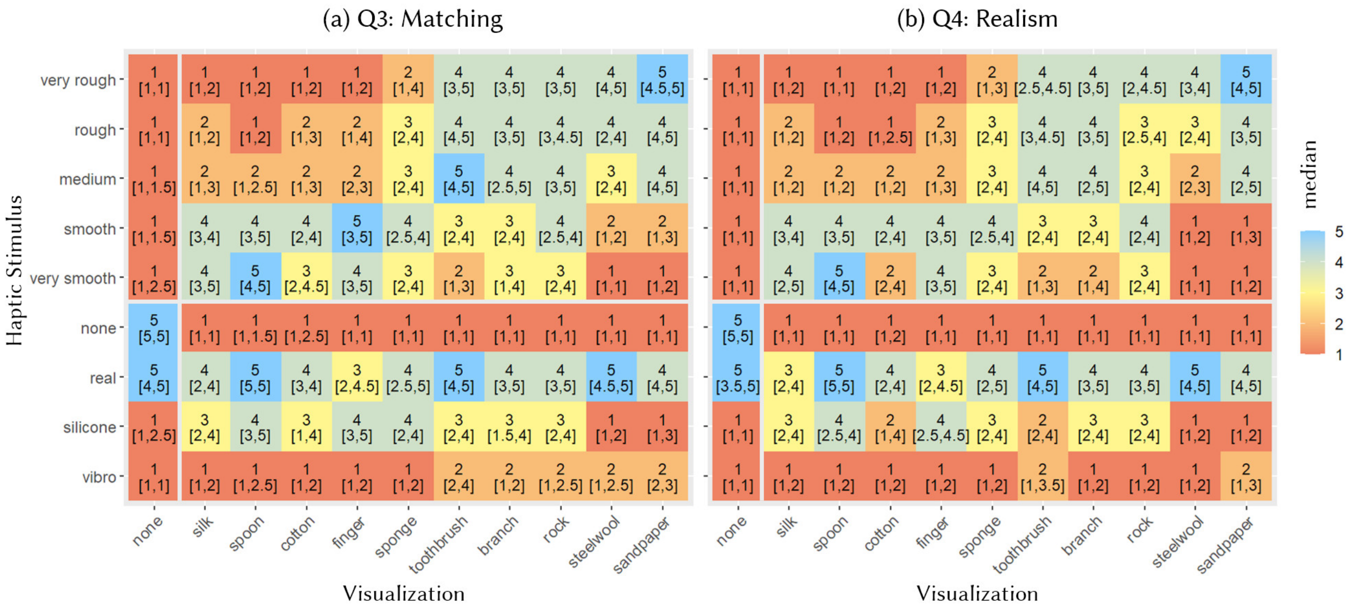

Figure 7: Heatmap representation of the results on (a) the matching, Q3, and (b) the realism rating of each combination of a Haptic Stimulus and a Visualization, Q4. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

differences for all contrasts involving the *no-visuals* baseline (all p <.001) except for *cotton* (p >.05). However, there were significant effects between the *cotton* and *spoon*, *sponge*, *toothbrush*, *branch*, *rock*, *sandpaper* and *finger* (all p <.001)Other significant effects were found for *spoon*-*silk*, *spoon*-*steel wool* (both p <.05), *spoon*-*toothbrush* (p <.01), and between *silk* and *toothbrush*, *branch*, *rock* and *sandpaper* (all p <.001), as well as for *finger*-*toothbrush*, *toothbrush*-*sponge*, *toothbrush*-*steel wool*, *steel wool*-*branch*, *steel wool*-*sandpaper* and *finger*-*vibrotactile* (last p <.01, rest p <.001).

Again, the analysis showed significant interaction effects between Haptic Stimuli and Visualizations ($F_{80,2941} = 18.75$, $p < .001$). The ratings of the *matching* are depicted in Figure 7b.

6.5 Pleasantness (Q5)

We found significant effects for the Haptic Stimulus on the pleasantness rating ($F_{8,2941} = 117.2$, $p < .001$. Post-hoc tests revealed that almost every contrasts had significant differences, most with p <.001, except for *vibrotactile*-*rough*, *vibrotactile*-*very rough*, *silicone*-*real*, *silicone*-*smooth*, *no-haptics*-*medium*, and *medium*-*rough* (all p >.05).

We observed significant effects for Visualization ($F_{10,2941} = 2.85$, $p < .01$). However, post-hoc tests only revealed significant differences between *toothbrush* and *no-visuals* and *sandpaper* (both p <.01), as well as *spoon*, *finger* and *steel wool* (all p <.05). Lastly, we found significant interaction effects ($F_{80,2941} = 2.22$, $p < .001$). The ratings of the *pleasantness* are depicted in Figure 8.

6.5.1 *Influence of Haptic Roughness and Matching on Pleasantness.*

After reviewing the data, we expected the pleasantness to be also dependent on the *matching* rating with the ratings of the *haptic roughness perception*. Therefore, we fitted a *cumulative link mixed model* (CLMM) to predict the *pleasantness* (Q5) with the *haptic roughness* (Q1) and *matching* (Q3) ratings. The model included the participant as random effect ($N = 31, SD = 0.86$). The measures of goodness-of-fit were calculated as $pseudo{-}R^2_{McFadden} = 0.202$ and $pseudo{-}R^2_{Nagelkerke} = 0.472$. An analysis of variance based on mixed ordinal logistic regression indicated no statistically significant effect of Q1 on Q5 ($\chi^2(4, N = 31) = 0.00, p > .05$) or of Q3 on Q5 ($\chi^2(4, N = 31) = 0.00, p > .05$). However, there was a statistically significant interaction of $Q1 \times Q3$ ($\chi^2(16, N = 31) = 31.98$, $p < .05$).

6.6 Post-Questionnaire: Overall Enjoyment and Realism

Participants were asked to rate the *haptic strokes*, *vibrotactile* feedback, and *no-haptic* feedback in the post-questionnaire with regards to the overall *enjoyment*. Here, participants rated *haptic strokes* as best ($\tilde{x} = 4$), followed by *no-haptic* ($\tilde{x} = 3$), and *vibrotactile* ($\tilde{x} = 2$, Figure 9a). Friedman's test showed significant results ($\chi^2(2) = 24.3$, $p < .001$) and Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects for *haptic stroke-no-haptic* and *haptic stroke-vibrotactile* (both p <.001). No significant effects were found for *no-haptic-vibrotactile* (p >.05). In general, the majority of the participants responded to enjoy the whole experiment (12 strongly agreed, 14 agreed, 3 neither agreed nor disagreed, and 2 disagreed, $\tilde{x} = 4$).

As for the overall *realism* between the three modalities, *haptic strokes* were ranked first ($\tilde{x} = 4$), followed by *vibrotactile* ($\tilde{x} = 3$), and *no-haptic* feedback ($\tilde{x} = 2$, Figure 9b). Friedman's test found

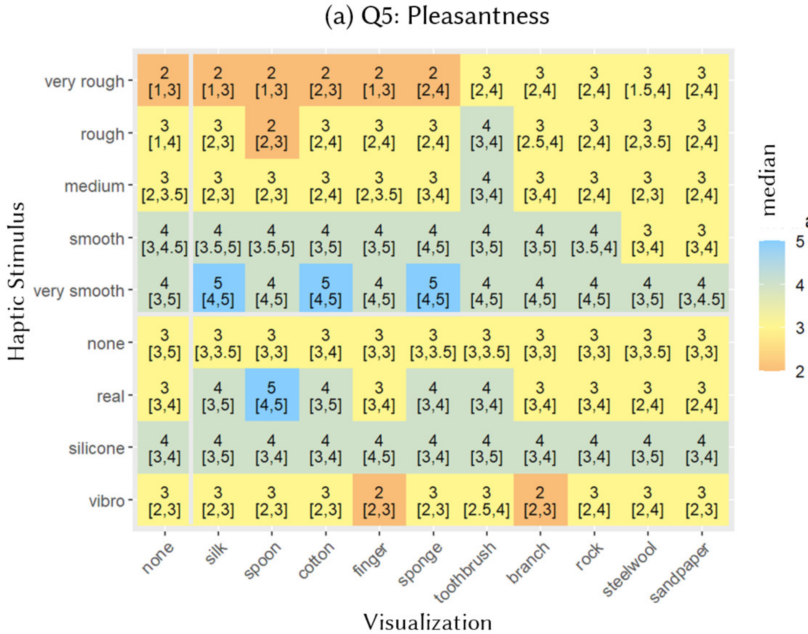

Figure 8: Heatmap representation of the results on the pleasantness, Q5. Each cell contains the median rating and the 1st and 3rd quartile in brackets. The horizontal line separates the five physical textures (top) from the four baselines (bottom).

significant results ($\chi^2(2) = 21.4$, $p < .001$. Bonferroni-corrected Wilcoxon rank-sum post-hoc tests revealed significant effects for *haptic stroke-no-haptic* and *haptic stroke-vibrotactile* (both p <.001). No significant effects were found for *no-haptic-vibrotactile* (p >.05).

The majority of the participants responded to be able to identify haptic textures reliably over all conditions (6 strongly agreed, 13 agreed, 10 neither agreed nor disagreed, and 2 disagreed, $\tilde{x} = 4$). Also, the consensus was that the whole experiment was pleasant (12 strongly agreed, 13 agreed, 3 neither agreed nor disagreed, and 3 disagreed, $\tilde{x} = 4$).

6.7 Subjective Feedback

The experiment was overall well-received, especially if "the haptic fitted to the visualization" (P29, P20). P21 explained to have "*wow* moments when it already closely match the object". This also showed in multiple participants describing the haptic stroke sensation as "realistic" (P15, P21, P23, P24, P27, P29), "very convincing" (P31), and even "increases the immersion when the haptic feedback matches the scene" (P2). In particular, participants liked "when the object feels as expected and seemed real" (P10) and "the haptic stroke matched the visual object" (P19). Interestingly, P29 said that "the haptic also influenced my expectations towards the object" and "concluded additional information (wet sponge, cold hands)". Contrary, non-matching stimuli were reported as unpleasant or "weird" (P16). P26 described it felt "less realistic [..] and also felt much more uncomfortable" when "very rough haptic stroke feedback was felt for very smooth looking objects". Confirming the analysis, rougher textures were usually considered as more unpleasant (P25, P27) but had more positive feedback if roughness was matching (P9, P17, P25).

For P14 it was "super exciting to see how the visual appearance changed in imagination when the haptic feedback was unexpected". For P8 it was "an interesting challenge to try to identify what is touching you" and P10 said that "you could forget for a moment that you are in VR due to the well-depicted objects".

Although the study focused on the roughness of haptic stimuli and visualizations, some participants also reported feedback for other characteristics, such as the temperature. For example, P5, P6, P7 and P15 highlighted that materials, such as the *real spoon*, felt more cooler, and P11 stated that a matching temperature "fits to the expectation".

Most negative comments were related to the *vibrotactile* feedback as "it was just not a nice feeling" (P9) and "felt unrealistic" (P19) or "unnatural" (P20). In terms of roughness, there was a tendency of describing it as rough or scratchy rather than smooth (P17, P22, P27). However, participants described the vibration as quite fitting for a toothbrush, if it had been electric (P7, P9, P11, P13, P20, P21), or a virtual smartphone notification (P2), and P21 perceived it as "small electric impulses when you are in love" (P21).

If there was no Haptic Stimulus, participants were often unsure how to respond. For example, P10 stated that "nothing touched me, but I don't know" and P21 described it as "Fake? I have the impression that I feel something, although there was nothing there". However, in some cases even the *no-haptics* stimulus was somewhat convincing, e.g., P20 described "I felt nothing, but it was still kind of a match because it seemed so light."

7 DISCUSSION

The results of our controlled experiment indicate that the visual expectation of roughness is affecting the haptic perception to a

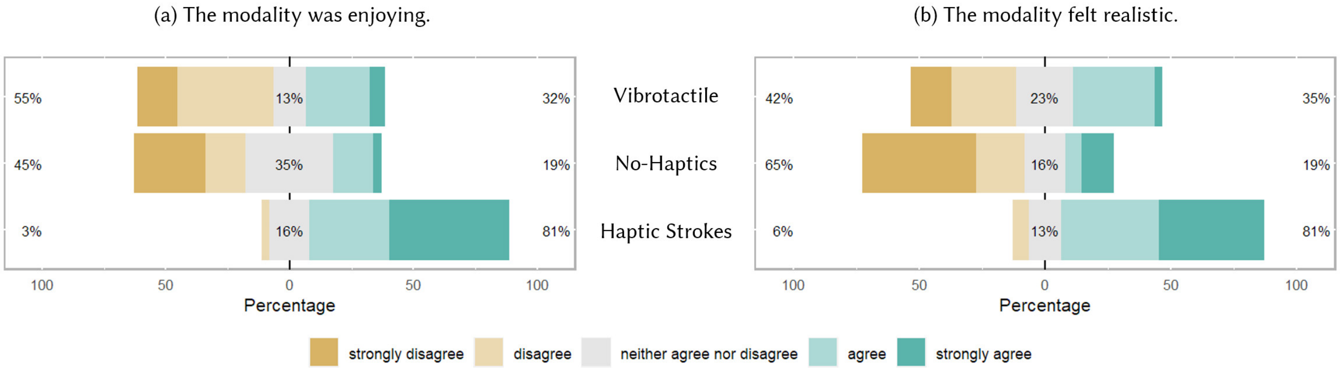

Figure 9: Likert responses of the post-questionnaire asking for (a) the enjoyment, and (b) the realism comparing vibrotactile, no-haptic, and haptic stroke feedback.

degree that a *smooth* and *very rough* texture can be sufficient enough to convey matching and realistic experiences. Further, we found that the pleasantness is not only depending on the roughness of a physical texture but is also influenced by the matching of stimuli. In the following, we will discuss our findings in more detail.

7.1 Two distinct Textures can be sufficient for a Matching and Realistic Experience

Our results have shown that it is possible to fully convey all ten visualizations with only two levels of roughness (*smooth* and *very rough*). While we observed that different rough textures of Haptic Stimuli can be accurately discriminated, the mere expectation about the roughness of a Visualization is sufficient enough to blur the boundaries of haptic perception. Across all visualizations, we were able to produce a high matching and estimate of realism with only two physical textures in a similar quality to the Visualizations' real-world counterparts. In other words, participants seemed to distinguish the haptic sensation only in binary relation whether something feels smooth or rough, and adjusted their expectations and perception accordingly. In particular, the two rough textures (*rough* and *very rough*) were consistently close in their perception. Smoother textures were also rated similar, however, differences between *smooth* and *very smooth* were slightly more visible. For example, the *very smooth* texture during the *spoon* visualization (visually *very smooth*) was perceived to be closer to a *smooth* texture, further emphasizing our hypothesis of the binary selection process.

For future haptic systems, this means that we do not necessarily need to provide a large variety of physical textures with different levels of roughness in order to create an immersive experience in VR. As such, haptic devices can be kept more compact by using only two textures of different roughness and still provide a realistic experience for a broad range of virtual objects. Furthermore, this leaves additional space in wearable devices to include other material characteristics, such as temperature or hardness.

7.2 The Expectation of a Visualization's Roughness adapts to the Haptic Stimulus

Complementary to the previous subsection, some Visualizations (*sponge*, *toothbrush*, *branch*, and *rock*) were rated as equally matching across several haptic levels of roughness. For these four Visualizations, the visual expectation was mentally classified correctly, however, as soon as the Haptic Stimulus was perceived, the perceived visual roughness readjusted, although the Visualization remained unchanged. This led to situations, where some participants mentioned, e.g., that a rock could be both, *smooth* or *rough*. We think that this occurred especially because it could also be interpreted as a somewhat angular pebble, although the visualization of the *rock* was edgy and sharp. Similarly, other objects, such as the *branch*, were also convincing (matching) despite having the same appearance but when applying different haptic stimuli. Again, participants described both, rough and smoother stimuli, as matching, as the bark of the *branch* might be scratchy or slightly flattened, e.g., depending on the type, dryness, or age of the wood. Further, both examples were items that occur in nature in a wide range of variations and were, therefore, well known in different forms. Although the mental models and roughness expectations were similar purely on the basis of visual appearance (cf. results of the pre-study and Section 6.2), more atypical smooth stones or branches were also considered as realistic since they also occur naturally.

In contrast, objects such as the *steel wool* or *spoon* were perceived less variably as the expectation seems to be stronger here. The *steel wool* was always described as very rough and scratchy, and when asked, no participant could imagine that it could also be smooth. The *spoon* (or its bottom side), on the other hand, only worked with smoother haptic stimuli, since here the known expectation corresponds to just such a smooth surface (a very rough *spoon* is rather untypical since it could injure the oral cavity, and a rusty *spoon* would, however, be recognizable due to the changed appearance).

As a consequence, this means that the Haptic Stimulus can override the roughness expectation without negatively affecting the matching or realism. As an implication for future applications, objects of the same type but with different visual appearances could be actuated using the same Haptic Stimulus and will still fit the expectations of users.

7.3 Pleasantness depends on Roughness and Matching

In general, *smooth* stimuli are perceived as more pleasant compared to *rough* stimuli which is in aligned with related work [26]. However, we found that the extent of matching between Haptic Stimuli and Visualizations has an influence on pleasantness as well. In particular, we observed that a high matching rating has positively affected the pleasantness even if the Haptic Stimulus is *rough*, e.g., for the *toothbrush*. On the other side, a lower matching lets participants perceive the same *rough* Haptic Stimulus as significantly more unpleasant. Similarly, a *very rough* texture was typically perceived less pleasant for *very smooth* or *smooth* Visualizations than for expected *rough* or *very rough* Visualizations. Vibrotactile feedback, however, was mostly reported as non-matching which was reflected in a general lower perceived pleasantness.

Potential future devices therefore might convey pleasantness and unpleasantness by providing matching and non-matching Haptic Stimuli without altering visual appearances. However, as we could observe that textures with different levels of roughness are distinguishable but tend to be aggregated as a whole, we would recommend using only a *rough* texture instead of a *very rough*, which has a slightly lower realism rating but feels more pleasant.

7.4 Prefer Physical Textures over Vibrotactile over no Haptics

Haptic strokes using either a physical texture or the real-world material were considered as more enjoying and realistic. *Vibrotactile* feedback, in contrast, was considered largely negative due to a less matching experience. Also, participants sometimes were uncertain what they perceive but could still describe a moving vibration. Still, vibrotactile feedback was reported to be more favorable than the *no-haptics*, supporting results from literature (e.g., [28]). Interestingly, during early trials, participants were often uncertain if *no-haptics* was really a non-existent Haptic Stimulus. This suggests, if participants are in a more distracting environment, a haptic actuation may not be required. Also, we expect that the benefits of a vibrotactile actuation will persist until true haptic actuation is more feasible and wearable.

8 LIMITATIONS AND FUTURE WORK

We are convinced that our results provide valuable insights into the perception of roughness in VR. However, there remain some limitations and potential directions for future work.

8.1 Selection of Visualizations and Textures

We carefully selected a set of Visualizations and Haptic Stimuli during pre-studies covering a broad spectrum of objects with different levels of roughness. However, as the pre-study for the selection of the Visualizations only provided descriptions without showing any visual examples, it is possible that some participants might not have had a precise conception of some of the 50 objects. Yet, during the evaluation it became apparent that these objects had a high dispersion of the responses and were therefore not considered for the Visualizations of the main study. For the 10 final Visualizations used in the main study, the results could show that those shared a common expectation across the participants (cf. Section 6.2.1). Still, the final Visualizations and Haptic Stimuli remain just a subset of almost infinite possibilities. Also, while it might not be always typical to *feel* a spoon or steel wool on the arm, all visualizations were chosen based on the idea that people are familiar with it (typically felt them in the hand or even on the body) and, therefore, have an expectation of their roughness characteristics. For future work, however, it will be interesting to investigate further to which degree our results apply to other items and how the combination of simultaneous stimuli might affect haptic perception.

8.2 Other Object Characteristics

In our experiments, we focused on the roughness of objects which is essential for haptic perception [65]. Therefore, we tried to minimize the influence of other characteristics as much as possible. For example, as the temperature can affect the pleasantness [35, 107], we provided all materials with the same temperature at room level. Due to the thermal conductivity of the materials, they all felt similarly warm except for the real-world spoon that was perceived colder by participants, even while having the same temperature. Regarding the hardness of real-world objects, we tried to have always one material on the more harder side, and one on the softer side for each level of roughness. Stickiness was similar among all materials and textures, however, we reduced the stickiness of the silicone finger by applying magnesia chalk. Additionally, while similar experiments in HCI have been conducted for the perception of visuals on temperature [13, 27, 35], further research is necessary for the remaining aspects, such as the hardness, stickiness, or combinations of them. Also, as the spatial resolution on the arm is rather low [71, 95], it will be interesting to investigate how spatially accurate a haptic actuation within VR has to be to still convey a realistic illusion (similar to [116]).

8.3 Affective Responses

The focus in this work lied on the *discriminative* aspects of *passive touch* and we mostly included static objects as Visualizations. However, we intentionally included the *fingertip* as it is typical for caress and *affective* response. Due to the setup, though, we were unable to use a real finger for the real-world baseline, as this would not have guaranteed that the physical and virtual movements would be performed at the same velocity and consistent intensity. As a result, the matching and realism were considered as rather low for the silicone finger. Interestingly, however, the *Silicone Cushion* without a texture performed more positively and was perceived as *smooth* with high matching.

8.4 Pleasantness over Time

The pleasantness of the full experiment was reported as positive. However, the study took 90 minutes on average, leading to a high density of physical strokes on the arm. This might have resulted in skin fatigue and, thus, lower pleasantness or higher roughness rating over time. However, when designing the study, we tried to mitigate negative effects by randomizing the condition order for each participant. Therefore, we also compared variations of the median ratings of pleasantness and perceived haptic roughness between each trial. Here, we could only observe a minor trend for lower pleasantness and higher haptic roughness ratings (less than 0.5 between the first and last trials). Although this small effect could still be a coincidence due to the condition order, prolonged exposure to the haptic stimuli could cause greater fatigue or even sensory over-stimulation. Therefore, further research is necessary to better understand how the density and intensity of physical strokes over a longer period of time affect the perception.

8.5 Applicability for Active Touch

While this work focused on *passive touch* that is related to being touched, the general idea could be also transferred to *active touch*. However, as both rely on different skin types with different discriminative traits (*hairy* and *glabrous* skin), the parameters for *active touch*, which is mostly performed with the own hands, probably need to be largely different, e.g., by using more fine-grained textures. As such, applying these concepts to *active touch* might have different outcomes and further research is necessary.

8.6 Technical Limitations

From a technical perspective, our system reliably conveyed stroking stimuli on the skin. However, while the *Guiding Rail* allowed for a compensation of slight arm movements, the setup was stationary. This made observations and focusing the attention for participants more robust but not wearable for future systems. Also, textures were glued onto the *Silicone Cushion*s in order to provide different levels of roughness. While suitable for the experiment, future systems should embed rough structures directly on the actuators. For example, we initially planned to cast rough textures directly in the *Silicone Cushions* (e.g., [112]), however, first tests showed that this could not render textures rough enough. Still, we are confident that our results can support smaller designs that fit directly into wearable devices for VR.

9 CONCLUSION

In this work, we investigated how users *discriminatively* perceive haptic and visual stimuli in VR during *passive touch* on the example of texture roughness. During a controlled experiment, we found significant evidence of how the roughness expectation of visualizations affects the haptic perception. With only two physical textures (*smooth* and *very rough*), we could convey a matching and realistic illusion of being touched by all visualizations. Our results further indicate that some visualizations are also matching for many different levels of roughness, even if they are discriminated differently. Additionally, we found that the pleasantness is influenced by the haptic roughness and the matching of stimuli.

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