



# "Kapow!": Studying the Design of Visual Feedback for Representing Contacts in Extended Reality

Julien Cauquis, Victor Rodrigo Mercado, Géry Casiez, Jean-Marie Normand, Anatole Lécuyer

## ► To cite this version:

Julien Cauquis, Victor Rodrigo Mercado, Géry Casiez, Jean-Marie Normand, Anatole Lécuyer. "Kapow!": Studying the Design of Visual Feedback for Representing Contacts in Extended Reality. VRST '22 28th ACM Symposium on Virtual Reality Software and Technology, Nov 2022, Virtual/Tsukuba, Japan. 10.1145/3562939.3565607 . hal-03797952

**HAL Id: hal-03797952**

**<https://hal.science/hal-03797952>**

Submitted on 7 Nov 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

# “Kapow!”: Studying the Design of Visual Feedback for Representing Contacts in Extended Reality

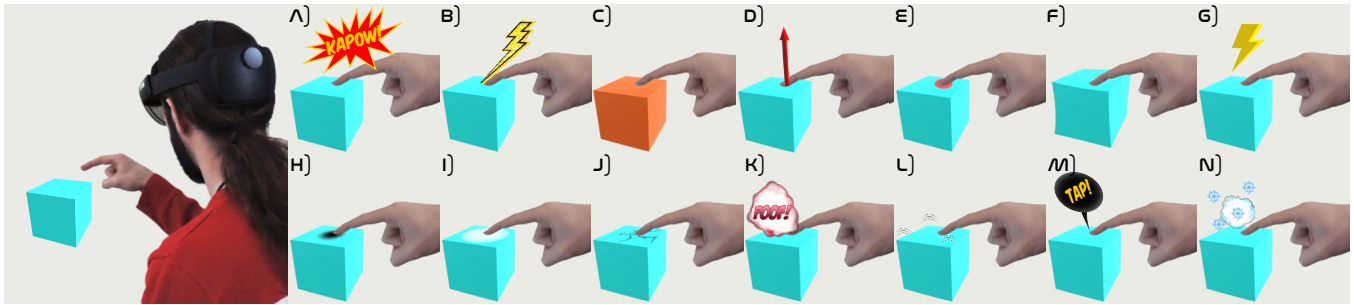
Julien Cauquis\*<sup>†</sup>  
Inria, Univ Rennes, CNRS, IRISA,  
Arts et Métiers Institute of Technology  
Laval, France  
julien.cauquis@gmail.com

Víctor R. Mercado\*  
Inria, Univ Rennes, CNRS, IRISA  
Rennes, France  
vrmercado@outlook.com

Géry Casiez<sup>‡</sup>  
Univ. Lille, CNRS, Inria, Centrale Lille,  
UMR 9189 CRISTAL  
Lille, France  
gery.casiez@univ-lille.fr

Jean-Marie Normand  
Nantes Université, ENSA Nantes,  
École Centrale Nantes, CNRS,  
AAU-CRENAU, UMR 1563  
Nantes, France  
jean-marie.normand@ec-nantes.fr

Anatole Lécuyer  
Inria, Univ Rennes, CNRS, IRISA  
Rennes, France  
anatole.lecuyer@inria.fr



**Figure 1:** Our set of visual feedback techniques meant to represent contact in extended reality. These techniques were conceived using the design space presented in this paper and implemented in a Microsoft HoloLens 2 (left). The techniques are the following: A) Kapow, B) Lightning, C) Color Change, D) Arrow, E) Disk, F) Deformation, G) Spark3D, H) Hole, I) Ripple, J) Crack, K) Poof, L) Shaking, M) Bubble3D, and N) Snowflakes.

## ABSTRACT

In absence of haptic feedback, the perception of contact with virtual objects can rapidly become a problem in extended reality (XR) applications. XR developers often rely on visual feedback to inform the user and display contact information. However, as for today, there is no clear path on how to design and assess such visual techniques. In this paper, we propose a design space for the creation of visual feedback techniques meant to represent contact with virtual surfaces in XR. Based on this design space, we conceived a set of various visual techniques, including novel approaches based on onomatopoeia and inspired by cartoons, or visual effects based on physical phenomena. Then, we conducted an online preliminary

user study with 60 participants, consisting in assessing 6 visual feedback techniques in terms of user experience. We could notably assess, for the first time, the potential influence of the interaction context by comparing the participants’ answers in two different scenarios: industrial versus entertainment conditions. Taken together, our design space and initial results could inspire XR developers for a wide range of applications in which the augmentation of contact seems prominent, such as for vocational training, industrial assembly/maintenance, surgical simulation, videogames, etc.

## CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; **Interaction paradigms**; **Mixed / augmented reality**; **Virtual reality**;

## KEYWORDS

Extended Reality, Contact, Visual Feedback, User Experience, Design Space

\*Both authors contributed equally to this research.

<sup>†</sup>Current affiliations: IMT Atlantique, Lab-STICC, UMR CNRS 6285, Brest, France and CLARTE, Laval, France

<sup>‡</sup>Also with Institut Universitaire de France.

**ACM Reference Format:**

Julien Cauquis, Victor R. Mercado, Géry Casiez, Jean-Marie Normand, and Anatole Lécuyer. 2022. "Kapow!": Studying the Design of Visual Feedback for Representing Contacts in Extended Reality. In *28th ACM Symposium on Virtual Reality Software and Technology (VRST '22)*, November 29–December 1, 2022, Tsukuba, Japan. ACM, New York, NY, USA, 11 pages. <https://doi.org/10.1145/3562939.3565607>

## 1 INTRODUCTION

Extended reality (XR) has become increasingly popular over the last decades due to the democratization of technologies that allow rendering virtual objects with which users can interact. In particular, hand tracking increases users' immersion by allowing the XR systems to detect when users "touch" a virtual object, leading to more responsive mixed environments. Touching objects in XR has led to augment scenarios in different contexts: daily-life usage [24], entertainment [7], industry [23], and medicine [19].

A current challenge for immersive technologies such as virtual (VR), augmented (AR), and mixed reality (MR) is to provide a cogent sensation when touching or grasping virtual objects (in this paper, no physical proxy object is mentioned). Indeed, virtual objects do not have a tangible counterpart in a real environment thus touching them does not elicit any haptic feedback. To address this challenge, both industry and research have considered using visual feedback to indicate that an action occurred when users "touch" a virtual object. The considered solutions rely on user interface (UI) messages and abstract signaling and/or highlighting the virtual objects. Without visual feedback for representing contact, users are prone to trespassing the objects' meshes when touching them, thus compromising their immersion in the virtual environment [37]. For that reason, this paper explores the design of visual feedback for representing contact with virtual objects in XR. We created a design space with a comprehensive list of characteristics conveyed by visual feedback in terms of object's and contact's properties.

We used this design space to create a set of visual feedback techniques (see Fig. 1). This set reproduced some techniques from the literature and also introduced new techniques to represent physical properties as well as visual effects from comics. The contributions of this paper can be summarized as follows: (i) a design space for conceiving visual feedback to represent contact with virtual objects in XR (see Fig. 2); (ii) a literature analysis and classification of visual feedback to represent contact with virtual objects in XR; (iii) the implementation of 14 visual feedback techniques conceived from different combinations of our design space's features and the conduct of an online preliminary user study to evaluate 6 of them in terms of user experience, both meant to illustrate the pertinence of our presented design space.

The remainder of this paper is structured as follows: Section 2 describes related work. Section 3 presents our design space, while Section 4 presents the implemented visual feedback techniques. Section 5 presents our preliminary user study. The discussion and conclusion are found in Sections 6 and 7 respectively.

## 2 RELATED WORK

Related works on visual feedback to represent contact with virtual objects have considered the use of visual techniques. Here we first explain and decompose the contact task in XR. Then, we present

the different types of visual feedback techniques previously used for representing contact. Last, we present the evaluation methods used in the literature to assess these techniques.

### 2.1 Contact in Extended Reality

Contact can be defined as the action of two bodies touching each other [33]. From this definition, Sreng et al. described contact with two states: free motion and contact. Then they proposed the following terms to better characterize the second state: a contact starts with an impact and ends with a detachment. This could be seen as a three-phases decomposition: free motion (before contact), impact (at contact), and detachment (after contact).

This decomposition in three phases of the *touching* interaction could also be applied to another common hand-based interaction in XR environments: *grasping*. Grasping can be bare handed or not, as one of the differences between VR and AR is the fact that AR favors controller-free interactions [31, 35]. Within MR, freehand grasping is the manual grip between a (real) user and a (virtual) object without using wearable sensors. [1] decomposed grasping in several phases: planning, reaching, pre-load, load, transition, and release. This definition could be simplified, as planning, reaching, and pre-load refer to what happens before the contact, load and transition are phases happening during the contact, and release refers to what happens after contact.

Thus, similarities exist for both touching and grasping in matters of movement's decomposition with three phases of approach (before contact), contact (at contact), and releasing (after contact). This decomposition appears in the proposed design space (Section 3), as the following features proposed by Sreng et al. to characterize a contact: its position, its direction, its distance, and its force [33].

### 2.2 Visual Feedback for Representing Contact in Extended Reality

In the absence of haptic feedback, visual feedback can be used to acknowledge a contact occurrence as it was shown since the 90s: in the absence of haptic feedback, sensory substitution (with visual feedback) increased the grasping performance [12]. More recently, it has been observed that visual feedback increased the performance to carry out a simple task such as a "3D pong" task in a virtual environment [13]. Visual feedback strategies for contact augmentation have considered integrating techniques that signal when a contact with a surface occurs.

Sreng et al. proposed in 2006 a set of visual feedback designed to display information about distance, contact and effort between objects. It enclosed the addition of light sources, and glyphs (arrows, disks, spheres) when the manipulated object is close or in contact with another virtual object. Visual animations such as color change, size change, and shape deformation were applied to the glyphs, as a function of distance between objects or amplitude of contact forces. Their results suggest that user preference for a visual feedback varies with the modality of use, as for instance the deformation of the glyphs seems to be preferred regarding a better understanding of the contact situations, while the change of the glyph's color seems to be preferred concerning the perception of distances between the virtual objects. Concerning preference over the glyphs' shape,

participants ranked the disk first, the sphere second, and the arrow third [34].

Inspired from this work, Prachyabrued and Borst proposed later a set of visual feedback techniques for representing object grasping comprising the following: no interpenetration between hand and object, full hand-object interpenetration, object see-through, using an auxiliary hand rendering for displaying interpenetration, coloring the hand fingers in contact with the object, coloring the touched object, displaying arrows representing the interpenetration size, and virtual hand vibrations. Their results suggest that grasp techniques should use object color changing or finger color changing when designers want to favor user preference over grasping performance [28]. Differences between penetration and interpenetration visual feedback techniques were then further evaluated by [8] who also analyzed the performance, level of ownership, and user preference of eight different visual feedback techniques for virtual grasping. Their results indicate that users prefer visual feedback that represents the users' hand outside the object, showing no interpenetration at all, which is also in line with the results from [28].

In 2018, the work of [15] retrieved the color changing, transparency, and shaking techniques proposed by [28] and added other visual feedback techniques such as flashing, highlighting, and deforming virtual objects upon contact. Results of their study also suggest that color changing and highlighting techniques perform the best in terms of response time and participant's satisfaction [15]. Rendering transformation and especially visual feedback techniques based on color changing are also used in the work of [38], who presented a usability evaluation of four common visual feedback for grasp-and-release tasks using bare hand interaction: object coloring, connecting lines, shadow, and object halo. Results from their study suggested that some feedback techniques are more usable than others regarding particular measures only, which is consistent with previous studies. They suggest using proximity-based coloring techniques for visual feedback. Depending on the application goals, they recommend "object coloring" for better performance and "object halo" for better user satisfaction. Later, [14] investigated the performance of visual feedback also based on object color changing for representing object grasping. Their results showed that users preferred when additional hand color feedback is provided within the VR environment. These results also suggest that user experience differs according to the different feedback types and that some can furthermore decrease this experience (in their case the addition of a picture coupled with the touched object's color change). According to [14] results, it is important to choose suitable task-oriented feedback that could contribute the most to users' experience, which is in line with the results of [34].

Contact augmentation in AR has also considered the possibility of subtracting parts of the virtual object, which is another rendering transformation, to give users the sensation of grasping an object as shown in the work of [35] and in the work of [2]. However, they did not compare such visual feedback techniques with others. Another noteworthy work considering visual feedback in AR is [41], where contact augmentation is used to allow the user to be aware of the tracking boundaries of a device, thanks to the addition of a glyph (coordinate lines), or changes in boundaries' render. Touch with more traditional objects is acknowledged with a color change, while

grasp is highlighted with the addition of an arrow, guiding the user during the object displacement.

Recently, in the domains of commercial products, XR development kits such as SteamVR (version 1.19) and Microsoft's Mixed Reality Toolkit (MRTK - version 2.7.0) propose solutions for informing contact with surfaces in XR. SteamVR uses a highlight around the object's contour when it is selected and touched. Microsoft's MRTK has allowed designers to attach a bounding volume around the virtual object to signal that a contact had occurred. Contact with this bounding box's anchors was also acknowledged thanks to the anchor's visible deformation when touched by the user. Recently, they proposed a visual effect that highlights a part of the virtual object's mesh and its entire contour upon contact [30]. Another company showing interest in the design of virtual contacts is Ultraleap, who offers some guidelines to help creating objects' affordances [36].

## 2.3 Evaluating Visual Feedback for Representing Contact Information

Regarding the evaluation of visual feedback techniques for representing contact with virtual surfaces in extended reality, existing techniques rely primarily on the assessment of visual feedback performance as in the case of [8, 14, 15, 28, 38, 41]. Performance is evaluated either through a measure of the time needed to complete a task or a part of it [8, 14, 15, 28, 38, 41], a measure related to finger penetration [8, 28], a measure of task precision [28, 38], physiological responses [15] or errors while performing the task [38, 41].

Global preference of visual feedback techniques was also used as a secondary form of evaluation, except for [34] who focused their evaluation on user preference. These evaluations were based on subjective questionnaires designed to rank the different visual feedback [15, 28, 34, 38, 41]. Finally, user experience has also been evaluated by the User Experience Questionnaire (UEQ) [32] in the studies of [14, 41]. However, to the best of our knowledge, the influence of the use case scenario on visual feedback techniques in terms of user experience was never evaluated.

## 2.4 Summary

As mentioned above, work has been carried out by the community regarding the design and evaluation of visual feedback to represent contact with virtual objects. According to our literature review, this is mainly achieved through rendering transformations, such as color changing. However, as far as we know, there are no guidelines, nor design recommendations to follow when creating visual feedback for contact. As a consequence, in this paper, we first introduce a design space to help designing visual feedback to represent contact with virtual objects for XR applications. Then, we propose a set of visual feedback techniques, before conducting a preliminary evaluation of a subset of these techniques in terms of user experience and in different application contexts.

## 3 DESIGN SPACE

As the analysis of existing literature has exhibited, augmenting contact with virtual objects can be enhanced through the use of visual feedback techniques. The design of these techniques can take

a large number of possibilities. Therefore, we created a design space to guide designers and researchers through the different paths that could be taken to conceive visual feedback specifically related for representing contact with virtual objects.

### 3.1 Design Space Organization

The design space is organized through five blocks answering the questions: What?, Who?, Where?, When?, and How?. The structure of this design space is inspired on the method of asking questions which are considered fundamental for gathering information about an event [43] and has been used in other design spaces [18]. The work of [29] also emphasizes these five questions: “Touch is a cultural practice imbued with social norms concerning who can legitimately touch what and who, where, how and when” [29]. The questions intend to describe the way the visual feedback technique is implemented for providing contact information. Our design space is presented in Fig. 2.

A visual feedback technique is iteratively crafted by exploring each of the five proposed blocks of our design space. The branches of these blocks can be explored once or several times depending on the questioning (e.g. When? is always asked once for creating one visual feedback, while What? could be answered several times for the same feedback) to create different iterations of visual feedback.

The block **What?** refers to the properties of the object that are going to be represented through the visual feedback. Two branches are considered in this block. The first, considers the possibility of representing *object's properties* through visual feedback. The object's properties branch considers *physical properties* such as temperature, hardness/softness, brittleness, surface roughness, etc. An instance of softness visual feedback could be seen in the work of [31]. This block also considers *object's affordances* such as the object's harmfulness, grasping features, etc. Affordances arise from the combination of some features of the object/environment and some features of the animal (e.g. a user), it concerns both the function of artifacts (e.g. a virtual object) and how artifacts are manipulated [11]. In the work of [3, 23], visual feedback is used to notify the graspable aspect of certain objects within their virtual environment. In [41], visual feedback allow boundary awareness. The second branch is designed to help researchers to specify the different properties related to contact with a surface such as occurrence, location, force, direction, and distance (including interpenetration) as seen in the work of [34]. The aforementioned work considers the use of glyphs such as arrows, spheres and disks for depicting these contact-related information when touching a virtual object.

The block **Who?** refers to the target object on which the visual feedback will be applied. Three possibilities are considered in this dimension: (i) applying the visual feedback to the *manipulator object* such as the users' hand model or the virtual or real object manipulated by the user's hand, such as a stylus; (ii) applying the visual feedback to the *touched object*, and (iii) applying the visual feedback to an external, *dedicated object*, such as a helmet visor, a virtual billboard, etc. For instance, Fabiani et al. used a dedicated LED bar as a visual feedback in their experience [12]. When designing a visual feedback, designers can only choose one feature

of this block, making the choices mutually exclusive. Examples of visual feedback applied to the manipulator object can be found in the work of [28] in which the users' virtual fingers are colored in red when they are in contact with an object in VR. Color changing can also be applied directly to the touched object [15, 26].

The block **Where?** brings designers and researchers different possibilities for selecting the location of the visual feedback with respect to the target object. This block offers mutually exclusive choices. The feedback could be *co-located* with respect to the contact area or it could be located onto the target object's *surface* [25] or *volume* [5]. This block also considers the possibility of placing the visual feedback at a location with a certain *offset* from the actual target object [20]. The work of [34] displays disks co-located at the zone of contact between users and virtual surfaces. An instance of offset between the visual feedback and the target object's surface can be observed in the work of [9], where onomatopoeia are displayed next to the touched virtual objects. The purpose of this feedback is to recreate an onomatopoeia effect the same way sound feedback is visually represented in comics [22].

The block **When?** addresses when the visual feedback appears once a contact with a surface has happened. Based on the definitions of the touching and grasping phases (see Section 2), this block offers three possibilities: making the visual feedback appearing (i) *before* contact, (ii) *at* contact, and (iii) *after* contact. This block offers mutually exclusive choices.

The block **How?** details how the visual feedback is going to be displayed in the virtual environment. There are six branches in this block: the target object's (i) *transformation*, the (ii) *addition* of an element, the visual feedback's (iii) *intensity*, (iv) *duration*, (v) *dimension*, and (vi) *animation*. The first two branches (i-ii), cannot be explored at the same time when creating a visual feedback technique since they describe how the technique behaves. The other branches (ii-vi) must be explored simultaneously every time when creating a visual feedback technique since they describe the technique's display properties. In the case of target object transformations, this design space considers the following possibilities: *deformation*, *breaking*, *rotation*, *translation*, *scaling*, and *rendering* transformation (such as the most used color changing effect). The work of [15] considered object transformations such as rotation, translation, and scaling when contact was applied to the object's virtual surface.

This block also considers the possibility of integrating other visual elements as visual feedback, such as *lights*, *particles*, *onomatopoeia*, and *glyphs*. Examples of light addition can be found in the recent contact representation technique proposed by Microsoft [30] and in the work of [15] where conical and spherical light effects were evaluated. The *intensity* of the visual feedback can be fixed or variable. A *fixed* intensity means that the visual feedback is displayed in an identical way every time it is elicited. The intensity can vary either discretely or continuously. A *variable* intensity means that the visual feedback display can augment or diminish according to other parameters related to contact (e.g., the contact force, the contact's duration). An example of variable intensity display can be seen in the work of [34] in which the contact force defines the color of the visual feedback.

The *duration* of the visual feedback can be permanent, fixed or variable. A *permanent* duration means that the feedback does not disappear after being displayed. A *fixed* duration means that the feedback is displayed during a pre-determined amount of time. A *variable* duration means that the duration differs according to other parameters (e.g., the contact force, the contact's duration). The duration can vary either discretely or continuously. The *animation* branch in this block considers if the visual feedback is animated or not. The *dimensionality* feature considers if the feedback is represented over three dimensions (3D) or within a plane (2D).

This design space helps to describe, generate, and compare visual feedback for augmenting contact with virtual objects in XR. Hereby, we classify more than fifty visual feedback from more than twenty different contributions within its branches, as shown in Fig. 2.

#### 4 VISUAL FEEDBACK TECHNIQUES FOR REPRESENTING CONTACT IN XR

We implemented a set of 14 visual feedback techniques that illustrate different combinations of our design space (see Fig. 1 and our accompanying video). These techniques were implemented using the Unity 3D engine and Microsoft's MRTK. We tracked the user's index finger, and attached to its tip a Unity sphere collider. This allowed us to acknowledge the occurrence of a contact with virtual objects by using the Unity 3D physics engine. These techniques were run and tested with a Microsoft HoloLens V2.

This set includes techniques to represent contact with virtual surfaces based on physical effects such as brittleness and roughness, as well as graphical elements inspired from comic books such as onomatopoeia (Kapow and Poof as seen in Fig. 1 A and K) or other graphical elements such as Lightning and Bubble3D (Fig. 1 B and M). We also implemented visual feedback techniques based on previous literature such as Disk [34], Arrow [28], and Color Change [15] (see Fig. 1 E, D, and C).

With this set of visual feedback techniques, we aimed at exploring branches of our design space that were not explored before in previous work. In the block What? we intended to explore the representation of the object's properties. Concerning the block Who? and When? we decided to keep all our techniques focused on the touched object and displayed at the moment of contact since we wanted to homogenize our visual feedback techniques implementations according to those proposed by previous works. In the block Where? our techniques explored different positions of the visual feedback with respect to the contact point between the users' hand and the virtual object. As for the block How? we intended to illustrate the addition of elements such as onomatopoeia, particles, and glyphs of the What? block of our design space. We also explored the possibilities of having animated techniques, as well as exploring techniques with different types of intensity displays and duration. The table in the supplemental materials depicts how our set of visual feedback techniques is implemented with respect to our design space.

A subset of visual feedback techniques is inspired by physical phenomena. We designed the Crack technique to represent the target objects' brittleness by projecting a crack over its surface (Fig. 1 J). We created two techniques (Hole and Deformation) to represent the target object's deformation after a contact (Fig. 1 H and F). The

Hole technique displays a representation of a cavity on the target object's surface where the contact happened. The Deformation technique deforms the entirety of the target object's volume upon contact. The Snowflakes technique aimed at representing the target object's temperature through a mist and snowflakes when a contact occurs (Fig. 1 N). We also implemented the Ripple technique that displays rippling waves on the object's surface on contact (Fig. 1 I).

We considered that visual feedback techniques for representing contact could be enriched with the integration of comic-inspired graphical elements. These graphic elements, such as onomatopoeia, are often used in comics to represent the sound of an action, usually related to punches or explosions [22]. In the case of onomatopoeia, we created a set of visual feedback techniques such as Kapow and Poof. These two techniques display an onomatopoeia presenting the text "Kapow!" and "Poof!" respectively. These onomatopoeias are often used in comics for representing collisions, and therefore, we considered them for the techniques' implementations. Concerning the techniques that display other graphical elements that come from the comic context, the Bubble3D technique displays a dialog bubble that originates from the contact point with the target object. The Spark3D (Fig. 1 G) and Lightning techniques render a spark and a lightning bolt respectively in the contact area location. We also coded the Shaking technique, which displays waves around the target object to represent that the object is shaking (Fig. 1 L).

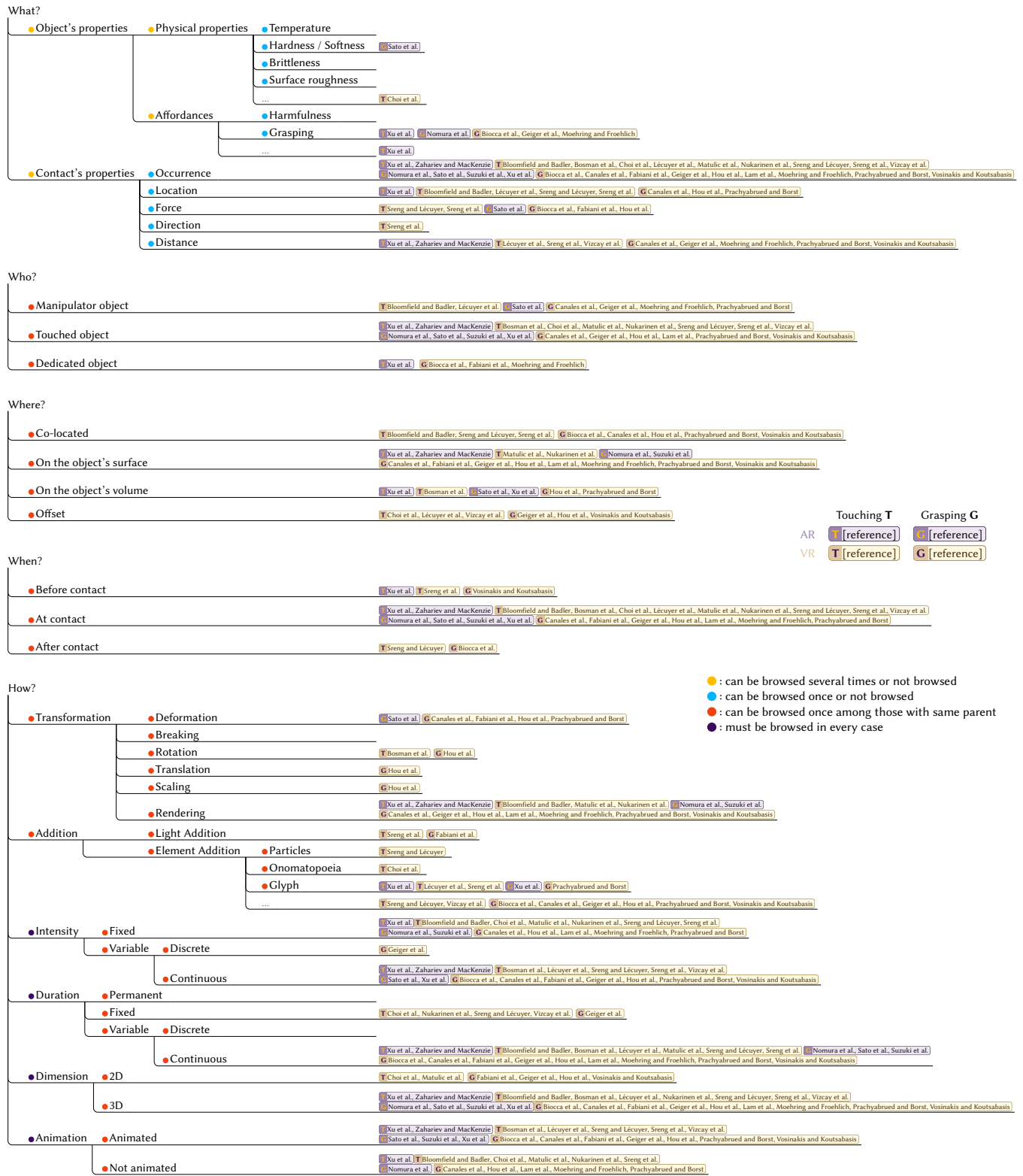
Techniques from previous research works were also implemented in this paper. The Disk technique consists in displaying a circle directly co-located with the contact point between the users hand and the virtual object. This technique was implemented based on the work of [34]. The Arrow technique was also recovered from the work of the previous authors. This technique consists in displaying a three-dimensional arrow going in the same direction as the vector normal to the surface where contact occurred. The origin of this 3D arrow is co-located with the contact point at the target object's surface. The Color Change technique was also implemented for signaling contact since these techniques has been commonly used in previous research works [4, 8, 14, 15, 19, 21, 23, 25, 26, 28, 35, 38, 41, 42].

#### 5 PRELIMINARY USER STUDY

Contact representation with virtual objects can be used in a wide range of scenarios. Thus, we designed a user study to identify if the use case scenario has an influence on the visual feedback techniques in matters of user experience. Due to the COVID-19 context, we used short videos that participants could watch online.

##### 5.1 Hypotheses

First, inspired from [14] who found that the user experience of a grasping task in VR differs due to different feedback, we hypothesized that user experience under the conditions of our preliminary study is affected by the type of visual feedback used, as some feedback can better represent contact information or can be more pleasant (H1). Our second hypothesis is that the use case scenario influences how different visual feedback methods affect the user experience (H2). Indeed, while different visual feedback's influence on user experience has been previously evaluated by comparing techniques within a specific application context, to the best of our



**Figure 2: The Design Space for Visual Feedback Techniques for representing contacts with virtual objects in extended reality. This representation includes references of previous research works.**



knowledge, the influence of the use case scenario was never evaluated. For example, some visual feedback inspired by comics may be more appropriate in a game compared to a more technical scenario.

## 5.2 Experimental Design

We considered two scenarios that are representative of major XR application contexts: industry and entertainment. The industrial scenario (industrial) consists of a car interior prototyping application. The entertainment scenario (entertainment) recreates a Whack-a-mole game (see Fig. 3). Both scenarios required to represent contacts between the users' fingers and virtual objects.

We tested a set of six visual feedback techniques that covers different features of our design space, namely: Arrow, Color Change, Deformation, Disk, Kapow, and Lightning. We chose this subset by taking into account techniques from the literature that were already tested in industrial and research contexts such as Disk, Arrow and Color Change (thus referred as industrial techniques) but also techniques that we designed with an entertainment scenario in mind, such as Kapow, Lightning and Deformation (thus referred as entertainment techniques). This set of visual feedback techniques should allow us to answer H1. We limited the number of conditions mainly to reduce the duration of the experiment. Additionally, these techniques were selected in order to have clusters that could be evaluated under different scenarios as previously stated for H2.



**Figure 3: Scenarios.** These images (industrial scenario top, entertainment scenario bottom) were shown to the participants in an online questionnaire to provide visual information about the context of use of the visual techniques.

Our two hypotheses define two independent variables: visual feedback (VF) and scenario (SCENARIO). To avoid learning and novelty effects, we used a mixed design where scenario was a between-subjects factor and visual feedback a within-subjects factor.

## 5.3 Procedure

Participants had to download an application made with Unity 3D that displayed six videos, each one depicting one of the six visual feedback techniques selected, in a random order. Each video lasted 12s where the same finger movement touching three times a virtual cube colored in cyan (as recommended by [17] to consider the Purkinje phenomenon) elicited a visual feedback under three different intensities (indicated by a text label). The displayed techniques have the same duration of one second and contact with the cube acted

as a trigger. Participants could watch the six videos as many times as they wanted and pause/resume them at any moment if desired.

Depending on their group, participants could find with these videos a description of the context where these techniques were going to be used. They were shown an image depicting one of the two possible scenarios, and were asked to have the corresponding industry (industrial) or entertainment (entertainment) context in mind when watching the videos (see Fig. 3). Accompanying the image, there was a brief description of the scenario to help participants understand the application context for the visual feedback, as well as a description of the task they had to imagine themselves performing (touching an element of a car interior or tapping a mole). In order to allow reproducibility, the videos and the scenarios' scripts used in the experiment are provided as supplemental material.

## 5.4 Collected Data and Population

The online questionnaire first collected consent from participants, before asking them demographic data. They were then instructed to fill the full version of the User Experience Questionnaire (UEQ) [32] six times, once per videos. The UEQ was integrated to understand the elicited user experience under three dimensions: attractiveness, pragmatic quality (covered by questions concerning the techniques' efficiency, perspicuity, and dependability), and hedonic quality (i.e. regarding the techniques' stimulation and novelty). Participants could also leave their comments about each technique.

60 participants (14 female, aged 19-27,  $M=22$ ,  $SD=1.8$ ) took part in the experiment. Half of them experienced the industrial scenario while the other half experienced the entertainment scenario. The participants were pseudo-randomly assigned to each group to obtain homogeneous groups in terms of gender and mean age. The experiment lasted ~25 minutes per participant. The questionnaire used in this experiment can be found in the supplemental material.

## 5.5 Results

Statistical analyses were performed using R and  $\alpha = 0.05$ . We used mixed ANOVA when normality assumption was met. When using ANOVA, Greenhouse-Geisser corrections were applied to DoFs when sphericity was violated. We used Bonferroni corrections, where the p-values are multiplied by the number of comparisons. When normality assumption was not met, we tried to normalize the data using a Box-Cox transformation [6]. If it failed we processed data using an Aligned Rank Transform (ART) [40].

In the UEQ, attractiveness is the main criterion corresponding to the overall impression of the visual feedback. Perspicuity, Efficiency and Dependability are pragmatic quality aspects, while Stimulation and Novelty are hedonic quality aspects of Attractiveness [32].

**Attractiveness.** A mixed ANOVA found a significant effect of VF ( $F_{3,8,221.2} = 24.0$ ,  $p < 0.001$ ,  $\eta_G^2 = 0.24$ ) and a significant SCENARIO  $\times$  VF interaction ( $F_{3,8,221.2} = 3.5$ ,  $p = 0.01$ ,  $\eta_G^2 = 0.04$ ) on attractiveness. Significant differences ( $p < 0.001$ ) were found between Arrow and all the other techniques except Lightning.

**Perspicuity** measures the ease to get familiar with the visual feedback. Mixed ANOVA found a significant effect of VF ( $F_{5,290} = 24.9$ ,  $p < 0.001$ ) on perspicuity. Pairwise comparisons show significant differences ( $p < 0.001$ ) between Disk and all other feedback except



Color Change, for which significant differences were found with Arrow, Kapow, and Lightning.

*Efficiency* measures users' ability to solve their task without unnecessary effort. Mixed ANOVA found a significant effect of VF ( $F_{5,290} = 23.0, p < 0.001, \eta_G^2 = 0.23$ ) and a significant SCENARIO  $\times$  VF interaction ( $F_{5,290} = 2.7, p = 0.02, \eta_G^2 = 0.03$ ) on efficiency. Significant differences ( $p < 0.005$ ) were found between Disk and all techniques except Color Change. Color Change is also significantly different ( $p < 0.001$ ) from all other techniques except Disk and Arrow.

*Dependability* measures at which point the user feels in control of the interaction. Mixed ANOVA found a significant effect of VF ( $F_{5,290} = 17.2, p < 0.001, \eta_G^2 = 0.17$ ) and a significant SCENARIO  $\times$  VF interaction ( $F_{5,290} = 4.5, p = 0.001, \eta_G^2 = 0.05$ ) on dependability. Pairwise comparisons show significant difference ( $p < 0.04$ ) between Kapow industrial and entertainment. In addition Disk shows significantly higher ( $p < 0.02$ ) dependability compared to all other feedback except Color Change.

*Stimulation* measures the excitement and motivation to use the visual feedback. Mixed ANOVA found a significant effect of VF ( $F_{3,7,214} = 15.6, p < 0.001, \eta_G^2 = 0.17$ ) and a significant SCENARIO  $\times$  VF interaction ( $F_{3,7,214} = 4.8, p = 0.001, \eta_G^2 = 0.06$ ) on stimulation. Significant differences ( $p < 0.001$ ) were found between Deformation and all other techniques except Color Change and Kapow.

*Novelty* measures how innovative and creative the visual feedback is. Novelty is higher for the feedback in the industrial scenario. Mixed ANOVA found a significant effect of VF ( $F_{5,290} = 27.8, p < 0.001$ ) and SCENARIO ( $F_{1,58} = 4.8, p < 0.03$ ) on novelty. Pairwise comparisons show a significant difference ( $p < 0.03$ ) between entertainment and industrial. They also show that Disk has significantly lower ( $p < 0.001$ ) novelty compared to all other techniques. Deformation is significantly different ( $p < 0.001$ ) from all other techniques except Kapow and Lightning.

## 6 DISCUSSION

This paper studied the design of visual feedback techniques that could be used for representing contact with virtual objects in XR. To do so, we first created a design space to help designing these techniques. Then, to demonstrate the usage of our presented design space, we created a set of 14 visual feedback techniques from our design space features to explore its generative capabilities, and evaluated 6 of those techniques in an online preliminary user study ( $n=60$ ) under two different use case scenarios: industrial and entertainment.

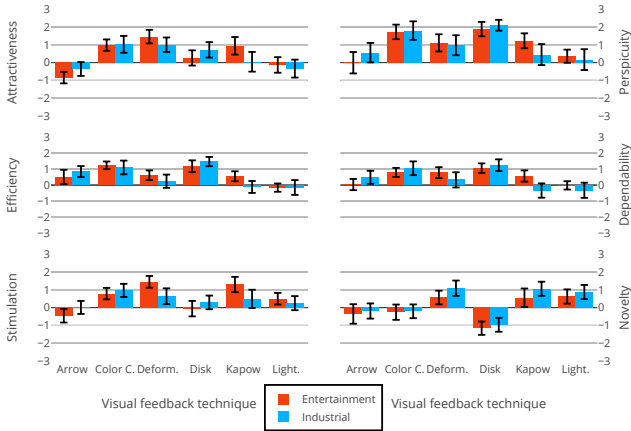
We used the UEQ [32] to evaluate users' experience of our visual feedback techniques on three different aspects: (i) *attractiveness*, i.e. the overall impression of the participants, (ii) *hedonic quality*, i.e. whether participants found them original or stimulating, and (iii) *pragmatic quality*, i.e. whether the techniques were perceived as perspicuous (clear and easy to understand), efficient or dependable (secure and predictable) for representing contact. We observed that the Color Change and Deform techniques obtained a high score on attractiveness. This might be due to the user's familiarity with these techniques in other media.

Techniques that used visual feedback that was simple to understand by participants, such as Color Change and Disk, were better evaluated in the pragmatic quality aspect of the UEQ. Regarding hedonic quality, we observed that the entertainment techniques obtained the highest scores. Another interesting feature about these techniques is that they all explored the *animated* branch of our design space.

We noticed that visual techniques which give feedback that is in some extent "familiar" to the context of touching objects is overall better appreciated by participants. This was the case of Color Change that can be found in user interfaces in other media such as mobile, web, and desktop applications. The participants' comments also qualified the Color Change feedback as simple and efficient. These results are coherent with previous works which suggest that coloring techniques yield good performance as visual feedback [15, 38]. The Disk technique also delivered good results concerning user experience. This might be due to the Disk's ability to locate on the target object the position of contact.

In contrast, techniques relying on visual feedback that cannot be found in real life contexts received mixed to negative results. For instance, participants' comments about the Kapow technique suggested that the technique was efficient for indicating that a contact occurred. However this technique did not show good results for the pragmatic quality aspects of the UEQ. The Lightning and Arrow techniques often obtained the lowest scores in the user experience evaluation. Regarding Arrow, this could be explained by the fact that the arrow always went in the direction opposite to the contact, as noticed by some participants. This result is in line with the work of [34] where the arrow technique was also ranked the lowest in terms of user experience. As for the Lightning, participants commented that it was not fit for the technical scenario and that it gave them the impression of doing something dangerous.

Based on these results, we can suggest that the low performance of these techniques in terms of user experience was due to the fact that what the feedback conveyed cannot be found in a context "familiar" enough to participants or because these representations



**Figure 4: User Experience Questionnaire results. Error bars represent 95% CI for the mean. Means are rated on a seven points Likert scale ranging from -3 (worst) to +3 (best).**

usually convey other information in real-life (e.g. the Lightning). We expected the low performance of the entertainment techniques (Kapow, Lightning, and Deformation) for the industrial scenario since they were most likely perceived as unfit for a professional, industrial scenario.

Overall these results suggest that user experience could indeed be affected by the visual feedback used, validating H1. These findings are aligned with those of [14] who suggest that user experience varies according to the provided visual feedback technique. In addition, our study's preliminary findings suggest that there is an influence of the use case scenario on visual feedback techniques in terms of user experience. Results show that the type of scenario, entertainment or industrial, impacted user experience's ratings of attractiveness, efficiency, dependability, and stimulation, but only for some of the techniques. Further research could be useful for investigating H2 and the factors behind the impact of the scenario on visual feedback.

## 6.1 Design Considerations

Based on the results of our preliminary experiment, we propose initial design considerations that could be useful for designers and researchers when considering the integration of visual feedback for representing contact with virtual objects.

We observed that visual techniques which display simple information are more appreciated by users. For some visual feedback techniques, context is an important element to consider. The design of visual feedback should be as pertinent as possible to their context. As seen in our study, user experience diminished when participants found that some techniques were not pertinent to the use-case scenario. Designers and researchers should also be aware of the semantics and meaning of elements they use to signal a contact. As we noticed, some visual feedback can be even interpreted as a warning rather than just information about contact. We noticed that the techniques that signaled the contact's location on the object's surface were better evaluated in terms of pragmatic quality.

We hope that the insights taken from our preliminary study could be applied to further research that would seek to study the impact of visual feedback for touching objects in XR. Nevertheless, caution is necessary since the results obtained in AR cannot be extrapolated to VR nor vice-versa. Future work should thus consider exploring separately VR and AR.

## 6.2 Limitations and Future Work

A study involving participants experiencing these effects in XR or in any other interactive environment was not possible mainly due to the global pandemic context. However, the visual feedback techniques were firstly implemented and tested in the HoloLens 2. Despite this, results from our online user study are in line with those from the literature [14].

To focus on techniques that could be suitable for our experimental evaluation, we narrowed the exploration of our design space. Future work could explore other branch combinations of our design space and also add other factors that could be valuable for designing visual feedback techniques. Since our evaluation focused on the qualitative aspect of the techniques, a study on practical aspects of techniques for contact representation could be carried out. Future

work could also explore the impact of the use case scenario on task performance.

The implemented visual feedback techniques in this paper gave rise to very different visual design and layout, despite having explored the same branches of our design space. This could impact users' experience. An alternative visual feedback design could certainly have influenced the results. Visual feedback in general relies on strong aesthetic components that determine their impact on user experience [14]. Further research work could explore the impact of the aesthetic components of visual feedback under different contexts in XR that require touching or grasping virtual objects. The study of the visual feedback comprehensibility could be another direction to take for future work.

Future work could further study the impact of aesthetics and clustering for visual feedback for representing contact in XR. Additionally, pseudo-haptic effect could be explored in future work to identify which types of visual pseudo-haptic feedback could be used to convey information not only about contact but also about the shape of the touched object as well as its material properties. We mainly focused our work on the sense of sight, said to be dominant over the others [27]. However, it has been shown that multi-modal feedback could help improving user performances in VR applications [10]. Thus, future work should also explore the addition of new branches in the design space to create multi-modal feedback including auditory and haptic feedback for contact augmentation. A starting point could be the work of [16] who proposed a taxonomy for sound in VR, or the works of [39] which explores the interactions between visual and haptic feedback mechanisms. Finally, even if we focused on two very representative XR application scenarios (industrial and entertainment), other scenarios could also be explored in future work.

## 7 CONCLUSION

In this paper we proposed a design space for visual feedback for augmenting the contact sensations when touching virtual objects in XR. Using this design space, we conceived a set of visual feedback techniques that illustrate its generative capabilities. We conducted a preliminary user study to assess information about user experience. Participants were divided into two groups that were asked to consider either an entertainment or an industrial use case scenario when evaluating visual feedback techniques presented in a series of videos. Results suggest that the application scenario could influence their user experience evaluation. The design space presented in this paper could pave the way to the design and evaluation of visual feedback techniques for representing contact with virtual surfaces within XR environments as a means to maintain users' sense of presence.

## ACKNOWLEDGMENTS

The author would like to thank all the participants for the time they spent in the completion of the user study, and the French National Research Agency (ANR) for funding the LobbyBot project.

## REFERENCES

- [1] Maadh Al Kalbani. 2019. *Natural freehand grasping of virtual objects for augmented reality*. Ph. D. Dissertation. Birmingham City University.

- [2] M. Al-Kalbani, I. Williams, and M. Frutos-Pascual. 2016. Analysis of Medium Wrap Freehand Virtual Object Grasping in Exocentric Mixed Reality. In *2016 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE Computer Society, Los Alamitos, CA, USA, 84–93. <https://doi.org/10.1109/ISMAR.2016.14>
- [3] Frank Biocca, Yasuhiro Inoue, Andy Lee, and Heather Polinsky. 2002. Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence. *Proceedings of presence* (01 2002), 410–428.
- [4] A. Bloomfield and N. I. Badler. 2007. Collision Awareness Using Vibrotactile Arrays. In *2007 IEEE Virtual Reality Conference*. IEEE Computer Society, Los Alamitos, CA, USA, 163–170. <https://doi.org/10.1109/VR.2007.352477>
- [5] Isak De Villiers Bosman, Koos De Beer, and Theo J.D. Bothma. 2021. Creating pseudo-tactile feedback in virtual reality using shared cross-modal properties of audio and tactile feedback. *South African Computer Journal* 33, 1 (2021), 1–21. <https://doi.org/10.18489/sacj.v33i1.883> arXiv:<https://journals.co.za/doi/pdf/10.18489/sacj.v33i1.883>
- [6] George EP Box and David R Cox. 1964. An analysis of transformations. *Journal of the Royal Statistical Society. Series B (Methodological)* (1964), 211–252. <https://doi.org/10.1111/j.2517-6161.1964.tb00553.x>
- [7] Hugo Brument, Rebecca Fribourg, Gerard Gallagher, Thomas Howard, Flavien Lecuyer, Tiffany Luong, Victor Mercado, Etienne Peillard, Xavier De Tinguy, and Maud Marchal. 2019. Pyramid Escape: Design of Novel Passive Haptics Interactions for an Immersive and Modular Scenario. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Osaka, Japan, 1409–1410. <https://doi.org/10.1109/VR.2019.8797848>
- [8] Ryan Canales, Aline Normoyle, Yu Sun, Yuting Ye, Massimiliano Di Luca, and Sophie Jörg. 2019. Virtual Grasping Feedback and Virtual Hand Ownership. In *ACM Symposium on Applied Perception 2019 (Barcelona, Spain) (SAP '19)*. Association for Computing Machinery, New York, NY, USA, Article 4, 9 pages. <https://doi.org/10.1145/3343036.3343132>
- [9] Hyeonah Choi, Jiwon Oh, Minwook Chang, and Gerard J. Kim. 2018. Effect of Accompanying Onomatopoeia to Interaction Sound for Altering User Perception in Virtual Reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology (Tokyo, Japan) (VRST '18)*. Association for Computing Machinery, New York, NY, USA, Article 80, 2 pages. <https://doi.org/10.1145/3281505.3281614>
- [10] Natalia Cooper, Ferdinando Milella, Iain Cant, Carlo Pinto, Mark White, and Georg Meyer. 2015. The Effects of Multisensory Cues on the Sense of Presence and Task Performance in a Virtual Reality Environment. Lecco, Italy. <https://livrepository.liverpool.ac.uk/2035799>
- [11] Erica Cosentino. 2021. Artifacts and affordances. *Synthese* 198, 17 (2021), 4007–4026. <https://doi.org/10.1007/s11229-019-02297-4>
- [12] L. Fabiani, D. Gomez, N. Langrana, and G. Burdea. 1996. Human interface using the Rutgers Master II force feedback interface. In *Virtual Reality Annual International Symposium*. IEEE Computer Society, Los Alamitos, CA, USA, 54. <https://doi.org/10.1109/VR.1996.490510>
- [13] Jacqueline M Fulvio and Bas Rokers. 2017. Use of cues in virtual reality depends on visual feedback. *Scientific reports* 7, 1 (2017), 1–13. <https://doi.org/10.1038/s41598-017-16161-3>
- [14] Andreas Geiger, Imke Bewersdorf, Elisabeth Brandenburg, and Rainer Stark. 2018. Visual Feedback for Grasping in Virtual Reality Environments for an Interface to Instruct Digital Human Models. In *Advances in Usability and User Experience, Tareq Ahram and Christianne Falcão (Eds.)*. Springer International Publishing, Cham, 228–239. [https://link.springer.com/chapter/10.1007/978-3-319-60492-3\\_22](https://link.springer.com/chapter/10.1007/978-3-319-60492-3_22)
- [15] Wenjun Hou, Shupeng Zhang, and Zhiyang Jiang. 2018. Research on Visual Feedback Based on Natural Gesture. In *Human Centered Computing*, Qiaohong Zu and Bo Hu (Eds.). Springer International Publishing, Cham, 627–637. [https://doi.org/10.1007/978-3-319-74521-3\\_65](https://doi.org/10.1007/978-3-319-74521-3_65)
- [16] Dhruv Jain, Sasa Junuzovic, Eyal Ofek, Mike Sinclair, John Porter, Chris Yoon, Swetha Machanavajhala, and Meredith Ringel Morris. 2021. A Taxonomy of Sounds in Virtual Reality. In *Designing Interactive Systems Conference 2021 (DIS '21)*. Association for Computing Machinery, New York, NY, USA, 160–170. <https://doi.org/10.1145/3461778.3462106>
- [17] Hanseob Kim, Myungho Lee, Gerard J. Kim, and Jae In Hwang. 2021. The impacts of visual effects on user perception with a virtual human in augmented reality conflict situations. *IEEE Access* 9 (2021), 35300–35312. <https://doi.org/10.1109/ACCESS.2021.3062037> Publisher Copyright: © 2013 IEEE..
- [18] Nataliya Kosmyna and Anatole Lécuyer. 2017. Designing Guiding Systems for Brain-Computer Interfaces. *Frontiers in Human Neuroscience* 11 (July 2017), 396. <https://doi.org/10.3389/fnhum.2017.00396>
- [19] Meng Chun Lam, Haslina Arshad, Anton Satria Prabuwono, Siok Yee Tan, and S. M. Kahaki. 2018. Interaction Techniques in Desktop Virtual Environment: The Study of Visual Feedback and Precise Manipulation Method. *Multimedia Tools Appl.* 77, 13 (July 2018), 16367–16398.
- [20] Anatole Lécuyer, Christine Mégard, Jean-Marie Burkhardt, Taegi Lim, Sabine Coquillart, Philippe Coiffet, and Ludovic Graux. 2002. The effect of haptic, visual and auditory feedback on an insertion task on a 2-screen workbench. In *Proceedings of the Immersive Projection Technology Symposium*, Vol. 2.
- [21] Fabrice Matulic, Aditya Ganeshan, Hiroshi Fujiwara, and Daniel Vogel. 2021. Phonetroller: Visual Representations of Fingers for Precise Touch Input with Mobile Phones in VR. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 129, 13 pages. <https://doi.org/10.1145/3411764.3445583>
- [22] Scott McCloud. 1994. *Understanding Comics : the Invisible Art*. HarperPerennial, New York, NY, USA, 215 pages.
- [23] M Moehring and B Froehlich. 2011. Effective Manipulation of Virtual Objects within Arm's Reach. In *Proceedings of the 2011 IEEE Virtual Reality Conference (VR '11)*. IEEE Computer Society, USA, 131–138. <https://doi.org/10.1109/VR.2011.5759451>
- [24] Peter Mohr, David Mandl, Markus Tatzgern, Eduardo Veas, Dieter Schmalstieg, and Denis Kalkofen. 2017. Retargeting Video Tutorials Showing Tools With Surface Contact to Augmented Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (Denver, Colorado, USA) (CHI '17)*. Association for Computing Machinery, New York, NY, USA, 6547–6558. <https://doi.org/10.1145/3025453.3025688>
- [25] Ryota Nomura, Yuko Unuma, Takashi Komuro, Shoji Yamamoto, and Norimichi Tsumura. 2017. Mobile Augmented Reality for Providing Perception of Materials. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia (Stuttgart, Germany) (MUM '17)*. Association for Computing Machinery, New York, NY, USA, 501–506. <https://doi.org/10.1145/3152832.3157810>
- [26] Tomi Nukarinen, Jari Kangas, Jussi Rantala, Toni Pakkanen, and Roope Raisamo. 2018. Hands-Free Vibrotactile Feedback for Object Selection Tasks in Virtual Reality. In *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology (Tokyo, Japan) (VRST '18)*. Association for Computing Machinery, New York, NY, USA, Article 94, 2 pages. <https://doi.org/10.1145/3281505.3283375>
- [27] Michael I. Posner, Mary J. Nissen, and Raymond M. Klein. 1976. Visual dominance: An information-processing account of its origins and significance. *Psychological Review* 83 (1976), 157–171. <https://doi.org/10.1037/0033-295X.83.2.157> Place: US Publisher: American Psychological Association.
- [28] M. Prachyabrued and C. W. Borst. 2014. Visual feedback for virtual grasping. In *2014 IEEE symposium on 3D user interfaces (3DUI)*. IEEE, Minneapolis, MN, USA, 19–26. <https://doi.org/10.1109/3DUI.2014.6798835>
- [29] Sara Price, Carey Jewitt, and Nikoleta Yiannoutsou. 2021. Conceptualising touch in VR. *Virtual Reality* 25 (09 2021), 863–877. <https://doi.org/10.1007/s10055-020-00494-y>
- [30] Oscar Salandin. 2021. Touching Holograms - How the Microsoft Mixed Reality Studios explored more immersive interactions. <https://medium.com/microsoft-design/blank-story-e286ac1fb11a> Accessed: 2021-05-17.
- [31] Mie Sato, Sota Suzuki, Daiki Ebihara, Sho Kato, and Sato Ishigaki. 2016. Pseudo-Softness Evaluation in Grasping a Virtual Object with a Bare Hand. In *SIGGRAPH Posters*. ACM, New York, NY, USA, Article 40, 1 pages. <https://doi.org/10.1145/2945078.2945118>
- [32] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2014. Applying the User Experience Questionnaire (UEQ) in Different Evaluation Scenarios. In *Design, User Experience, and Usability. Theories, Methods, and Tools for Designing the User Experience*, David Hutchison, Takeo Kanade, Josef Kittler, Jon M. Kleinberg, Alfred Kobsa, Friedemann Mattern, John C. Mitchell, Moni Naor, Oscar Nierstrasz, C. Pandu Rangan, Bernhard Steffen, Demetri Terzopoulos, Doug Tygar, Gerhard Weikum, and Aaron Marcus (Eds.). Vol. 8517. Springer, 383–392. [https://doi.org/10.1007/978-3-319-07668-3\\_37](https://doi.org/10.1007/978-3-319-07668-3_37)
- [33] Jean Sreng and Anatole Lécuyer. 2013. Simulating Contacts between Objects in Virtual Reality with Auditory, Visual, and Haptic Feedback. In *Sonic Interaction Design*, K. Franinović and S. Serafin (Eds.). MIT Press, 309–326. <https://doi.org/10.7551/mitpress/8555.003.0021>
- [34] Jean Sreng, Anatole Lécuyer, Christine Mégard, and Claude Andriot. 2006. Using Visual Cues of Contact to Improve Interactive Manipulation of Virtual Objects in Industrial Assembly/Maintenance Simulations. *IEEE Transactions on Visualization and Computer Graphics* 12, 5 (Sept. 2006), 1013–1020. <https://doi.org/10.1109/TVCG.2006.189>
- [35] Sota Suzuki, Haruto Suzuki, and Mie Sato. 2014. Grasping a Virtual Object with a Bare Hand. In *SIGGRAPH Posters*. ACM, Article 51, 1 pages. <https://doi.org/10.1145/2614217.2630574>
- [36] Ultraleap. 2021. Virtual Objects - Ultraleap documentation. <https://docs.ultraleap.com/xr-guidelines/virtual-objects.html#affordances> Accessed: 2022-09-19.
- [37] Sebastian Vizcay, Panagiotis Kourtesis, Ferran Argelaguet, Claudio Pacchierotti, and Maud Marchal. 2021. Electrotactile Feedback For Enhancing Contact Information in Virtual Reality. *ICAT-EGVE 2021 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments* (2021), 10 pages. <https://doi.org/10.2312/egve.20211331> arXiv: 2102.00259.
- [38] Spyros Vosinakis and Panayiotis Koutsabasis. 2018. Evaluation of Visual Feedback Techniques for Virtual Grasping with Bare Hands Using Leap Motion and Oculus Rift. *Virtual Real.* 22, 1 (March 2018), 47–62. <https://doi.org/10.1007/s10055-017-0313-4>

- [39] Benjamin Williams, Alexandra E. Garton, and Christopher J. Headleand. 2020. Exploring Visuo-haptic Feedback Congruency in Virtual Reality. In *2020 International Conference on Cyberworlds (CW)*. 102–109. <https://doi.org/10.1109/CW49994.2020.00022> ISSN: 2642-3596.
- [40] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The Aligned Rank Transform for Nonparametric Factorial Analyses Using Only Anova Procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) (*CHI '11*). ACM, New York, NY, USA, 143–146. <https://doi.org/10.1145/1978942.1978963>
- [41] Wenge Xu, Hai-Ning Liang, Yuzheng Chen, Xiang Li, and Kangyou Yu. 2020. Exploring Visual Techniques for Boundary Awareness During Interaction in Augmented Reality Head-Mounted Displays. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, Atlanta, GA, USA, 204–211. <https://doi.org/10.1109/VR46266.2020.00039>
- [42] Mihaela A. Zahariev and Christine L. MacKenzie. 2003. Auditory, Graphical and Haptic Contact Cues for a Reach, Grasp, and Place Task in an Augmented Environment. In *Proceedings of the 5th International Conference on Multimodal Interfaces* (Vancouver, British Columbia, Canada) (*ICMI '03*). Association for Computing Machinery, New York, NY, USA, 273–276. <https://doi.org/10.1145/958432.958481>
- [43] Zhiyuan Zhang, Bing Wang, F. Ahmed, I. V. Ramakrishnan, Rong Zhao, A. Viccellio, and K. Mueller. 2013. The Five Ws for Information Visualization with Application to Healthcare Informatics. *IEEE Transactions on Visualization and Computer Graphics* 19, 11 (Nov. 2013), 1895–1910. <https://doi.org/10.1109/TVCG.2013.89>