Enhancing Texture Perception in Virtual Reality Using 3D-Printed Hair Structures

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ABSTRACT

Experiencing materials in virtual reality (VR) is enhanced by combining visual and haptic feedback. While VR easily allows changes to visual appearances, modifying haptic impressions remains challenging. Existing passive haptic techniques require access to a large set of tangible proxies. To reduce the number of physical representations, we look towards fabrication to create more versatile counterparts. In a user study, 3D-printed hairs with length varying in steps of 2.5 mm were used to influence the feeling of roughness and hardness. By overlaying fabricated hair with visual textures, the resolution of the user's haptic perception increased. As changing haptic sensations are able to elicit perceptual switches, our approach can extend a limited set of textures to a much broader set of material impressions. Our results give insights into the effectiveness of 3D-printed hair for enhancing texture perception in VR.

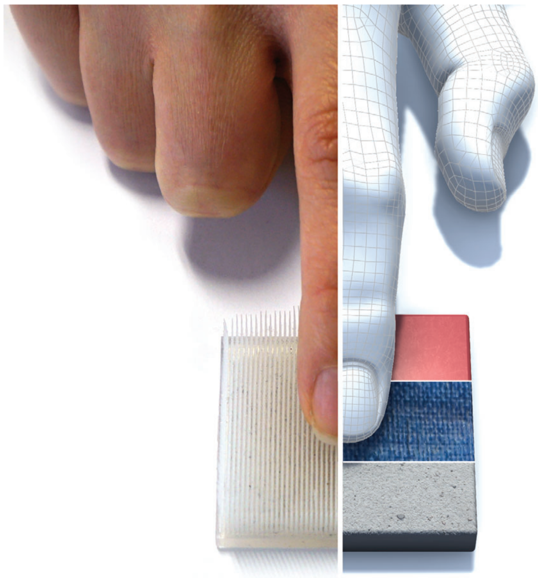

Figure 1: Augmenting texture perception by overlaying a physical structure with different virtual textures.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; *Haptic devices*; Virtual reality;

KEYWORDS

texture perception; passive haptic feedback; 3D printing

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1 INTRODUCTION

In virtual reality (VR), users can experience virtual worlds in an immersive way. When done right, one can feel *present* therein and respond realistically to events experienced in the immersive virtual environment (IVE) [23]. To support the feeling of presence, the plausibility of the experienced IVE is a crucial factor. As we are used to concurrently experiencing the real world through multiple modalities, high expectations are placed upon interacting with virtual scenes. The system has to fulfill these requirements to a certain degree in order to maintain the illusion of the virtual environment.

State-of-the-art VR systems already provide extensive visual and auditory impressions of virtual scenes, but lack in providing realistic haptic impressions. In literature, different approaches have been investigated to support haptic feedback beyond standard hand-held controllers. One such technique called passive haptics [11] enables users to touch and feel their virtual surroundings through passive haptic proxy objects. There props are physical representations of virtual objects, typically registered in a 1-to-1 fashion. A naïve implementation of passive haptics requires virtual objects with varying materials to be represented by the same number of physical objects with corresponding materials.

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While this technique can provide highly realistic haptic details, it remains bound by several limitations. As continuous synchronization of physical and virtual objects is required for every change in the virtual environment, it is inherently inflexible. Additionally, when IVEs consist of large numbers of objects each with their own different surface material, scaling issues arise as the required collection of physical materials to equip proxies with increases rapidly.

Our aim is to counter the limitations of passive haptics by looking towards novel fabrication techniques for constructing more flexible proxy objects. Similar to the evolution of the paper printer, 3D printers will take their place into the everyday lives of consumers. As the resolution of these printers is already high enough to produce rich and fine-grained tactile structures, they have the potential to extend IVEs with customized haptic feedback. To this intent, we explore the design of 3D-printed hair structures to serve as versatile proxy surfaces for influencing texture perception.

In this work, we present a user study in which we used hair samples of different lengths overlaid with visual textures to investigate the users' perception of virtual materials in VR. Our results describe how participants experienced both virtual and haptic textures separately and how both modalities are influenced through mixed visual-haptic combinations. We discuss practical findings for the future of fabricating passive haptic feedback.

2 RELATED WORK

In the following section, we provide an overview of work related to our investigation.

Haptic Feedback for Virtual Reality

To ensure interactions in virtual environments remain plausible and intuitive for users, VR aims to replicate real world sensations. Interactive VR, thus, needs to include haptic feedback in line with visual and auditory stimulation of the user [25]. Research distinguishes three basic types of haptic feedback for VR, namely active, passive and mixed approaches.

Active haptic approaches rely on computer-controlled actuators that exert forces onto the user [25]. An early example is the PHANToM [17] device equipped with an actuated stylus able to render forces. Major consumer-grade VR systems primarily use hand-held controllers with vibrotactile actuation for haptic effects. Active haptic approaches typically suffer from a limited workspace, comparably high computational and mechanical complexity, high costs and potential safety issues, as failure may harm the user.

The technique most relevant to our work is passive haptic feedback [8, 11]. Here, physical objects are spatially registered to virtual objects to provide touch feedback in IVEs. When reaching out to touch a virtual object, the user touches a corresponding physical prop to experience appropriate feedback. While perfect replicas provide the most realistic haptic feedback, in practice, discrepancies in shape, size, weight, or texture are unavoidable. Their influence in various dimensions has been investigated [12, 14, 22, 33]. Often, visual feedback can compensate for different extents of discrepancy. Kitahara et al. [12] considered how several different haptic surfaces are perceived when overlaid with virtual textures in an augmented reality setup. Using mixed sensory input, they focused on the properties of hardness and edge sharpness, while also considering the perception of texture. However, their work used a fixed set of materials and did not consider fabricated physical surfaces. We focus on physical hair structures and their fabrication to influence tactile surface properties.

Mixed techniques such as dynamic passive haptic feedback [34] combine active and passive haptics by equipping passive proxies with actuating elements. Used at runtime, these elements modify the proxy's passive haptic properties, e.g., weight distribution [34]. Interesting for our work is the Haptic Revolver [30] which is able to dynamically switch the haptic material perceived by a user when touching a virtual object. Similarly, our approach could be dynamically presented in a mixed environment to improve the perception of virtual materials using passive 3D-printed hair samples. Further related concepts, such as robotic graphics or encountered-type haptics, build a robotic environment in which robotic arms hold passive proxy elements in front of the user at predicted touch locations [18, 27]. By swapping the prop held at the actuated arm, a single robot can provide feedback for many different objects [1]. Here, too, one can imagine combinations with 3D-printed hair structures.

Mixed Texture Perception

As the brain combines signals from all sensory channels to produce a coherent interpretation, perceptual channels are weighted differently in accordance to their reliability [5]. In the presence of mismatching stimuli, e.g., facing a visual-haptic mismatch in texture perception, vision plays an important role as it can dominate other senses. This effect is typically referred to as visual dominance. Gibson stated that the haptic perception of a physical shape is altered when perceiving the shape with distorting lenses [7]. More recently, Kohli [13] introduced redirected touching, a technique to enhance the reusability of passive haptic environments for VR by exploiting visual dominance. Here, the virtual space is distorted and visual geometries are mapped to discrepant physical objects [35]. During interaction, the user's hand is offset from the physical hand's location and users interact in the distorted space. This can enable users to perceive straight edges and surfaces as being curved. A similar technique influences the perception of weight as the virtual hand is offset while lifting objects [21]. In haptic retargeting techniques [2, 4], a user's perception is tricked such that a single physical proxy provides feedback for multiple differently shaped virtual objects. Visual dominance plays an important role in our investigation as we study how discrepant visual-tactile stimuli, i.e., physical hair structures overlaid with different visual textures, are perceived in VR.

Previous research on pseudo-haptics investigated the perception of stiffness of a virtual spring, and how different degrees of visual deformations of the object modify the perceived stiffness [16]. Moreover, research investigated the perception of textures in mixed reality (MR) environments using techniques that exploit the visual dominance effect [10, 26]. Figure 1 illustrates superimposing virtual texture images on top of physical textures. Iesaki et al. [10] state that although tactual impressions can be intentionally changed by providing appropriate visual stimulation, the coarseness of the visual and tactile textures have to be close to each other. In our study, we intentionally did not exclude cases with high discrepancies as we were also interested in the subjective impressions that would arise. Similarly, Hirano et al. [9] were interested in the psychophysical effects of influencing hardness through MR visual stimulation. They found that users sensed different hardnesses by emphasizing the dent deformation of an overlaid virtual animation. Building on this, Punpongsanon et al. [20] influence the user's perception of softness through visual cues when pressing a fixed object.Our work goes beyond the sensation of hardness by including roughness as a distinct feature for texture perception and explores the space of representable materials.

Personal Fabrication for Tactile Textures

Emerging from early research on rapid prototyping, the field of fabrication has grown to be more accessible through better and more affordable consumer electronics [3]. The promise of personal fabrication aims to provide "*the ability to design and produce your own products, in your own home, with a machine that combines consumer electronics with industrial tools*" [6]. Although high-end devices still remain outside the financial scope of the home environment, many affordable solutions for 3D printing exist. This enables the home user to create increasingly more complex and detailed physical objects from digital representations. As these technologies become more accurate and robust, the underlying digital to analog process can serve as an ideal opportunity to explore how fabrication can enrich VR experiences at home.

Research on the fabrication of tactile textures investigates the design of objects with a certain *feel* to them when touched. An intuitive approach is Haptic Print [29], a specialized tool which allows the user to apply a specified surface texture onto an object's surface such that the surface provides a predefined haptic feeling. Similarly, by increasing and decreasing the amount of material extruded during printing with a fused deposition modeling (FDM) printer, it is possible to control output thickness, creating aesthetic pattern sheets with a desired haptic feeling [28]. More recently, Yasu [32] describe a prototype to print magnetic patterns on the surface of magnetic rubber sheets which when rubbed together provide haptic stimuli. Another approach explores how objects can be augmented with fabricated 3D hair or bristles for both FDM [15] and stereolithography printers [19]. Our work builds upon the latter as our physical structures were created in a similar fashion.

Figure 2: A sample book to explore different fabrics.

3 HAIR-LIKE STRUCTURES FOR TEXTURE PERCEPTION

The following section introduces our approach to enhance texture perception in VR using 3D-printed hair structures.

Use Cases

Our aim was to investigate the perception in terms of roughness and hardness of combined visual and haptic sensations using fabricated structures. To test the appropriateness of potential fabrication designs, we motivated two use cases in which our approach could fit.

A customer looking to buy a couch uses a furniture store's mobile application to browse through their collection. The novel augmented reality (AR) functionality makes it easier to decide on size and color by visualizing the couch in the customer's living room. As sitting in a couch stimulates the tactile senses, its *feeling* in terms of fabric and material is extremely important. Similar to a fabric samples book available in stores (see Figure 2), the customer is able to explore different types of upholstery at home using a limited set of 3D-printed samples. Combined with visual information, each sample is able to convey a much larger set of materials.

An interior designer working on cars goes through an elaborate process to configure every small aspect according to the needs and requirements of the company. Physical prototypes give detailed visual and tactile impressions, but can become extremely expensive. Using VR, the designer

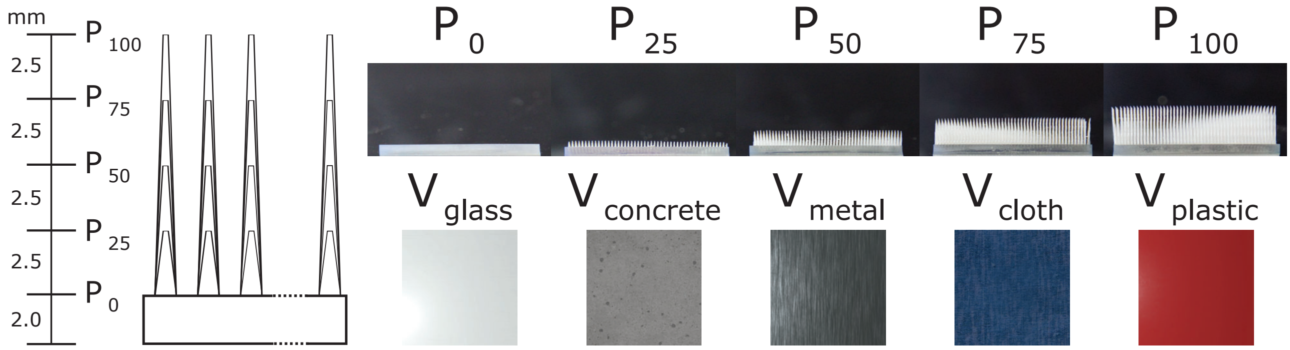


Figure 3: Overview of the five physical surfaces and five virtual textures used in our study. Note that the material used for glass is highly transparent and would reflect the environment.

is able to experience both visual aspects of 3D designs and tactile elements using passive haptic feedback. This approach is supported by fabricating tactile structures as they reduce the cost of the proxy objects while ensuring reconfigurability. Additionally, a varying set of material impressions is offered to potential customers at local car dealers.

3D-Printed Hair

During our initial exploration, we aimed to find a uniform structure which allowed a maximum of haptic variance in roughness and hardness, yet minimized the degrees of freedom in the print. After exploring a multitude of fabrication techniques and designs using different printers and materials, 3D-printed hair-like structures promised to be the most favorable haptic structures. While relatively easy to fabricate, we noticed changes in design directly influenced perceived tactile properties. After printing a large set of samples varying hair length, density and thickness, We found that decreasing the density or the thickness severely harmed the structural integrity of the design. An increase rapidly affected the flexibility of the hairs causing hardness to reach a plateau. The length of hair was found to be a crucial parameter strongly affecting tactile impressions. While short 3D printed hair conveyed a very rough and hard feeling, with increasing hair length samples grew smoother and at the same time softer. Thus, we designed and printed a set of hair structures to experimentally investigate during VR interaction.

Our set of hair-like structures (see Figure 3) was printed using an Autodesk Ember[1] with an X-Y resolution of 50 µm and a layer thickness of 25 µm. Our printing technique was based on the staircase approach described in [19]. The maximum length we could print reliably was 1 cm as longer designs would not produce uniform structures. To keep the experiment feasible with regard to time and user fatigue, we limited our final set of prints to 5 different samples with enough haptic variance. As an interesting extreme case, the first sample was a flat surface without attached hairs, i.e., a sample with hair length of 0 cm. Each subsequent structure increased the hair length by 2.5 mm. The structures were printed on a 800 px × 800 px (40 mm × 40 mm) base with a height of 2.0 mm. Each individual hair consisted of a 8 px × 8 px base, converging to a 2 px × 2 px top. Depending on its length, each hair print resulted in a growing cone-like shape. All hairs were spaced apart by 8 px, yielding a 50 × 50 grid.

[1]Autodesk Ember - https://ember.autodesk.com/

Augmented Virtual Textures

Based on the expected tactile feeling of the five tested hair samples, we chose five materials to be haptically augmented by them in VR. For every sample, we chose a representative texture that matched the anticipated feeling of the hair sample with regard to hardness and roughness. For the flat, hard and smooth sample without hairs (P_0), we chose *glass* as a representative texture. For the short-haired samples (P_{25}, 2.5 mm & P_{50}, 5 mm), we chose *concrete* and brushed *metal*, respectively. The decrease in hardness and roughness of the last two samples (P_{75}, 7.5 mm & P_{100}, 10 mm), we associated with a medium rough *fabric*, i.e., jeans, and the soft and smooth *plastic* of a balloon, i.e., latex. To improve recognizability, every texture's color hinted at its intended material. The virtual textures, seen in Figure 3, were purchased from various sources and imported into the Unity environment.

4 STUDY

In this section, we describe the design of the user study where we presented participants with different physical samples overlaid with different virtual textures in VR and recorded the perception of roughness and hardness.

Apparatus

We performed the user study in our lab. The hair structures, fabricated as described above, were attached in a clockwise manner on a circular wooden board. This board was raised in order to allow the placement of a Vive controller used for registration and tracking. A Leap Motion controller used for hand tracking, was statically positioned above the table facing downwards. This setup, shown in Figure 4, allowed participants to precisely hit a required hair structure without touching a different surface.

The virtual environment consisted of a virtual apartment model where the user was positioned in a small room in front of a virtual work desk. The construction carrying the hair structures was represented by a 1-to-1 scale model of a wooden cylinder. The location of each sample was indicated by a cuboid with a neutral gray texture. To prevent participants from colliding with the physical Vive controller, we placed the upper half of a virtual sphere over its physical location. By applying the active texture to the sphere, the reflected environmental lighting allowed participants to better inspect the material's surface properties. Additionally, participants could reposition their head to receive better impressions of the visual details.

Rendering was done in Unity 5.6 using a HTC Vive headset connected to a desktop computer with an Intel i7 CPU, 16 GB RAM and an Nvidia GeForce GTX 980Ti graphics card. The experimenter recorded the participants' answers in a spreadsheet on a second computer.

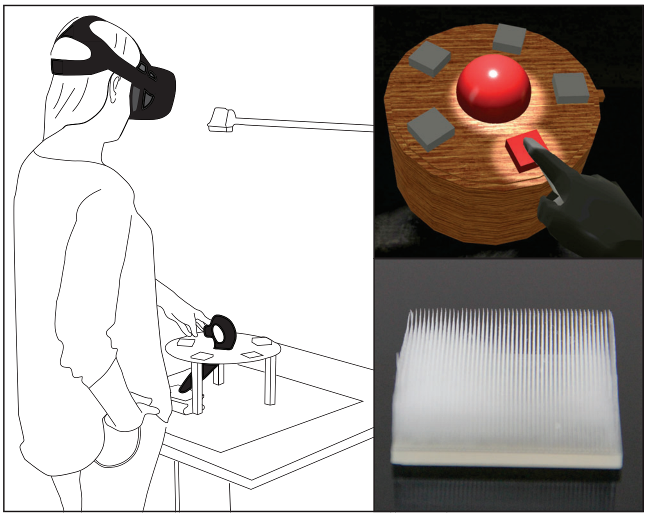


Figure 4: Experiment Setup. *Left:* A user touching a physical sample on the proxy plate with a Vive controller in the center and a Leap Motion positioned above the user's hand. *Right Top:* First person view of a user touching a virtual plastic material. *Right Bottom:* A patch of 3D-printed hair.

Participants

A total of 10 participants (7 male, $22 - 29$ years, avg. 26 years) volunteered for our study. All participants were right-handed and 2 wore glasses or contact lenses. Participants rated on a scale from 1 (= never) to 5 (= regularly) how often they played 3D video games ($M = 3.00$, $SD = 1.49$) and how frequently they used VR technology ($M = 2.00$, $SD = 1.25$). We asked how regularly the participants performed precise handcrafts on the same scale and received responses between 1 and 4 ($M = 2.90$, $SD = 1.20$). Sickness ratings on a scale from 1 (= I never felt ill) to 5 (= I felt ill all the time) after completion of the experiment verified the absence of cyber-sickness as all participants responded with 1. The post-experiment SUS presence [24] scores ($M = 1.20$, $SD = 1.62$) suggested low but sufficient immersion of the virtual experience.

Procedure

Before starting the experiment, each participant signed a consent form and was briefed regarding the course of events.

During the initial phase, each participant performed two separate baseline assessments. Here, we collected visual and haptic baseline ratings of both roughness and hardness for each virtual texture and each physical sample.

During the haptic baseline assessment, the view of the virtual environment in the HMD was blacked out. This was to ensure no visual input would influence the participant's haptic sensation. The operator guided the participant's dominant hand to each of the physical samples and asked them to rate on a scale from 1 to 10 how rough the sample felt (1 = very smooth, 10 = very rough) and how hard the sample felt (1 = very soft, 10 = very hard). These questions were simultaneously visible in the blacked out HMD.

During the visual baseline assessment, the participant was shown the virtual environment where each visual texture appeared one by one. For each visual texture, the participant was asked to rate on a scale from 1 to 10 how rough the texture looked (1 = very smooth, 10 = very rough) and how hard the texture looked (1 = very soft, 10 = very hard). Touching any object in the real world was not allowed to ensure no haptic input would influence the visual assessments.

Upon completion of both baseline phases, each combination of physical sample and virtual texture was shown 5 times per participant, resulting in 125 individual trials per participant. For each trial, the virtual cuboid corresponding to the location of the active physical sample was assigned the active visual texture. Participants were instructed to both look at and touch the sample, see Figure 4, while answering 6 questions, i.e 2 regarding haptic sensations, 2 regarding visual sensations, and 2 regarding the combined haptic and visual sensations. The questions depicted in the virtual environment on the wall in front of the participant, were:

(1) On a scale from 1 to 10, how **rough** does this object **feel**? (1 meaning very smooth, 10 meaning very rough)

(2) On a scale from 1 to 10, how **hard** does this object **feel**? (1 meaning very soft, 10 meaning very hard)
(3) On a scale from 1 to 10, how **rough** does this object **look**? (1 meaning very smooth, 10 meaning very rough)
(4) On a scale from 1 to 10, how **hard** does this object **look**? (1 meaning very soft, 10 meaning very hard)
(5) On a scale from 1 to 10, how well do you think the visual perception of the object **matches** the tactile perception? (1 meaning no match, 10 meaning perfect match)
(6) What do you think the **material** of the object is? (Open question)

The observer noted the responses for each trial and activated the next sample upon completion of the 6 questions. The table containing the physical samples was rotated after each set of 25 combinations to counterbalance any learning effect associating positional knowledge to haptic properties. During this, the rendering of the virtual object was disabled to ensure participants were not able to see the manipulations.

After the experiment, participants completed two post-study questionnaires. One inquired about their demographics, and the SUS presence questionnaire [24] recorded the experienced presence in the virtual environment.

Design

We used a within-subjects experimental design consisting of two baseline phases, i.e., the tactile perception of the printed structures and the visual perception of the visual textures, and a main phase in which we assessed all visual-haptic combinations. We distinguish 2 independent variables (the hair length on the physical sample and the type of visual texture shown on top), each with 5 different instances.

In order to balance for first-order carry-over effects, we constructed experimental design tables according to the Williams design using Latin squares [31]. For an uneven number of conditions such as our 25 visual-haptic combinations, each table consists of two Latin squares, i.e., a 50×25 experimental design table. Here, the Latin square was completed exactly once as each of the 10 participants achieved 125 trials by assessing each of the 25 combinations 5 times. During the analysis, the results were averaged for each participant. The visual and haptic baseline stages were counterbalanced amongst the participants using a Latin square of $n = 2$ and in both stages, the texture exposures were counterbalanced using a Latin square design of $n = 5$.

We further distinguish 6 dependent variables: the ratings of how rough a combination feels, how hard it feels, how rough it looks, how hard it looks and how well tactile and visual perception match, each on a 1-to-10 Likert scale. The sixth dependent measure was the open answer in which participants stated which material they thought to experience. For this open question, participants were not provided a list of materials to choose from, but were free to provide any answer they saw fit.

5 RESULTS

In the following section, we describe the analysis and the obtained results from our texture perception study.

Baseline Results

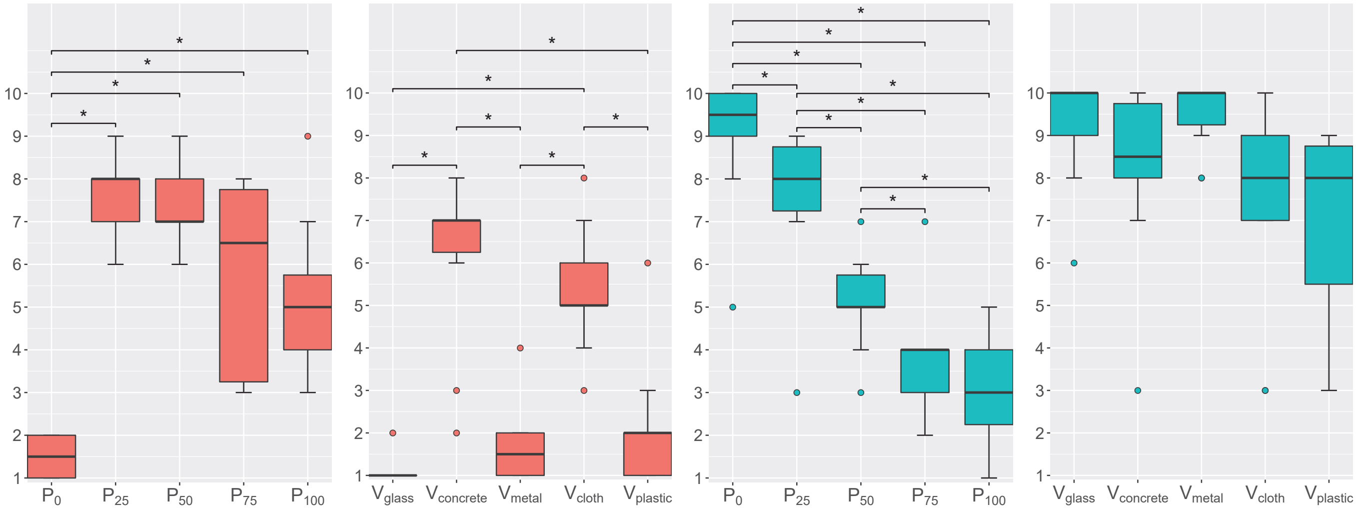
Participants' assessments of both baselines allowed us to test our initial assumptions about the perception of each physical sample and each virtual texture. We distinguish between roughness and hardness for *the haptic ratings of physical samples* without visual information (see Figure 5a and 5c) and *the visual ratings of virtual textures* without haptic information (see Figure 5b and 5d). For each case, we conducted a Friedman test with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction.

Haptic Baseline. The haptic ratings of roughness and hardness were found to significantly differ depending on the type of physical sample presented to the user (roughness, $\chi^2(4) = 28.908, p < .001$; hardness, $\chi^2(4) = 38.184, p < .001$). Pair-wise analysis of roughness showed a significant increase from the P_0 sample to all others ($p < .05$), however, no differences were found between P_{25}, P_{50}, P_{75} and P_{100}. Hardness significantly decreased for each step of hair length for all physical sample combinations ($p < .05$), excluding the increase from P_{75} to P_{100}. The brackets in Figure 5a and 5c indicate significant differences.

These results reveal that the addition of hair to the surface of a sample was clearly noticeable by users. While most increases in hair length were above the just-noticeable difference (JND) threshold for the perception of hardness, there was no significant change in the feeling of roughness.

Visual Baseline. Depending on the virtual texture presented to the user, visual roughness and hardness were found to change significantly (roughness, $\chi^2(4) = 32.978$, $p < .001$; hardness, $\chi^2(4) = 14.262, p < .001$). For roughness, we found V_{cloth} and $V_{concrete}$ to be substantially rougher than V_{glass}, $V_{plastic}$ and V_{metal}. The virtual textures did not significantly vary in terms of visual hardness.

When asked what material was recognized for each visual texture, V_{glass} was identified the best as all participants indicated *glass*. For V_{metal} 9 participants correctly appointed *metal* and one participant specified the material *onyx*, a banded variety of quartz mineral. While 7 participants assigned *plastic* for $V_{plastic}$, 2 indicated it could be *wood*, leaving one participant with *rubber*. Stone-like materials in $V_{concrete}$ were viewed by 8 participants, with 4 participants indicating *stone*, 3 indicating *concrete* and one indicating *marble*. $V_{concrete}$ was also designated once as *polystyrene foam (Styrofoam)* and once as *sponge*. V_{cloth} demonstrated the widest



(a) Haptic roughness **(b) Visual roughness** **(c) Haptic hardness** **(d) Visual hardness**

Figure 5: Boxplots depicting the baseline assessments. Haptic ratings of the physical samples without visual information for roughness (a) and hardness (c). Visual ratings of the virtual textures without haptic information for roughness (b) and hardness (d). Brackets connect groups with statistically significant differences ($p < .05$).

range of possible materials, including *stone* (3), *denim* (2), *wood* (2), *soil* (1), *marble* (1) and a *shell* (1).

These results show that our set of virtual textures were divided into 2 groups when considering how rough they appeared. Where V_{cloth} and $V_{concrete}$ were regarded medium-high in roughness, V_{glass}, $V_{plastic}$ and V_{metal} were considered to be very smooth. The resolution and quality of the image projected in the HMD seemingly had an effect on the details and visual artifacts that hinted towards more a more diverse roughness. All virtual textures were believed to be generally high in hardness. While V_{glass} and V_{metal} were clearly identifiable, other textures left some confusion as to what they represented. Here, the static visual representation of our textures might have caused a lack in visual hints.

Baseline Matching. Our set of virtual textures was compiled based on the expected tactile feeling of the 3D-printed hair samples. Even though we did not expect the visual ratings to perfectly match the haptic ratings, it is worthwhile to reflect on the appropriate matching of the visual and haptic choices.

As expected, V_{glass} paired almost exactly as the physical sample P_0, i.e., very smooth and hard. Even though absolute average ratings clearly deviated, the textures $V_{concrete}$, V_{cloth} and $V_{plastic}$ showed a similar downwards trend in roughness and hardness compared to their physical pairs P_{25}, P_{75} and P_{100} respectively. In contrast to our intended brushed metal texture, V_{metal} was visually assessed as very smooth and very hard. We believe that the visual quality of the HMD is in part responsible for this, as fine reflections and bumps that indicate the roughness were hard to identify.

Roughness and Hardness Augmentation

For all visual-haptic combinations, we recorded users' visual and haptic assessments of roughness and hardness. Similar to the baseline, Friedman tests were used to detect overall significant differences with post-hoc analysis using Wilcoxon signed-ranks tests and Bonferroni-Holm correction applied. In the analysis we considered 2 statistical variants, i.e., *the cross-modal influence* and *the multi-modal influence.*

Cross-modal Influence. For the analysis of the cross-modal influence, we assessed how consistently a modality is rated while the other modality is changed. For each visual texture, we compared how users visually rated them while experiencing different physical samples underneath. For each physical sample, we compared how users rated haptic properties while varying visual textures are visualized on top. In these 2 cases, the baseline assessments are considered an extra group, i.e., visual ratings without haptic information and haptic ratings without visual information respectively. For both analyses, we did not find any statistically significant differences between groups.

While rating one modality, users consistently assess perceptual properties belonging to that modality. There was no apparent guidance of one modality onto the other.

Multi-modal Influence. In the analysis of the multi-modal influence, we investigated how a changing modality is rated in the presence of another fixed modality. Here, we firstly compared how the haptic perception between physical samples changes while a fixed visual texture is shown. We found that

Table 1: Perception and Matching Rate Summary. ***P:*** **Percentage each combination was identified as *some* material.** ***M:*** **Average visual-haptic match on a scale from 1 to 10.** ***A:*** **Percentage of used adjectives for positive perceptions.**

	V_{glass}			V_{cloth}			$V_{concrete}$			$V_{plastic}$			V_{metal}		
	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)	P (%)	M	A (%)
P_0	94%	8.70	30%	64%	4.86	60%	56%	5.74	64%	98%	9.10	16%	88%	8.46	36%
P_{25}	28%	4.02	100%	84%	7.02	48%	84%	8.06	36%	66%	5.34	61%	62%	5.60	68%
P_{50}	24%	3.16	92%	78%	7.08	41%	72%	6.70	28%	48%	4.82	42%	44%	4.64	55%
P_{75}	24%	2.70	67%	68%	6.40	24%	54%	4.90	19%	34%	4.04	53%	18%	2.80	22%
P_{100}	18%	2.60	56%	64%	5.78	34%	50%	4.24	32%	44%	4.28	32%	18%	2.50	45%

regardless of the visual texture present, the haptic ratings between physical samples significantly change ($p < .001$). More specifically, the feeling of roughness significantly decreases with increasing hair length for all cases ($p < .05$) excluding the increase in hair from P_{75} to P_{100} when V_{glass} or $V_{plastic}$ were visible. For all samples with hairs attached, the rating for hardness significantly decreases with increasing hair length regardless of the visual texture shown ($p < .05$). The addition of hair from P_0 to P_{25} did not cause a significant decrease in the perception of hardness.

Secondly, we compared how the visual assessments differ across visual textures while a fixed physical sample is present. Similar to the trend in the visual baseline, the rating of visual roughness for V_{cloth} and $V_{concrete}$ was significantly higher than V_{glass}, $V_{plastic}$ and V_{metal} regardless of the physical sample active (P_0 & P_{50}, $p < .05$; P_{25} & P_{75} & P_{100}, $p = .05$). In the case of visual hardness, users rated V_{cloth} to be significantly softer than V_{metal} (P_0 & P_{25}, $p < .05$; P_{50}, $p < .01$; P_{100}, $p = 0.05$) and V_{glass} (P_{50}, $p < .05$; P_{100}, $p = 0.05$).

These results show that the perception of haptic roughness for varying hair lengths became clearly pronounced for most cases in the visual-haptic augmentation. While the difference in haptic hardness between P_{75} and P_{100} also became more apparent, the change from P_0 to P_{25} fell below the JND threshold. This indicates that haptic perception benefits from the presence of visual information. Considering visual roughness, the same trend of 2 groups of virtual textures appears compared to the visual baseline, however many of the significances were borderline. While visually the textures did not seem to differ in hardness during the visual baseline, the presence of most physical samples caused a difference to occur between V_{cloth} and V_{metal} and to a lesser degree between V_{cloth} and V_{glass} during the visual-haptic augmentation. Visual perception of haptic properties can thus be enhanced by haptic presence, however to a much lesser degree than the inverse due to the effect of visual dominance.

Perception and Matching Rate

For each visual-haptic combination, we recorded the matching rate by asking participants how well the experienced haptic and visual perceptions agreed. Additionally, material perceptions for all combinations were recorded by asking participants what they thought the material they experienced, was. If the participant was able to provide a meaningful material or object assignment to a combination, that trial was indicated as a positive perception.

The perception rate combined with each combination's matching rate provided insights into how specific combinations were identified. As expected, certain combinations showed high perception percentages and were perceived as a better match, which can be seen in Table 1. The combinations of V_{glass}, V_{metal} and $V_{plastic}$ with P_0 clearly had very high recognition rates. Here, the haptic feedback of a smooth and hard surface matched the expected feeling implied through the visuals. Both $V_{concrete}$ and V_{cloth} were recognized most in combination with P_{25}. As they showed overall perception ratings $\geq 50\%$ across all physical samples, these textures showed the highest perceptual flexibility. The look of $V_{plastic}$ left room for interpretation regarding the expected roughness and hardness. Therefore $V_{plastic}$ showed moderate to high recognition rates $\geq 34\%$ across all haptic samples. However, as V_{glass} and V_{metal} seemed to unarguably convey a distinct feeling of smoothness and hardness, perception rates decreased rapidly with increasing roughness and softness. These results imply that, when facing textures that visually provide strong indications of their tactile properties, modifying the user's perception with discrepant tactile cues is harder. Contrarily, visual surfaces with more ambiguity can show shifts in haptic perception.

Performing a Kendall's rank correlation coefficient test, we found the matching and the perception rates to significantly correlate across the entire dataset ($p < .001$, $N = 1250$). This positive correlation indicates that when users have a concrete idea of the material they engage with, they typically perceive

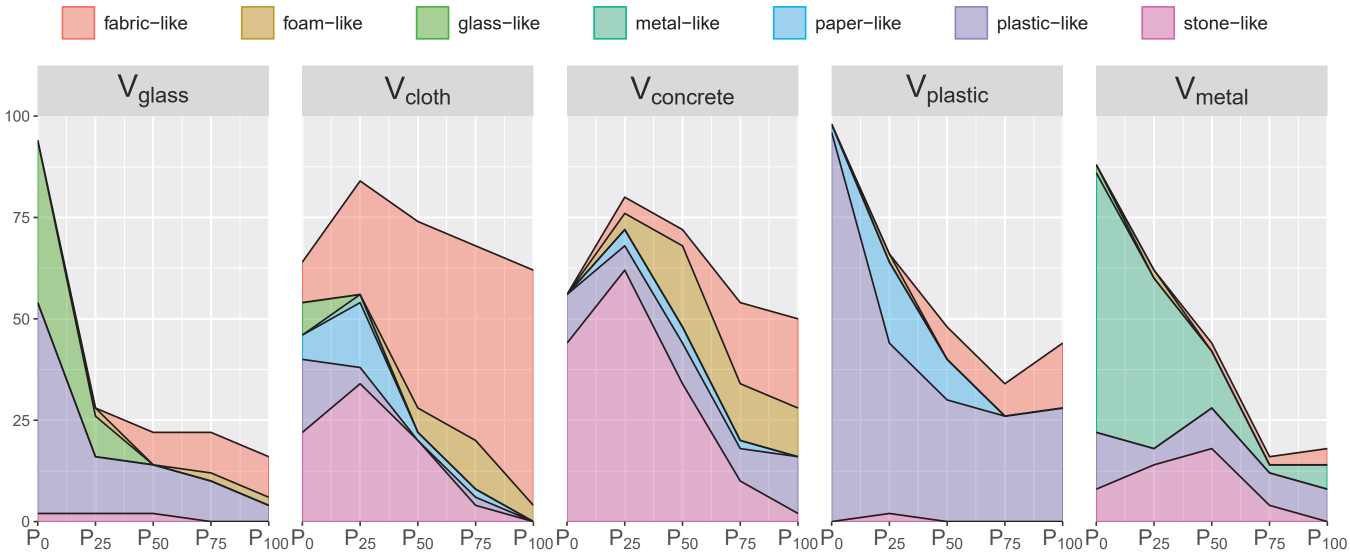


Figure 6: Stacked perception graphs per virtual texture indicating for each physical sample the percentage of samples identified per material category. Unassigned space depicts the percentage of times no meaningful material or object was assigned.

the visual texture and the haptic surface as matching. Viceversa, if users are unable to create a mental model of the mixed texture impression, they tend to regard both stimuli as a weak match. This suggests that in borderline cases, providing additional information about the mixed texture could push users towards perceiving a better match through priming their expectations.

Subjective Material Perception

The anecdotal data of the perceived materials was further analyzed by manually extracting the materials and objects identified by the participants. In total, we characterized a set of 35 distinct perceived materials, both abstract and concrete depictions. These were grouped into 7 categories, namely *fabric-like* (brush, carpet, denim, fabric, fiber, flanel, fur, silk, wool), *foam-like* (polystyrene, sponge), *glass-like* (crystal, glass), *metal-like* (aluminum, metal, steel), *paper-like* (drywall, paper, sandpaper, wood), *plastic-like* (crayon, linoleum, plastic, rubber, silicone), and *stone-like* (coal, concrete, coral, chalk, clay, granite, marble, mineral, stone, tarmac).

The percentages per group for each visual-haptic combination are plotted in Figure 6. Colored areas represent the percentage and distribution of identified materials, while unassigned space in the graphs reflects the users' inability to provide meaningful perceptions. This is clearly illustrated by V_{glass} where increasing the length of hair quickly restricted meaningful impressions. Both within and in between groups, we observed switches in material perception for the same visual texture presented with different physical samples. For example, V_{cloth} with shorter hair length samples led to variations of *fabric-like* and *stone-like* while an increase in length more consistently indicated *fabric-like* perceptions. Interestingly, increasing the hair length for $V_{concrete}$ caused users to note more *fabric-like* or *foam-like* materials, e.g., *polystyrene*.

During the study, participants used adjectives to clarify their impression as they felt a simple material or object would not suffice. Three distinct groups of adjectives were noted, i.e., visual, haptic and other. Visual adjectives indicated properties referring to cues such as coloring, reflectance or observable visual artifacts. Haptic adjectives described tactile impressions, e.g., details in roughness or hardness. Lastly, other adjectives elaborated on features such as age, quality or temperature. For each combination, the percentage of adjectives for all positive perceptions is shown in Table 1. Kendall's rank correlation coefficient tests indicated inverse correlations for the adjective usage to the rate of perception and to the average matching rate (both $p < .05$, $N = 25$).

6 DISCUSSION

Motivated by related work [12], we used fabricated passive proxy objects with varying tactile properties overlaid with different virtual textures. We aimed to determine the effectiveness of 3D-printed hair samples as more flexible and universal structures for the perception of roughness and hardness. As we expected to see interactions between the visual and haptic modalities, we assessed how our approach influenced the users' material impressions. Here, we discuss our results which support using 3D-printed hair to enhance texture perception in VR and open questions for future work.

How does hair length influence users' haptic perception in terms of roughness and hardness? From the baseline assessment of our physical samples, we find that the addition of hairs was clearly perceived in terms of roughness and hardness. Without visual information, an incremental increase of hair length did not cause the expected decrease in the perception of roughness. For hardness, the expected decrease for each increasing step in hair length was noticed by the users, excluding the step from P_{75} to P_{100}. In a multi-modal setting with virtual textures overlaid on physical samples, the sensation of roughness rises above the JND. A shift in hardness perception caused the difference between P_{75} and P_{100} to appear while the difference between P_0 and P_{25} faded.

These results support the use of hair-like structures for roughness and hardness perception in the presence of visual information. By combining our approach with state-of-the-art redirection techniques, users are able to experience different variations of physical proxies with varying tactile properties. While we only focused on hair-like structures, other fabrication designs could extend our results with more detailed tactile variants or might include alternative perceptual properties, such as stickiness.

How do users rate haptic properties of visual textures in terms of roughness and hardness? In terms of roughness, our set of virtual textures was divided into two groups with V_{cloth} and $V_{concrete}$ visually appearing medium rough while V_{glass}, V_{metal} and $V_{concrete}$ seemed smooth. In the presence of haptic information, the results indicated the same trend to occur. When considering hardness, users consistently rated all virtual textures to be hard in the baseline assessment. The limited differences that arose in the presence of haptic input were not consistent across physical samples.

From this we can see that influencing the perception of visual information is much harder. Although visual dominance remains highly present, our results suggest that the potential for the tactile to guide the visual does occur. As our set of visual textures was limited, a much broader range could uncover visual aspects important in the interplay between visual and haptic modalities.

How consistently is one modality rated in the presence of another changing modality? In our study, neither the visual nor the haptic modality was able to overwhelm, as indicated by the lack of significant differences in the analysis of the cross-modal influence. This shows users were consistently rating perceptual properties belonging to each modality. A user asked to rate visual properties focused on the visual information presented and, vice-versa, focus on haptic input when asked to rate haptic properties. Making one modality convincing enough to guide the other, remains future work.

How are visual-haptic combinations perceived in terms of material perception? A total of 35 materials were perceived from our set of 5 visual textures and 5 different physical samples. As perception and matching rates correlated, most of these materials were perceived when users found both haptic and visual information to be corresponding. In cases where matching rates were low, the use of adjectives for explaining materials increased. In certain instances, the variation in haptic perception for a given virtual texture led to perceptional switches where perception of a material changes.

These results show users actively try to make sense of sensory input, whether matching or not. By providing additional information related to the texture in borderline combinations, the user's perception could be primed. This might lead to more precise and consistent material perceptions and would open up our approach for practical applications.

7 CONCLUSION

Based on multi-modal perception, this paper investigated how 3D-printed hair structures can serve as versatile passive haptic structures for VR. In a user study, we found that visual-haptic augmentations enhance the user's haptic perception by making small variations in hair length distinguishable. We show that higher rates of matching perceptions correlate to material recognitions. As users actively make sense of mixed modalities, mismatches are clarified with adjectives and varying augmentations cause perceptual switches.

In this work, the single parameter of hair length allowed users to perceive a larger set of material impressions. While other designs could more controllably guide perception, active approaches might build upon our results by manipulating hair length in real-time. Future experiments improving consistency and accuracy would require a larger amount of participants. By combining our approach with techniques for redirection in VR, the perception of a large set of materials can be supported by a limited set of fabricated proxies.

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