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Cross-modal interaction of stereoscopy, surface deformation and tactile feedback on the perception of texture roughness in an active touch condition

Interaction intermodale de la stéréoscopie, de la déformation de surface et de la retour tactile sur la perception de la rugosité de la texture dans un état tactile actif

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Research has shown that interaction with tactile surfaces can benefit from the addition of haptic feedback. The perception of this feedback is influenced by other modalities, visual and auditory, making it possible to reinforce or enrich it. However, the effect of visual depth cues, such as stereoscopic rendering and surface deformation, on the tactile perception of textures has not been studied yet, especially in an active touch condition. In this paper, we investigate the perceptual interaction between stereoscopy, surface deformation, and haptic feedback in the condition of active touch implemented using friction modulation based on ultrasonic vibrations. The experimental study is based on a Visual-Tactile exploration of a virtual texture. Our objective is to understand the interaction of one modality over the other for roughness and depth perception. Participants were asked to make visual and tactile texture roughness judgments and to estimate the depth of deformation of the texture below their fingers. Our results suggest that: 1) perceived tactile roughness can be modified by adding stereoscopic rendering and/or visual surface deformation but only for smooth tactile textures, 2) perceived visual roughness can be modified by increasing the tactile roughness, 3)the overall roughness (Visual + Tactile) is mainly impacted by the tactile perception.

CCS Concepts: • **Human computer interaction (HCI) → Interaction paradigms**; **Virtual reality**; **Haptic devices**; **Displays and images**; **Laboratory experiments**; **Interaction devices**.

Additional Key Words and Phrases: Surface haptic, Stereoscopic vision, Texture perception, Multimodal interactions

La recherche a montré que l'interaction avec les surfaces peut bénéficier de l'ajout de retour haptique. La perception de cette retour haptique est influencée par d'autres modalités, telles que visuelles et auditives, ce qui permet de le renforcer ou de l'enrichir. Cependant, l'effet des textures 3D dans la réalité augmentée (AR), comme le rendu stéréoscopique et la déformation de surface, sur la perception tactile des textures n'a pas encore été étudié, en particulier dans une condition tactile active. Dans cet article, nous étudions l'interaction perceptuelle entre la stéréoscopie, la déformation de surface et la retour haptique dans un état actif. La retour haptique a été mise en œuvre en utilisant une modulation par friction basée sur des vibrations à ultrasons, tandis que la retour visuelle a été implémentée avec une paire de lunettes 3D en AR. L'étude expérimentale est une exploration visuelle-tactile d'une texture virtuelle. Notre objectif est de comprendre l'interaction d'une modalité sur l'autre pour la rugosité et la perception de la profondeur. Nous avons demandé aux participants de porter des jugements de rugosité de texture visuelle et tactile et d'estimer la profondeur de la déformation de la texture sous leurs doigts. Nos résultats suggèrent que : 1) la rugosité tactile perçue peut être modifiée en ajoutant un rendu stéréoscopique et / ou une déformation de surface visuelle mais uniquement pour les textures tactiles lisses. 2) La rugosité visuelle perçue peut être modifiée en augmentant la rugosité tactile. 3) La rugosité globale (visuel + tactile) est principalement impactée par la perception tactile.

Mots-clés additionnels : Haptique de surface, Vision stéréoscopique, Perception de texture, Interactions multimodales

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1 INTRODUCTION

Interaction with digital content has benefited from the development of auditory, visual and haptic feedback technologies, which can make this interaction more efficient, more immersive and perceptually richer. Moreover, the combination of multiple modalities has long been an essential topic in Human-Computer Interaction, as demonstrated by early research [5] and their continuation in the more recent years [11, 40]. More specifically, multimodal feedback combining haptic and visual modalities has been shown to improve and enrich interfaces. For instance, this combination improves the performance of both 3D [44, 47] and 2D interaction techniques [7]. In the case of touch interfaces, it also offers opportunities for the visual-haptic exploration of virtual textures, which is an essential component in fields such as medical imaging , artistic expression, cultural heritage, or retail. Indeed, visual-tactile interactions may allow scientific data exploration for medical purposes, enrich artistic or historical expositions, and can be used to allow consumers to interact with products such as "touching" a virtual object before buying it. In this context, multiple technologies have emerged that allow the rendering of haptic textures on flat surfaces, e.g. touchscreens. In particular, ultrasonic vibrations can be used to modulate the interactive forces between the finger and the surface (i.e. friction) in active touch condition. According to the neuroscientific definition, active touch refers to the act of touching and implies voluntary, self-generated movement[8] and it is therefore suited in the case of virtual texture exploration. On the visual side, 3D displays have been developed which simulate a number of visual depth cues, both monocular (perspective, shadows, relative size, motion parallax ...) and binocular, allowing to render virtual textures with complex geometries on flat screens. In particular, they enable the separation of these cues so that their effect on texture perception can be evaluated. Combining such technologies therefore opens many opportunities for rendering and interacting with virtual content, which in turn makes it essential to understand the perceptual interaction between the visual and haptic modalities. Research on that topic has already led to many insights [6, 13] which can help design richer visual-tactile interactions. However, there has not been research on the specific interactions between 3D visual depth cues(in AR) and tactile feedback in the context of texture roughness perception. For this, we need to understand how from the perception point of view these two modalities interact with each other. In particular, this is important because it can change the user experience in an unpredictable way. Indeed if one wants to add visual cues to an haptic display, one can end-up with skewed results where the designed experience is different from the perceived experience.

In this paper we want to address the absence of research that associates haptic feedback, in active touch, with 3D visual depth cues in AR. In particular, we will focus on the interaction between AR stereoscopy and visual deformation on one side and tactile roughness on the other side. Our objective is to understand how these perceptual parameters affect the overall perceived roughness of a virtual texture rendered on a touchscreen, but also how they affect separately the perceived visual and tactile roughness.

By this investigation, we aim at improving the design of 3D user interfaces with richer feedback, especially when rendering visual-tactile textures represents a key element of the interface. We think this investigation can : 1) enrich the understanding of tactile and visual perception, and their interaction 2) inform the design of novel haptic-visual display technologies, such as mobile devices with 3D displays, or touch controllers in Mixed or Virtual Reality 3) open opportunities for new interactive applications such as 3D medical data exploration or rendering and designing virtual textures and objects.

2 RELATED WORK

In this section, we review the literature on visual-tactile perception and on interfaces which combine 3D displays and haptic feedback.

2.1 Visual-Tactile Perception

The integration of visual and tactile modalities represents a consequence of the natural way human senses interact together. Indeed, a key connection between vision and touch is represented by the shared spatial component, present in both modalities[11]. Therefore, it has been shown that haptic information does not need to be encoded into visual information and has direct access to spatial processing [12]. This indeed represents a key element of visual-tactile interaction, highlighting the importance of physically co-located interactions. In such context, Olsson et al. [31] investigated haptic interactions with 3D displays. In their study, they highlighted the importance of having visual-haptic co-located (aligning visual and haptic) workspaces, as they do in the real world. Also Kervegant et al. [22] reported a similar result about co-location. They combined a mixed-reality headset with an ultrasound array mid-air haptic device. Their system adds tangible (tactile) feedback to virtual content and the authors highlighted how the co-location of feedback drastically enhances the presence of the object itself. Moreover, the relation between vision and haptic has been shown to be important in multimodal integration already in the early stage of human development. In particular, it has been demonstrated that touch educates and calibrates our visual perception[6, 13]. Also Picard et al. [33] reported a partial equivalence between vision and touch in a matching task related to texture perception. Even closer to our interest, Bergmann et al. [4] confirmed the equivalence of visual and tactile modalities in the perception of texture roughness. Visual performance may also change depending on the type of tactile interaction, passive or active. Doorn et al. [43], as an example, performed an investigation over the perception of shapes and size with vision and touch in both passive and active conditions. Their results have shown that visual influence on size judgment was greater than the influence of haptic when passive touch was involved. However, when tactile information was allowed during the active exploration, size judgment was more influenced by the haptic modality. This result shows the importance of the active touch condition in the context of visual-tactile explorations. Other research have demonstrated the potential influence of the visual modality over various aspects of haptic perception such as stiffness[2], compliance[23] and roughness [20]. In the more precise subject of texture perception, much research has been conducted on the separate perceptual cues for visual and tactile but also on how these modalities interact (see Klatzky and Lederman [25] for a more detailed review), especially in the context of roughness perception. Research suggested that visual and tactile perceived roughness vary similarly with respect to physical roughness [4, 28]. However, some research has shown a prevalence of tactile over visual [16] when both stimuli are simultaneously available. Perceived roughness is also influenced by many visual and tactile factors, which can interact with each other. For instance, Ho et al. [18] suggest in their study that participants judged visual roughness according to their perception of shadows, which highlight the potential tactile depth of the texture, and not using binocular cues. Visual and tactile perceptual cues can also influence one another with respect to roughness. For instance, it has been reported that colors affect the perceived tactile roughness of surfaces[29]. This influence can also be seen in the use of pseudo-haptics techniques. We can define pseudo-haptics as the phenomenon that occurs when users experience haptic feedback by observing a visual stimulus that is designed to distort depending on user input [26]. In particular, Ujitoko et al. [42] showed that it is possible to modulate fine roughness perception of vibrotactile textured surface using pseudo-haptic effect. Ujitoko [41] shows that modulating the oscillation of the visual cue (the mouse pointer in his case) makes the user feel the vibrotactile surface more uneven. Indeed, their results suggest that the larger size of the visual oscillation enlarged the perceived vibrotactile amplitude of the signal wave. In other words, the visual oscillation presented during the experiment increased the perceived roughness. Günther et al. [14] also demonstrate that cross-modality allows for limiting the variety of haptic roughness levels (on physical textures) to produce a range of perceived roughness when combined with visual feedback in virtual reality. Previous research therefore suggests a somewhat equal role of visual and tactile modalities in the perception of roughness, the predominance of certain cues and the existence of crossmodal interactions, especially the effect of visual over tactile perception. With the development of 3D displays where depth cues can be separately controlled, it is essential to follow up on previous research and investigate how these specific cues influence roughness perception and how they interact with tactile perception.

2.2 Interfaces

Interfaces coupling visual feedback and tactile feedback (in passive touch condition) have become widespread in research in the past decade thanks to the increase in available technologies for both visual (such as stereoscopic displays and AR/VR headsets) and

tactile feedback(vibrotactile, shape-changing displays, electrovibration, mid-air haptics, etc.). Many research coupling these two modalities focus on understanding the possible interactions as well as modulation of perceived properties of materials such as stiffness, softness, compliance, etc. As an example, Punpongsanon et al.[34] used a camera and a projector to visually manipulate the sense of softness perceived by a user touching (pushing) a soft physical object. The authors also added a surface deformation effect and a body appearance effect to overcome the limitations of projection-based approaches. As a result, the perceived softness was manipulated by the system such that participants perceived significantly greater softness than the actual softness. Such augmentation of the perceived softness is interesting as the system only manipulates the visual feedback, leaving unaltered the tactile side (pseudo-haptic effect). Other research focus on the manipulation of the perceived stiffness. Yuki et al. [2], for example, developed a method to influence the perception of perceived stiffness of an object by using visual deformation of a virtual hand (instead of using object deformation). The authors show that the effect of modifying the perceived object stiffness using this method was effective. Indeed, their results suggest a stiffness increase of 1.6 times more than that with only modifying the degree of dent of virtual object. For what regards tactile compliance perception, Kidal et al.[23] used a technique called 3D-Press to give the illusion of tactile compliance. Then, the authors added visual feedback on a screen to reinforce such tactile illusion by synchronizing the modalities effects (when compliance is tactically felt, it is also seen). Their results seems to confirm again the importance of stimuli co-location but also, they highlight the relevance of stimuli synchronization. Indeed, the temporal component of stimuli presentation is also a key element of different interfaces. For instance, Romanus et al. [36] coupled a mixed reality head-mounted display, an ultrasound array haptic device, and a smartwatch to measure the heart rate. Their demonstration illustrates the possibility to temporally map the heartbeat (measured and displayed thanks to the AR glasses) to the haptic feedback. The update of the heart rate dynamically changes the haptic feedback and the animation, creating an enriched experience. Similarly, Han et al. [15] also coupled stereoscopic vision and haptic feedback. The main components of their interface are a stereoscopic system with beam-splitters and a thimble-formed pneumatic balloon display. Their system provides the illusion of touching 3D virtual contents while interacting directly and intuitively with these virtual objects.

To our knowledge, however, no research has been carried out on interfaces that combine co-located tactile feedback in active touch (ultrasonic friction modulation) with an AR stereoscopic display.

2.3 Contribution

In this paper, we study the effect of 3D visual feedback in AR and tactile feedback on the perception of texture roughness in an active touch condition. We provide insights on the perceptual interaction between stereoscopy, visual surface deformation, and tactile roughness. We study their effect on the perceived visual, tactile and overall roughness of a 3D virtual texture displayed on a touchscreen. We believe that these results, by deepening our knowledge of human perception, can help the HCI community achieve a more precise and controlled user experience when designing visual-tactile interfaces. We also propose potential applications to illustrate how our results can be used in practice.

3 EXPERIMENT

The focus of this experiment is to evaluate the possible interactions between tactile feedback and 3D AR visual feedback in an active touch condition. The performed task is a visual-tactile exploration of a synthetic textured surface. The experimental application, written using Godot Engine (v3.4), is running on a host PC with a Debian Linux OS (3.8 GB of RAM, NVidia Quadro 4000 graphics card). The application controls both the tactile and visual rendering of the textures.

3.1 Tactile feedback

The haptic feedback used in this experimental study belongs to a haptic category known as Surface Haptics (SH). From a technological point of view, SH aims at displaying tactile feedback to the users by modulating the interaction forces between the finger and the touched surface [3]. Indeed, when a finger slides over a plate vibrating at ultrasonic frequencies, the relative friction between the finger and the surface is reduced. Such friction reduction is function of the vibration amplitude and, in particular, it decreases as the vibration amplitude increases[39]. If amplitude modulation is applied to the vibration, friction is also modulated, as are the interaction forces, as if a textured surface is touched by the user. In this experiment, the tactile stimulator device is a glass plate resonating at 60 kHz thanks

to piezoceramic actuators glued to it. A microcontroller manages a power unit that shapes the voltage applied to the actuators. By controlling the input signal of the plate it is possible to render virtual tactile textures. More information about the device specification can be found in [45], [35]. Moreover, a closed control-loop running in the microcontroller ensure the vibration amplitude of the plate to be as the input signal. The choice of the rendered tactile textures is based on a tactile semantic investigation performed by Dariosecq et al [9]. Their results show that the amplitude and the waveform type of the amplitude modulation signal play an important role in perceiving a texture as smooth or rough. Moreover, they illustrate that spatial period is a possible modulator for different degrees of roughness or smoothness. Starting from the adjective of the textures illustrated, we used the parameters depicted in Table 1. For our experiment, we decided to use two textures, belonging to the clusters of textures associated respectively the adjectives *rough* (gray) and *smooth* (cyan), using the tactile parameters provided in Table 1, which correspond to one texture in each cluster.

For this reason, we decided to use a spatial period of 5000 μm for the selected textures while varying waveform (sine wave for smooth, and square wave for rough) amplitude (40 for rough, and 10 for smooth), and ratio (50%, only for square wave).

One must note that because we are using synthetic tactile textures rendered through friction modulation, it is not possible to control the actual height of the texture and to provide an absolute measure of roughness, contrary to related research employing physical textures.

Adjective	Waveform	Period (μm)	Amplitude
granulous	rect	5000	40
rough	rect	2500	40
sandy	rect	1000	40
smooth	sin	10000	10
delicate	sin	1000	10

Table 1. Tactile perception adjectives and possible corresponding synthetic texture parameters [9]. Gray and cyan rows represents adjectives related to the *rough* and *smooth* cluster respectively.

3.2 Visual Feedback

3.2.1 Stereoscopy. To introduce the illusion of visual depth in the rendering of textures, we used a 27" active (quad-buffer) stereoscopic display with a pair of NVIDIA 3D Vision glasses. The glasses are shuttered at 120 Hz frequency, updating each eye 60 times per second. The images are rendered in the portion of the screen (178x102cm) below the tactile plate, as shown in Figure 1. A plugin was developed for the Godot engine to enable quad buffer stereoscopy to be rendered with the NVidia Quadro GPU. The visual texture was chosen to

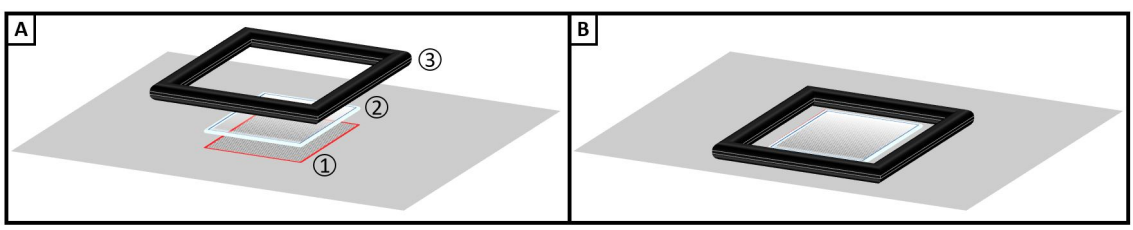

Fig. 1. Experimental Device. **A)** Layers composing the device. **A1**-Stereoscopic screen used during the experiment where the perimeter in red highlights the used portion of the screen. **A2**-Glass plate for tactile feedback delivery. **A3**-Infrared framed used for finger tracking. **B)** How the device appears once composed. Here Power source, control, and communication are not illustrated. More information can be found in [35]

be a synthetic abstract texture, to avoid bias due to realistic or known textures which might influence the roughness perception. In all

conditions, the texture was a discretized gradient noise with the same spatial frequency, chosen during preliminary tests so that the variations in luminance/depth are large enough to be perceivable but not too large, i.e. less than the fingertip size (<1cm), so that the participants did not expect bumps or holes in their tactile exploration. We, however, varied the seed randomly between conditions to generate variability, i.e. participants saw a different texture each time while preserving the overall visual roughness. Therefore we estimate that the visual roughness did not change among the trials due to the texture itself, but only because of the stereoscopy. To elicit depth perception, the texture was rendered on a plane mesh and a vertex shader displaced the vertices along the Y axis (below the screen surface) according to the texture pixel value (1/white being on the surface and 0/black at 5mm below the surface). Preliminary tests were performed to choose a texture depth (distance between dots displayed on the screen surface and dots below the surface) which was large enough for the stereoscopic effect to be perceivable but small enough to preserve the overall appearance of the texture between stereoscopic and monoscopic conditions. Finally, a depth of 5mm was found to be a good compromise. These values could be considered too large when compared with a typical profilometer measurement, such as sandpaper, where the diameter of the particles is around 500 μm [37]. However, in our work, we are not interested in displaying real textures with their proper congruent physical depth. Indeed, the choice of a synthetic abstract texture does not imply any constraints related to the texture depth, allowing designers to use larger depths than real textures profilometer measurements. In the experiment, we varied between the presence and absence of stereoscopy. When deactivating stereoscopy, the same image was displayed for both eyes, at a center position between the two eyes. Because we were interested in the effect of stereoscopy but not in an accurate perception of the depth of the texture, we chose a fixed interocular distance of 6cm for all participants and a fixed head position at 20cm above the screen. The two conditions are illustrated in Figure 2, with E and F showing how the texture is displaced below the surface of the screen when stereoscopy is activated, while in C and D all texture dots are displayed at the same level on the screen surface (i.e. monoscopic condition).

3.2.2 Surface deformation. In addition to stereoscopic depth, a visual deformation was adopted in the experimental design. Different research in pseudo-haptics has adopted surface deformation in order to reinforce or augment stiffness or elasticity properties of the rendered (real) textures. Argelaguet et al [1], such an example, used a pseudo-haptic feedback technique in order to enable the perception of local elasticity of real textures images (without any haptic device). Similarly, Kawabe [21] used a pseudo-haptic technique to modulate the perception of stiffness of objects displayed in a screen while the user, set in front of the screen, was performing gestures in mid-air without any tactile feedback. However, among different researches performed using surface deformation, to our knowledge, no research has been conducted on the possible influence produced by different deformation's shapes. Therefore, considering the type of deformation used in different researches, such as [24][49][1], and considering the neutral texture we chose for our experiment, a concave surface deformation was selected for our scope. The deformation has a sinusoidal shape (half-wave) and has been included to investigate the influence of tactile over the visual perception of deformation's depth as well as the influence of the deformation over tactile roughness perception. The deformation appears under the participant's fingertip. The deformation is synchronized with the position of the participant's fingertip and moves accordingly with the finger trajectory performing the texture exploration. The tracking of the finger is performed by an IR (Infrared) frame that surrounds the tactile plate and which exhibits a sampling frequency of 125 Hz. The finger position is indeed sent every 8ms to the OS. In the experiment, the deformation varied between no deformation (the surface remains flat below the finger) and a deformation of 10mm below the finger. Such value was chosen after pre-trial tests. We aimed to find the minimum value which could be perceived in both monoscopic and stereoscopic conditions, i.e. sufficiently deep to generate a visually perceivable change in the texture. The shape of the deformation (see Figure 2) was chosen to be not related to a specific elastic behavior of a real texture since we chose a synthetic abstract (neutral) texture as a visual cue. Even if the type of deformation may have itself an effect on the perceived tactile roughness, we counterbalance this possible effect by using the same deformation shape in the trials where the condition of deformation was present. Moreover, we decided to first investigate the influence of a non-complex deformation shape, having in mind to investigate possible influences of different deformation shapes in future works. We chose the boundaries of 0mm and 10mm since our interest lies in the difference in deformation (Perceived deformation / Rendered deformation) more than in the perception of absolute values of deformation's depth.

We then chose a fixed radius of 5mm for the deformation. Such value was chosen in order to allow participants to see the deformation around their finger, avoiding occlusion of the deformation due to the finger size. Finally, Figure 2 illustrates the two conditions for

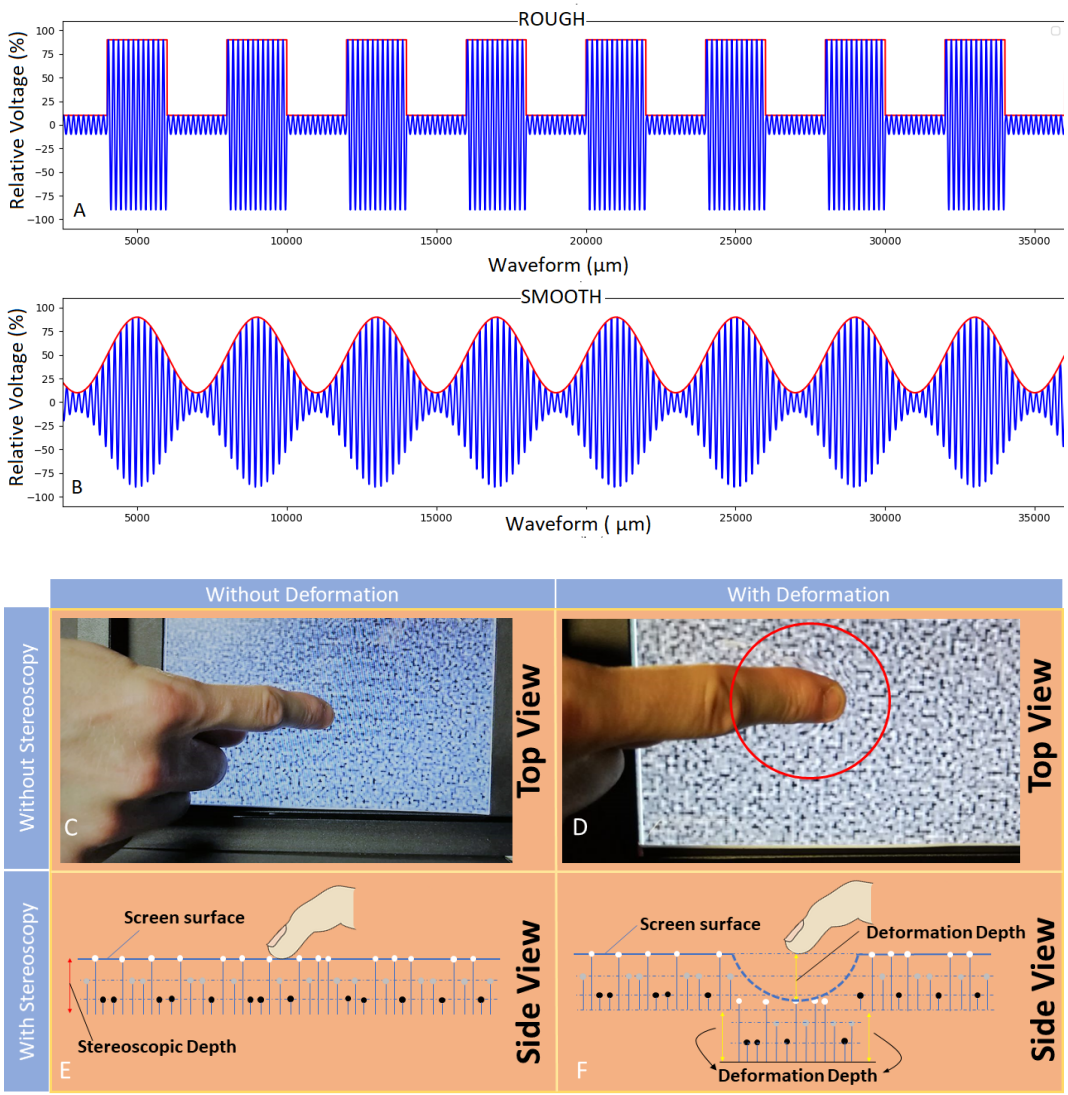

Fig. 2. Representations of the experimental conditions: A,B) Tactile Texture waveform samples resulting from the parameters selected in Table 1. Test conditions for Texture Deformation and Stereoscopic Vision: C) No Deformation, No Stereoscopy. D)With Deformation, No Stereoscopy. E) No Deformation, With Stereoscopy. F) With Deformation, With Stereoscopy. As quad-buffer stereoscopy would not be perceivable in a picture, we chose to represent a side-view of the texture displacement when is active. Screen surface and finger in Figure E and F are not in scale

deformation depth. In particular, Figure 2 D shows the deformation when stereoscopy is not active and Figure 2 F illustrates how the dots moves vertically when the finger is placed on the surface and stereoscopy is active.

3.3 Hypotheses

In this experiment, we want to study the interaction between 3D visual depth cues (stereoscopy and surface deformation below the finger) and tactile roughness on the perception of virtual texture roughness. Based on previous research, we consider 3 hypotheses.

- H1: 3D visual depth cues in the form of stereoscopy or surface deformation will influence our perception of tactile roughness
- H2: Tactile roughness will influence our perception of visual roughness
- H3: Both 3D visual depth cues and tactile roughness will influence our perception of the overall roughness

We separate the judgement of tactile and visual roughness perception from the overall roughness perception because we believe that one modality can take precedence over the other for overall roughness. Therefore we want to isolate their effect on the perceived roughness for each modality. To test these hypotheses we designed an experiment where we displayed a co-located visual and haptic virtual texture. We then varied the levels of tactile roughness, the depth of surface deformation below the finger, and the presence of stereoscopy, as described in sections 3.1 and 3.2.

3.4 Experimental protocol

The experiment used a $2x2x2$ within-subjects design for the factors: *Texture* (type of tactile texture : Rough or Smooth), *Visual* (with Stereoscopy or without Stereoscopy), and *Deformation* (Absent: 0mm; Present: 10mm).

3.4.1 ***Participants.*** A sample of 22 participants (16 males, 6 females, aged M=26.68 SD=4.01) was recruited for this experimental study. The original group was composed of 24 people but two were excluded as they did not pass the stereoscopic test. 10 out of 22 were using glasses or eye contact lenses. However, 18 participants stated to have good to excellent eyesight. 21 participants were right-handed and only 1 was left-handed. Their experience with tactile devices (M=3.04, SD=1.39) and Stereoscopic displays (M=2.68, SD=1.14) was on average competent on a five-level scale. None of the participants were suffering from motor impairment, numbness, or stereoscopic blindness. All participants took part freely in the experiment.

3.4.2 ***Exclusion criteria.*** Before starting the experiment, we checked that participants were outside our exclusion criteria (two in our case). First, participants were asked if they suffer from any kind of somatosensory problem, such as numbness (loss of feeling or sensation in an area of the body). This was selected since we want participants without tactile issues or tactile perception limitations. Second, we tested the stereopsis of participants using a TNO test reimplemented for our quad-buffer stereoscopic display. One butterfly (see Figure 3, top-left corner of the tactile display) was rendered over a circular dark background while a second one (bottom-right of the tactile display) was rendered against a random dots background. The first butterfly was easy to see (even in monoscopic condition) while the second one was more difficult to perceive, requiring a higher stereoscopic ability. Only people who were able to see both butterflies were accepted for the experiment. This second exclusion criterion was important to be tested since around 32% of the population have moderate to poor stereoscopic ability [17].

3.4.3 ***Apparatus.*** A schematic view of the device we used for the experiment can be seen in Figure 1. It employs a stereoscopic screen (A1, with associated NVIDIA 3D Vision shutter glasses) on top of which is placed a glass plate actuated by piezoceramic transducers, which generate the tactile feedback. Around the plate, there is an IR finger tracking frame. Parts of the stereoscopic screen are not used and are covered using a black foam board to avoid undesired visual cues. As a result the portion of the screen in use (in red in Figure 1 A1) is located at the center. Visually textures can be displayed without or with stereoscopy, i.e., respectively with all dots on the surface (0 mm) or with some of them 5mm below. The haptic feedback is delivered through the glass plate (Figure 1 A2)). Thanks to the finger tracking system (Figure 1 A3) virtual textures can also be deformed locally, appearing as being pushed below the finger. Finally, the full setup provides a co-localized 3D AR visual and haptic feedback.

3.4.4 ***Experimental procedure.*** Participants sat in front of the setup wearing a pair of 3D glasses and headphones playing white noise to hide the audible noise generated by the vibrating tactile plate (see Figure 3). After the application of the exclusion criteria, a training session was started. Participants were first presented with two tactile textures (on a blank screen) and were told that the first was at a level of 20/100 on our roughness scale, while the second was at a level of 80/100. These two textures corresponded to the two textures which were used for the smooth and rough tactile conditions, as described in Section 3.1. Such textures were used as a

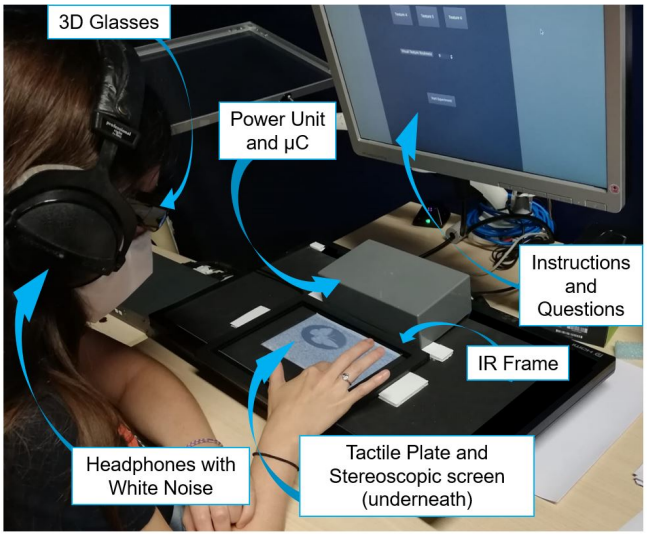

Fig. 3. Experimental set-up and illustration of the system.

reference and participants were asked to remember them in order to easily rate texture roughness in the linear scale (0 to 100). The reference values (20 and 80) were chosen because they correspond to textures from the smooth and rough clusters in [9] and because these values leave room for lower and higher roughness ratings. Participants were then asked to visually judge a texture in roughness with a value between 0 (completely smooth) and 100 (completely rough). This value was then used as a personal baseline for visual roughness judgment during the experiment. Once again, we are interested in differences between conditions and not in absolute values of visual roughness. Therefore, the visual textures remained very similar, as explained in Section 3.2.1, so that participant's perceived roughness would change only because of the experimental conditions. In the experimental phase, each participant therefore performed 16 visual-tactile explorations (2 *TactileFeedback* * 2 *Stereoscopy* * 2 *VisualDeformation* * 2 repetitions) for a total of 352 trials for all the participants. These trials represent all the combinations of tactile feedback (smooth or rough as described in Table 1), stereoscopy (presence or not) and surface deformation (presence or not). To avoid biases due to the presented order of the trials, the order of the conditions was counterbalanced between participants using a balanced Latin square algorithm. At each trial, the visual texture as depicted in Figure 2 C and D appeared in front of participants. At this point, participants performed the visual-tactile exploration. They were free to explore each texture (visually and tactically) for as long as they needed, using the index of their dominant hand. The exploration was restricted to a single finger as the hardware used for this experiment does not allow multitouch tactile feedback. We considered two repetitions for each condition were enough for participants to express their perception. Indeed, unlike pointing tasks, participants had time to explore the texture and judge their perception (approximately 2 minutes for each trial). In general, the 2 repetition for a given combination was consistent among participant. While exploring the visual-tactile texture, 5 questions were asked to the participants in order to verify our hypotheses : the level of perceived tactile roughness (between 0 and 100), the level of visual roughness (between 0 and 100), the depth of deformation below the finger in millimeters (between 0 and 10mm), the overall perceived roughness (on a scale of 1 to 5 between very smooth and very rough) and the presence of stereoscopy (yes or no, this data was kept for further studies). For both levels of tactile and visual roughness participants rely on levels given during the training phase. In the case of deformation depth, we asked participants to estimate depth in the continuous scale 0-10mm, although conditions were either 0mm or 10mm. We are not interested in absolute or precise values for the perceived deformation depth, but rather to detect changes due to variations of our three independent variables.

Finally, to evaluate the weight of all factors in a global roughness judgment scale, we use the overall roughness, for which we asked participant to evaluate their perception of roughness taking into account both modalities. The experiment duration averaged around 30 minutes per participant.

4 RESULTS

In this section, we present the obtained results for the dependent variables: Perceived tactile roughness (*TactileRoughness*), Perceived visual roughness (*VisualRoughness*), Perceived depth (*PerceivedDepth*), and Perceived overall roughness (*OverallRoughness*). For each, we performed a repeated-measures ANOVA for the factors *Stereoscopy* (Yes/No), *VisualDeformation* (Yes/No), *TactileFeedback* (Smooth/Rough). Normality was tested with a Shapiro-Wilk test. For variables that did not follow a normal distribution, namely *TactileRoughness*, *PerceivedDepth* and *OverallRoughness*, we applied an Aligned Rank Transform [48] before the ANOVA. We ran the analyses with R v4.0.3.

4.1 Perceived tactile roughness

The perceived tactile roughness for a trial was computed as the difference between the score (0-100) given by the participant during the trial and the score associated with the presented texture (smooth=20, rough=80, given to participants during the training phase). An ANOVA showed statistically significant main effects of *Stereoscopy* ($F(1,147) = 10.45, p = .001, \eta^2 = 0.189$), *VisualDeformation* ($F(1,147) = 8.28, p = .004, \eta^2 = 0.152$) and *TactileFeedback*($F(1,147) = 9.6, p = .002, \eta^2 = 0.173$). It also showed significant interactions *VisualDeformation*TactileFeedback*($F(1,147) = 15.09, p = .0001$) and *Stereoscopy*VisualDeformation*TactileFeedback* ($F(1,147) = 9.23, p = .002$). Post-hoc Holm adjusted pairwise t-tests showed a number of statistically significant differences. Some seem to be supported by changes in *TactileFeedback*, such as *StereoNo-TactileRough-DeformYes* and *StereoNo-TactileSmooth-DeformYes* ($t(147) = -4.207, p = .0011$), *StereoNo-TactileRough-DeformYes* and *StereoYes-TactileSmooth-DeformYes* ($t(147) = -4.385, p = .0006$). This suggests that switching from a smooth to a rough tactile feedback might increase the perceived tactile roughness, confirming our choice of tactile parameters from the literature. Other statistically significant differences seemed to be supported by changes in visual feedback (*Stereoscopy* and *VisualDeformation*) in the *TactileSmooth* condition, such as *StereoNo-TactileSmooth-DeformNo* and *StereoNo-TactileSmooth-DeformYes* ($t(147) = -5.275, p < .0001$), *StereoNo-TactileSmooth-DeformNo* and *StereoYes-TactileSmooth-DeformNo* ($t(147) = -4.07, p = .0018$), *StereoNo-TactileSmooth-DeformNo* and *StereoYes-TactileSmooth-DeformYes* ($t(147) = -5.45, p < .0001$). This suggests that in the case of a smooth tactile feedback, adding either stereoscopy or surface deformation below the finger increases the perceived tactile roughness, therefore confirming H1. Figure 4.a shows the differences in perceived tactile roughness when stereoscopy and surface deformation are enabled for smooth textures.

4.2 Perceived visual roughness

The baseline roughness, i.e., without tactile feedback, was quite high ($mean = 60.68, sd = 20.74$ on a scale from 0 to 100). The perceived visual roughness for a trial was computed as the difference between the score (0-100) given by the participant during the trial and the baseline score given on the visual texture without tactile feedback or deformation during the training phase. An ANOVA showed an interaction *Stereoscopy*VisualDeformation* ($F(1,21) = 8.843, p = 0.007, \eta^2 = 0.3$) and main effects of *Stereoscopy* ($F(1,21) = 5.12, p = 0.034, \eta^2 = 0.2$) and *TactileFeedback* ($F(1,21) = 25.69, p < .001, \eta^2 = 0.55$). Post-hoc tests reveal that the difference of perceived visual roughness between *TactileRough* and *TactileSmooth* is statistically significant ($t(174) = 3.79, p = .0002$), with almost no reduction of perceived visual roughness from the baseline in the case of a rough tactile feedback ($mean = -2.04, sd = 17.2$) to a larger reduction in the case of smooth tactile feedback ($mean = -12.8, sd = 20.3$). This suggests that a smoother tactile feedback leads to a lower perceived visual roughness (relative to the participants judgment of the texture without any feedback), as shown on Figure 4.b, and therefore confirm our hypothesis H2.

4.3 Perceived depth

An ANOVA performed on *PerceivedDepth* revealed statistically significant main effects of *Stereoscopy* ($F(1,147) = 13.42, p = .0003, \eta^2 = 0.077$), *VisualDeformation* ($F(1,147) = 513.23, p < .0001, \eta^2 = 0.828$) and a significant interaction *Stereoscopy*VisualDeformation* ($F(1,147) = 12.87, p = .0004$). Post-hoc Holm adjusted t-tests showed statistically significant differences between *StereoNo-DeformNo* and *StereoNo-DeformYes* ($t(147) = -13.98, p < .0001$), between *StereoNo-DeformNo* and *StereoYes-DeformYes* ($t(147) = -15.89, p < .0001$), between *StereoNo-DeformYes* and *StereoYes-DeformNo* ($t(147) = 13.93, p < .0001$), between *StereoYes-DeformNo* and *StereoYes-DeformYes* ($t(147) = -15.84, p < .0001$).

Differences in perceived depth went from almost none when no deformation was present ($mean = 0.3mm, sd = 1.01mm$) to almost half the actual deformation size when there was deformation($mean = 4.64, sd = 2.31$). This suggests that the difference in perceived depth are mainly due to the surface deformation, which were correctly detected by participants. However, we could not conclude on this as we did not see any statistically significant main effect of *TactileFeedback* over the *PerceivedDepth*.

4.4 Perceived overall roughness

An ANOVA performed on *OverallRoughness* revealed statistically significant main effects of *Stereoscopy* ($F(1,147) = 10.53, p = .001, \eta^2 = 0.071$) and *TactileFeedback* ($F(1,147) = 283.12, p < .0001, \eta^2 = 0.850$). No significant interactions were observed. This result partially confirms H3, with stereoscopy and tactile roughness both increasing the overall perceived roughness. We can however not conclude regarding the effect of surface deformation below the finger. The effect of *TactileFeedback* and *Stereoscopy* on overall perceived roughness is depicted on Figure 4.c and 4.d.

5 DISCUSSION

In this section, we provide an in-depth analysis of our results. We then discuss their implications and potential applications.

5.1 Modification of the perceived tactile roughness

Our results suggest that tactile roughness can be amplified on smooth textures by adding 3D visual feedback, in the form of stereoscopic rendering of the texture surface and/or by the deformation of this surface below the finger. More precisely, we observe an increase of more than 15 points (on a 100 points scale) when adding 3D visual feedback. This is especially interesting in the case of devices or tactile feedback technologies where smooth tactile feedback represents a key element of the system. In these circumstances, adding 3D visual feedback can help provide an impression of rougher tactile textures. Furthermore, some of our participants (P4, P14, P20, P21) explicitly stated that the combination of stereoscopy, surface deformation, and smooth tactile feedback was their preferred condition, with P4 describing it as a congruent experience. While texture deformation can easily be implemented on any display through mesh deformation at the touch coordinates, stereoscopy requires additional equipment, such as glasses for active or passive stereoscopy, or even auto-stereoscopic or multiscopic displays. However, such technologies are now widely accessible, from large screens to mobile ones. Although the effect on feedback amplitude would need to be confirmed by further experiments, we believe this could also help increase the perceived roughness in case of weak tactile feedback. However, we can not conclude on the preponderance of either stereoscopy or surface deformation on the perception of tactile roughness. We can neither conclude on the effect of stereoscopy nor surface deformation in the case of rough textures. We believe that this could be due to the preponderance of tactile over visual, with a strong tactile perception "taking over" the visual perception and masking its effect. Moreover, this result seems to confirm the founding of Ujitoko et al. [42] in a scenario where the presence of deformation, as pseudo-haptic feedback similar to cursor oscillations, increase the perceived roughness of textures.

However, in contrast with their results, in our experiment the increase of perceived roughness appears to happen only for textures defined as smooth [9]. We believe this could be due to the predominance of the tactile modality. In the case of rough textures, the added visual depth cues might not make a strong enough perceptual change, although this would need to be confirmed by further study.

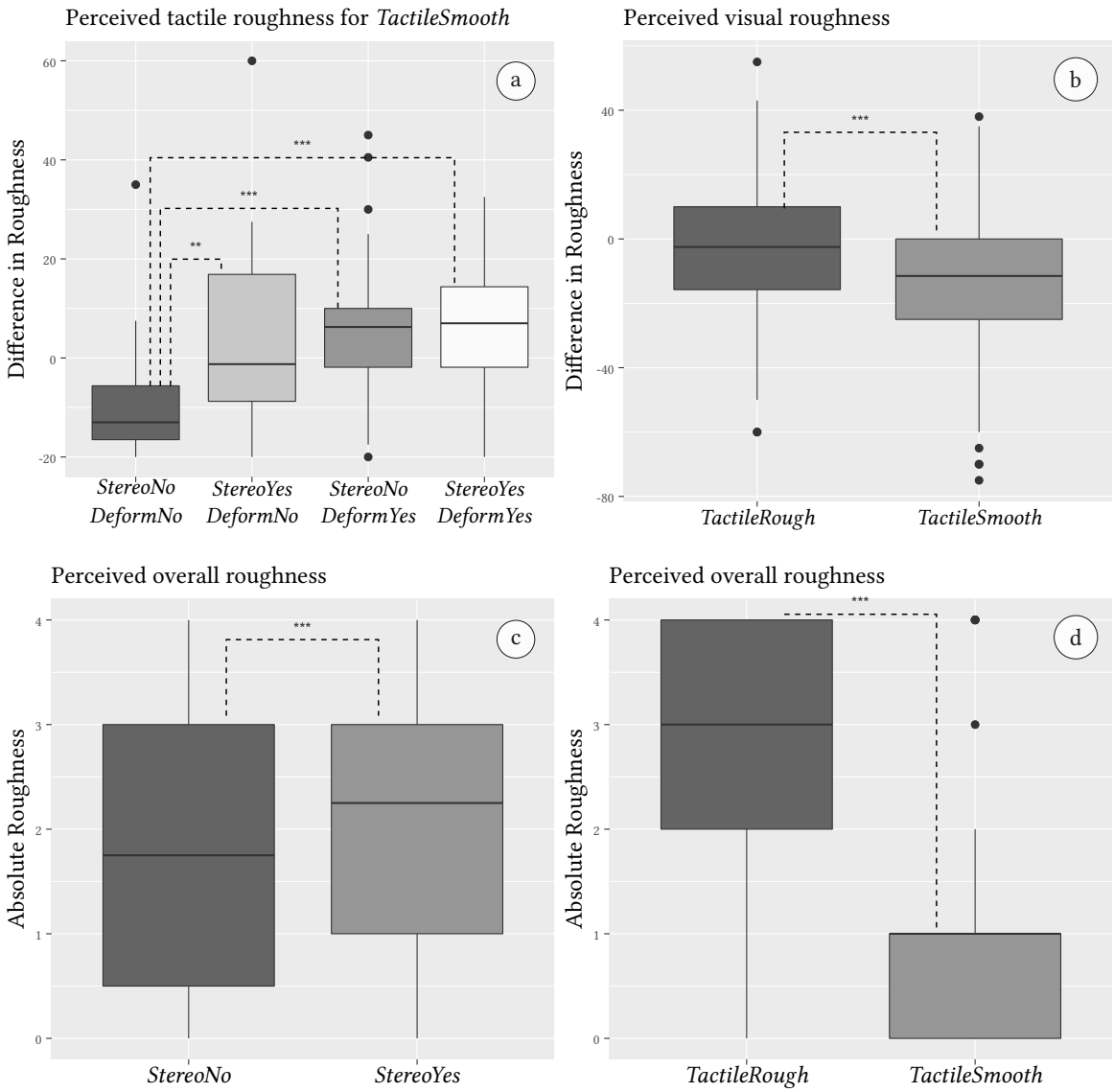

Fig. 4. Plots of statistically significant results: a) Effect of *Stereoscopy* and *VisualDeformation* on the perceived tactile roughness, b) Effect of *TactileFeedback* on the perceived visual roughness, c) Effect of *Stereoscopy* on the overall perceived roughness, d) Effect of *TactileFeedback* on the overall perceived roughness.

5.2 Modification of the perceived visual roughness

Our results suggest that the perception of visual roughness can be modified by changing the roughness of the tactile feedback, with an increase of more than 10 points in our subjective 100 points scale when using a rough tactile texture. In particular, it seems that using a square waveform instead of a sine waveform, which was proven to increase the perceived roughness on textures rendered with

ultrasonic friction reduction [9], increases the level of perceived visual roughness. This can be useful in cases where one wants to modulate the perceived roughness of a displayed texture, for commercial (e.g. allowing users to experience a wider range of material on displayed products), cultural (e.g. allowing visitors to get a more accurate feeling of the roughness of the surface of exhibited artifacts) or artistic applications (e.g. providing additional perceptual cues in an art gallery by designing multimodal experience, similarly to what was done by Vi et al. [46]). In addition, when the display resolution is too small (e.g. on mobile devices) to offer enough detail to render, tactile feedback can be used to modulate the perceived visual roughness when no more visual details can be added.

These results are important also because they confirm the correctness of the choice we made for the synthetic texture used during the experiment. Indeed, it seems that the participant's perception changed because of either the added stereoscopic rendering or the change in tactile feedback, meaning that the variations in roughness perception were due to the conditions but not to the small variations in the randomly generated visual texture, or to the nature of the texture itself. Our results finally seem in accordance with previous research on visual cues influencing roughness perception, such as light direction which emphasises reliefs. In fact, they suggest that stereoscopy and the induced binocular disparity could be another factor of perceived roughness on visual textures.

5.3 Modification of the overall roughness and preponderance of tactile feedback

In the overall estimation of roughness, although we see an effect of stereoscopy, we observe that it is mainly the tactile feedback that has an effect. Effects size indeed show that the statistically significant effect of stereoscopy remains small, while the effect of tactile roughness is very high and leads to an increase of around 2 points in our 5 points scale, representing an increase of the overall perceived roughness of about 40% in our subjective scale. Therefore, it seems that when participant have to judge the overall roughness (after the integration of visual and tactile information), the tactile information weighs more than the visual information. Indeed, this suggests that if the goal is to modulate the perception of the overall roughness on a visual-tactile texture, more relevance should be placed on tactile rendering, although stereoscopy can also increase the roughness but to a lesser extent.

This result may seem to contradict theories on multisensory cues integration [10], i.e. the visual modality should dominate the overall perceived roughness because of a lower estimation variance. However in our case the visual aspect of the texture did not change much between conditions (we used variations of the same visual noise), with only the added stereoscopic depth cue, which might explain the relative importance of haptic. We believe that by changing the visual frequency or smoothness of the texture the visual modality would dominate.

5.4 Limitations

Our results should be taken with precautions, given some limitations in our experiment. First of all, we used generated noisy textures to avoid the effect of known materials on the perceived roughness. Further experiments should investigate if our results remain with known / real 3D textures, i.e. fabric, wood, sand, and others. Moreover, we used a fixed head position on our 3D rendering to isolate the effect of stereoscopy in visual depth perception. However, head-tracking would provide additional visual cues of the depth of textures and might increase the perceived roughness. Our implementation of friction reduction by ultrasonic vibration did not take finger speed into account. Depending on the participant's finger speed during texture exploration, we may have introduced variability in the spatial period of perceived tactile textures. Even if we were interested in the effect of the tactile waveform (and not spatial period), we do not believe such (limited) variability was an issue. Indeed, it has been shown that roughness perception of macro-textures are not affected by finger velocity [19, 27, 38]. Finally, a fixed finger velocity of 60 mm/s has been set for our haptic surface and these value has been selected in a pretrial session. We did not use absolute scales for testing visual or tactile roughness. We used differences between scores given or obtained in training and scores of the experiment. Nevertheless, relying on an absolute scale, such as physical textures, may allow more precise measurement of perceived roughness. However, the objective of the investigation was to exclude the use of real texture to avoid bias due to known textures. The ratio of males and females in the experiment should be taken into account while considering the generality of the results. Even if we aimed to have a balanced population in terms of gender, due to the pandemic, we had to deal with a reduced number of participants. This results in a less balanced population where males represent approximately 72% of our population. Indeed, this unbalanced gender ratio may affect the generality of the insights but still, no research has been

conducted on the effect of an unbalanced group for this kind of studies [32]. Indeed, no guidelines exists suggesting which ratio between male and female is appropriate or which effect an unbalanced group may have on the results.

5.5 Example applications

In this section, we envision three example applications of our results with friction modulation feedback and stereoscopy or surface deformation.

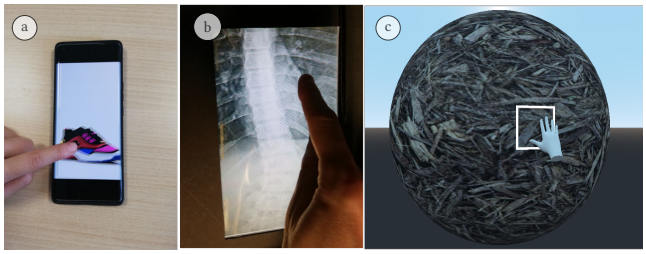

Fig. 5. Mockup applications of combined 3D visual and tactile texture exploration : a) an auto-stereoscopic mobile display for visual-tactile material rendering b) Visual-Tactile exploration of a 3D texture in a medical context c) Texture rendering / editing in Virtual Reality

5.5.1 ***Tactile textures amplification on mobile devices.*** A first possible application would be the use of mobile devices. In this scenario, it is possible to combine tactile feedback (based on friction modulation) and stereoscopic rendering (using auto-stereoscopy) for texture exploration. This combination would allow displaying textures with a wide range of perceived roughness and would be useful in different situations, ranging from commercial products presentation to the exploration of the surfaces of exhibited artifacts in cultural heritage contexts. A mockup for the exploration of the material of clothes is shown in Figure 5.a.

5.5.2 ***Exploration of 3D textures.*** A second application that we envision is to enrich the visual examination of 3D visual textures, such as MRI scans, by adding tactile feedback to amplify the perceived visual roughness. This combination could be useful in scientific data explorations, such as large point clouds, or medical 3D textures. Figure 5.b depicts a chest scan displayed on our prototype, which could be explored both visually and tactically with an increased range of roughness, therefore potentially helping the discrimination of zones with different densities in the texture.

5.5.3 ***3D objects interaction with visual-tactile surfaces.*** The third envisioned application involves the combination of stereoscopy, surface deformation, and tactile feedback in a virtual reality environment for the edition or exploration of 3D surfaces. As depicted in Figure 5.c, a virtual frame representing a physical handheld tactile plate could enable the selection and exploration of part of the 3D scene, similar to what was proposed by Montano et al. [30] for dense environments selection.

6 CONCLUSION

In this paper, we investigated the interaction between 3D visual cues (stereoscopy and surface deformation) and tactile feedback and their effect on roughness perception in the context of virtual texture exploration. Adding to general knowledge on perceptual interaction and visual-tactile display, our results suggest that stereoscopy and deformation modify tactile perception in the case of smooth tactile textures, that visual perception is affected by tactile feedback and that tactile feedback is prominent in the overall judgment of roughness. Our results can be used as guidelines for all interface designers that want to use stereoscopy/deformation and tactile feedback in an active touch condition (such as ultrasonic vibration, electrovibration, or others). Indeed, this can help designers in different fields such as education, scientific data exploration, medical applications, gaming, and many others. In future work, we want to implement stereoscopic vision using a VR headset with the addition of a head-tracking and hand-tracking system for

visual-tactile interactions. In this situation, we would like to investigate the effect of a virtual hand instead of a real one in visual and tactile perception. Finally, we aim at combining auditory feedback with our existing system. We are interested in how this modality can affect our visual and/or tactile perception since this still needs to be addressed.

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