When Tangibles Become Deformable: Studying Pseudo-Stiffness Perceptual Thresholds in a VR Grasping Task

Elodie Bouzbib, Claudio Pacchierotti and Anatole Lécuyer

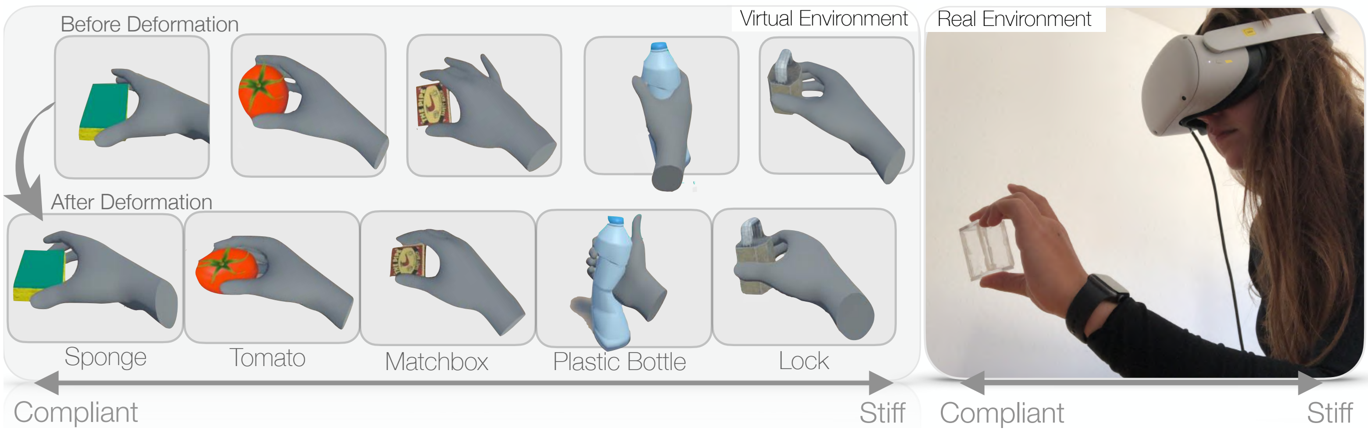

Fig. 1: When Tangibles Become Deformable: In the virtual environment, objects are displayed before and after being compressed, following a compliance-stiffness continuum (sponge, tomato, matchbox, water bottle, lock). In the real environment, a user is compressing a tangible object. Using pseudo-stiffness, she perceives this same range of stiffness, while only grasping a non-compressible object. We investigate the range of compliance and stiffness that can be elicited on a non-compressible tangible object.

Abstract— Pseudo-Haptic techniques, or visuo-haptic illusions, leverage user's visual dominance over haptics to alter the users' perception. As they create a discrepancy between virtual and physical interactions, these illusions are limited to a perceptual threshold. Many haptic properties have been studied using pseudo-haptic techniques, such as weight, shape or size. In this paper, we focus on estimating the perceptual thresholds for pseudo-stiffness in a virtual reality grasping task. We conducted a user study (n = 15) where we estimated if compliance can be induced on a non-compressible tangible object and to what extent. Our results show that (1) compliance can be induced in a rigid tangible object and that (2) pseudo-haptics can simulate beyond 24 N/cm stiffness ($k \geq 24N/cm$, between a gummy bear and a raisin, up to rigid objects). Pseudo-stiffness efficiency is (3) enhanced by the objects' scales, but mostly (4) correlated to the user input force. Taken altogether, our results offer novel opportunities to simplify the design of future haptic interfaces, and extend the haptic properties of passive props in VR.

Index Terms—Virtual Reality, Pseudo-Haptics, Pseudo-Stiffness, Grasp, Thresholds, Perception, Stiffness, Compliance, Consistency

1 Introduction

The use of real tangible objects in virtual reality (VR), also called *passive haptics*, is known to enhance users experiences [23]. Virtual reality offers wide interactions opportunities, yet rendering appropriate physical objects is still complex. Instantiating a 1:1 virtual:physical mapping of objects such as *Substitutional Reality* [40] can be time-consuming, costly, and increase drastically the number of props in a VR scene. Enabling physical interactions using a limited amount of physical props is therefore investigated [13], either by displacing the physical world, using robotised interfaces displaying the props in a N:1 virtual:physical mapping [11]; or by displacing the virtual world, using visuo-haptic illusions, to redirect the users' towards their chosen object of interest [5, 14, 17].

• *Elodie Bouzbib is with Centre Inria de l'Université de Rennes, IRISA, CNRS - Rennes, France. E-mail: elodie.bouzbib@inria.fr*
• *Claudio Pacchierotti is with IRISA, CNRS, Centre Inria de l'Université de Rennes - Rennes, France. E-mail: claudio.pacchierotti@irisa.fr*
• *Anatole Lécuyer is with Centre Inria de l'Université de Rennes, IRISA, CNRS - Rennes, France. E-mail: anatole.lecuyer@inria.fr*

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Beyond their physical presence, objects' intrinsic haptic properties also are to be replicated. In these regards, pseudo-haptic techniques [27, 46], leveraging users' visual dominance over haptics, are used to alter perception. Shapes [7, 45], weights [35], sizes [9] can therefore be simulated using a single tangible object. Pseudo-haptics create a discrepancy between the physical and virtual interactions, and are thus subject to a perceptual threshold, up to which this visuo-haptic illusion is not efficient anymore. We define the **point of subjective visuo-haptic consistency** as the threshold from which the visuo-haptic illusion is indeed efficient.

Many factors are to take into account when designing for pseudo-haptics. Thresholds might vary as a function of individuals [26], visual conditions (full immersion [35], 2D display [7]), or the performed task (navigation [34], exploration [6], manipulation [9]). Among VR tasks and interactions, *edition*, "the modification of an object structure" (such as scale or shape) [13], should benefit the most from pseudo-haptics. Tracking a real-time physical deformation requires sensors or actuation. Pseudo-haptics can thus be added to simplify this actuation [1, 15] or to literally replace it [3, 29].

In this paper, we first study whether compliance can be induced in a rigid tangible object in a VR grasp task, and second focus on estimating the consistency threshold for pseudo-stiffness in a VR grasping task. Pseudo-stiffness have so far been studied in non-immersive realities, using a single finger to push a piston [27]; or in VR using controllers [29] or handheld input devices [2]. Our scope is to quantify to which extent compliance can be added to a tangible non-hand-compressible object in a fully immersive VR. In these regards, we integrated force sensors into two non-hand-compressible cuboids made out of acrylic (see Figure 1 - Real Environment). We first conducted a preliminary study (n = 8) to refine the estimation range of pseudo-stiffness efficiency. Participants were aware that they were manipulating a tangible non-hand-compressible object, and defined intervals for which their visuo-haptic perception was consistent. We then used the previous results to conduct a user experiment (n = 15) and determine the **point of subjective visuo-haptic consistency for pseudo-stiffness in an immersive VR grasping task**. Results show that (1) compliance can be induced in a rigid object (theoretical *infinite* stiffness), (2) with varying stiffness beyond 24 N/cm ($k \geq 24N/cm$), between a gummy bear and a raisin). We demonstrate that (3) pseudo-stiffness' efficiency is enhanced by the objects' scales, and mostly (4) correlated to the user input force. The more force induced, the more consistent the pseudo-stiffness. Participants exerted a significantly higher force on large objects, and the best pseudo-stiffness results are shown for large objects and high input user force. When the pseudo-stiffness became to be consistent (at the consistency threshold), the virtual objects' were in average compressed up to 10% of their original sizes. Qualitatively, users reported that deforming the visually stiff objects was harder than for the visually compliant ones - even though the physical counterparts were not compressible.

Taken altogether, our results verify and quantify pseudo-stiffness efficiency; they offer novel opportunities to extend haptic properties of passive props and simplify the design of future haptic interfaces in VR.

Our main contributions are:

- A method to induce compliance into a rigid tangible passive prop in VR;
- Empirical results showing a pseudo-stiffness point of subjective visuo-haptic consistency of 24 N/cm;
- Empirical results showing scales and force input influences on pseudo-stiffness efficiency in VR.

2 Related Work

2.1 Pseudo-Haptics Perceptual Thresholds Conditions

Visual cues are dominant compared to haptic ones in the human perception [37]. Pseudo-haptics leverages these visual cues over haptic ones, in order to instantiate a haptic feedback while relying on user's vision; in these regards, it is also considered as a *visuo-haptic illusion*. These illusions however have a perceptual threshold, where the visuo-haptic rendering becomes inconsistent. This threshold can be expressed as an Absolute Detection Threshold - defined as the lowest intensity of a stimulus detected 50% of the time; a JND - Just Noticeable Difference, defined as the threshold at which a stimulus difference is noticed 50% of the time; or with PSE - Point of Subjective Equality, defined as the points at which a variable stimulus is judged by an observer as equal to a standard stimulus [54].

These thresholds differ on individuals [26], but also on the conditions in which pseudo-haptics is studied. Pseudo-stiffness has for instance been studied with a 2D display and a single finger pushing a (virtual) piston [27] and showed different results whether it relied on the grip and squeeze of a cell-phone [49] or of *Kooboh*, a simple tangible object [18].

Pseudo-haptics indeed provide different thresholds whether the visual cues are stimulated through 2D displays or immersive Virtual Reality (VR); whether the visual and physical hands are colocated [33]; or even whether the visual hand is visible or not [6]. They also vary as a function of the user input (e.g. force, displacement, press duration) and the visual stimuli (e.g. displacement, surface deformation, color, size) [46].

In this paper, we define the **Point of Subjective Visuo-Haptic Consistency** - as the value at which pseudo-stiffness stimulus is judged as consistent by an observer as equal to a surface deformation visual stimuli with a force input 50% of the time.

2.2 Haptic Properties Enhanced via Pseudo-Techniques

Pseudo-haptic techniques were shown efficient to alter various haptic properties. They can be coupled with grounded devices [30], wearables [36, 38], handheld devices [2, 44, 51], controllers [29, 35], or simply widen the extent of haptic properties proposed by a tangible object. Using a single prop, pseudo-haptics enable the exploration of various shapes [6, 7, 16, 52], the manipulation of various sizes [9], weights [39] or even temperatures [10]. The same techniques are also used for proprioceptive illusions - redirecting the user's limbs [4, 24, 43, 50], to multiply the number of physical props virtually available in the scene.

All of objects' intrinsic haptic properties are felt when performing exploratory procedures [28] - which can be translated as tasks in VR. For instance, *contour following* provides knowledge on the global and exact shape of an object - it was used in [7, 52] to alter the users' shape perception in a virtual **exploration** task. Similarly, the *enclosure* enables the knowledge of the objects' volume, and was leveraged in [9] to alter the users' scale perception in a **manipulation** task. In this paper, we focus on stiffness, which exploratory procedure is *pressure* and corresponds to an **edition** task - deforming and modifying the objects' structure [13]. In the same line of observations, tasks such as bending, stretching, twisting require pressure, and already have been enabled by pseudo-haptic illusions [22].

We focus here on a VR grasping task, in which users are compressing virtual objects within their bare-hands, and enable it with pseudo-haptics added to a non-hand-compressible tangible object.

2.3 Edition and Deformation in Virtual Reality

The modification of a virtual objects' structure, its scaling or deformation, is defined in [13] as an *Edition* task. Rendering a hand-object *edition* interaction is qualified as *palpation* when involving a single contact [21, 38, 53]; or a *compliance* manipulation [21, 29] when involving in-hand manipulations, such as a grasping task.

The deformation of objects in VR is complex: it first visually requires an understanding of the virtual objects' contact force distributions [47], which are secondly to be mapped in real-time on a physical object deformation. This deformation would therefore require many trackers, sensors and/or actuators. As opposed to shape-changing interfaces such as [19, 20], their control would thus rely on a user input.

To remove the constraints of tangible manipulations in VR, deformation was for instance investigated using head movements [25], or using ultrasounds haptics, enabling light force-feedback rendering when interacting with virtual clay in VR [8]. Tangibles only start exploring the use of soft materials in VR [32], yet enabling their in-hand deformation is still under-explored.

In this paper, we aim to simplify future haptic interfaces design and to widen passive props rendering capabilities by only relying on pseudo-haptic techniques over a rigid tangible object. We add compliance (e.g. "softness") to a rigid object, therefore the pseudo-stiffness phenomenon can also be defined as pseudo-compliance, as *Compliance* (cm/N) is the inverse of *Stiffness* (N/cm) .

We study the extent of believable pseudo-stiffness that can be induced when performing a VR grasping task over a tangible object.

3 Scope

In this paper, we study whether compliance can be induced on a tangible non-compressible object using pseudo-haptic techniques, and to which extent. The primary aim is to widen the intrinsic haptic properties of passive props in VR. We propose a fully immersive VR environment (e.g. wearing an Head Mounted Display - HMD) and let the users' hands free and available for interaction, with no additional equipment to wear. According to [46], we classify our study as to a force user input and a surface deformation visual stimulus. Stiffness is reciprocal to compliance: in this paper, we define the point of subjective visuo-haptic consistency as the threshold where the virtual deformation (compliance) is *detected* as believable when interacting with a physical rigid tangible object. We quantify (1) the Point of Subjective Visuo-Haptic Consistency for pseudo-stiffness; we study (2) the impact of objects' scales and (3) influence of input user force.

4 Visuo-Haptic Consistency Range Estimation

4.1 Hypotheses

In this paper, we have three main hypotheses:

H1 A rigid non-compressible object can be used for a wide range of stiffness (e.g. rigid) and compliance (e.g. soft) in a fully immersive virtual reality grasping task.

H2 Objects' scale impacts the amount of pseudo-stiffness added to the object.

H3 The user input force impacts the pseudo-stiffness perception.

Our first hypothesis reflects the scope of this paper. We want to identify the visuo-haptic consistency range for pseudo-stiffness in a fully immersive VR grasping task.

Our second hypothesis is inherited from *Resized Grasping* [9] - we believe that a smaller object would have a smaller range of pseudo-stiffness consistency than a large object. The users would potentially perceive a bigger proprioceptive discrepancy whenever their virtual fingers would be almost performing a pinch gesture while their physical ones would not. A larger object therefore might provide a larger range of stiffness to explore.

An object deformation is a function of its stiffness and the force applied to it; yet the visual deformation is key in a pseudo-haptic experiment. Our third hypothesis is thus that the participants' input force will impact their pseudo-stiffness consistency perception. We belive that participants applying a lot of force would probably expect an object to comply; reciprocally, participants applying a small amount of force would perceive a discrepancy if the object were to comply while interacting with a solid object.

4.2 Setup

We built a small (HxWxL = 30x35x55 mm^3) and a large (HxWxL = 30x35x85 mm^3) acrylic cuboid for manipulation. The acrylic material ensures the rigidity of the object and is fully transparent, thus enabling grasp interactions with the Meta Quest hands. We then clamped the cuboids to a table (see Figure 2 - Real Environment). We decided upon two cuboids (small, large) instead of three (small, medium, large) as *resized grasping illusions* can already be applied in a VR experiment [9]; we therefore believe some overlap can occur between the small and large object manipulations.

We integrated RP-C10-ST FSR pressure sensors on each acrylic cuboid, which we plugged as a voltage divider in series with a $10k\Omega$ resistor and a 5V input. We measured the voltage from the voltage divider using an Arduino Uno board, which we converted into FSR resistance - then converted into forces (N) using the FSR datasheet.

4.3 Apparatus

All participants were asked to wear the Meta Quest 2. We enabled the vision of the user's hands - and substituted their visual real hands with virtual avatar hands (see Figure 2 - a). Avatar hands were thoroughly following the user's real hands, but were subject to FinalIK's[1] Cyclic Coordinate Descent Inverse Kinematics algorithm when colliding with the zone of interest around the virtual object, to mimic the virtual compression of the object (see Figure 2 - b). In our subsequent experiments, we do not provide virtual textures, for visual biases to be removed as much as possible.

4.4 Preliminary Study

We conducted a preliminary study to provide a broad estimation of the targeted visuo-haptic consistency range for pseudo-stiffness using a static non-hand-compressible tangible object (i.e. which physical deformation is not perceivable), as "the range of pseudo-stiffness stimuli judged to be consistent by observers as equal surface deformation visual stimuli with a force input on average".

[1] http://www.root-motion.com/final-ik.html

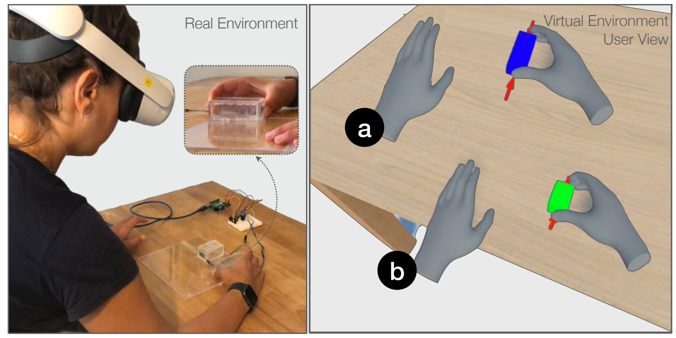

Fig. 2: Left: Real Environment. The user is interacting with the tangible rigid acrylic cuboid. A call-out shows the user's hand interacting. Right: Virtual Environment, User view. (a) User's avatar hand is grasping an object; (b) The object is "compressed" within the fingers.

4.4.1 Participants and Procedure

We recruited 8 participants (1 female), aged 23 to 33 (std = 3.1). Only one participant was novice in Virtual reality (62.5% experts). Fifty percent (4/8) of the participants were either novice or beginner with pseudo-haptics and visuo-haptics illusions (none or less than 5 experiments), 37.5% (3/8) were intermediate (between 5 and 10 experiments) and one (12.5%) was an expert in the field. Participants were informed that the study consisted in evaluating the consistency thresholds of pseudo-stiffness in VR, and aimed to define the stiffness from/to which pseudo-stiffness can be extended using a rigid non-compressible object. The duration of the study in the virtual environment was 12 min (std = 2 min).

4.4.2 Task and Stimuli

The physical scene was replicated virtually using Unity3D, similarly to Substitutional Reality [41], with virtual boxes sizes matching physical ones. The VR scene consisted of a cuboid on virtual table. Two arrows indicated where to compress the object (see Figure 3). In VR, participants were asked to *compress the object until it became green*. This color was achieved whenever participants applied up to $18N$ of force over the object. This value was chosen empirically, and ensured that participants sufficiently compressed the tangible object in this study. Visually, the object was deforming as a function of the applied force and the object's stiffness, as per its definition ($\Delta D = \frac{F}{k}$), and using the Unity asset *Deform*.

4.4.3 Design

In this preliminary study, we used a staircase design. The global range of stiffness for the experiment was from 1 N/cm (compliant, soft) to 70 N/cm (stiff). To remove the bias of order (increasing from 1 N/cm ↑ *or* decreasing from 70 N/cm ↓), each compressible object thresholds was evaluated from these two orders. Each participant therefore tested 4 Conditions: 2 Scales × 2 Orders (↑↓). We used a Latin square design for the experiment (small ↑, small ↓, large ↑, large ↓). The guidelines for the users in the environment were the following:

↑ Find the *minimum* of the visual/physical deformation consistency range (e.g. visuo-haptic consistency range).

↓ Find the *maximum* of the visual/physical deformation consistency range (e.g. visuo-haptic consistency range).

Users were manipulating the environment (changing the stiffness, pressing next) using a physical keypad, identically virtually represented as per [41] (see Figure 3). Users were using both their hands and did not have any indication regarding the hand they had to manipulate with.

Participants defined their visuo-haptic deformation consistency range iteratively, to refine from a broad exploration to a more precise threshold estimation. We thus used variable stiffness increment = {6, 4, 2, 1} N/cm in a decreasing order. Participant therefore tested 4 Increments × 2 Orders = 8 Reversals.

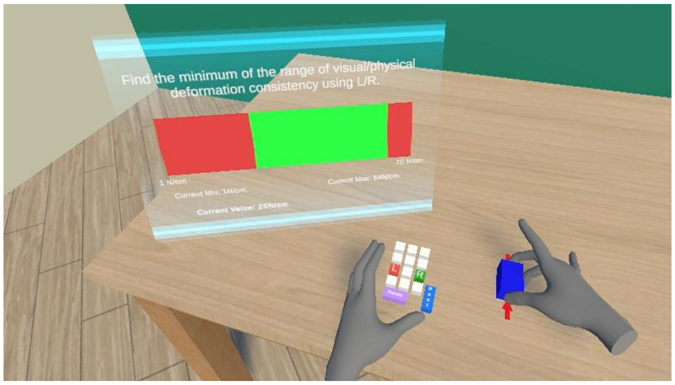

Fig. 3: Preliminary Study: Participants compress the tangible object; its virtual counterpart deforms within the user's fingers. Participants then use a keyboard to provide feedback on their perception of the visual/physical deformation consistency. The consistency range is visually represented by a slider (red: inconsistent, green: consistent).

The preliminary study design was therefore 8 PARTICIPANTS × 4 CONDITIONS × 8 REVERSALS = 256 TRIALS. We recorded each trial to refine our staircase.

4.4.4 Results

We notice on Figure 4 that a large visuo-haptic consistency range is acceptable using a rigid object, with a global mean maximum threshold at 48.5 N/cm (95-CI = 2.8N/cm) and a mean minimum threshold at 20.7 N/cm (95-CI = 2.2N/cm).

Our results indicate that a minimum and maximum thresholds do not overlap: this can be interpreted as a large visuo-haptic consistency range (see Table 1). A whole range between 20 N/cm and 50 N/cm can therefore be perceived using the same rigid tangible object. These values will be validated in the next experiment.

Thresholds (N/cm)	Minimum	Maximum
Mean (95-CI)	20.7 (2.2)	48.5 (2.8)
25 %	10.8	37.8
Median (50%)	19	52
75 %	32	64
Max	45	70

Table 1: Minimum and Maximum thresholds and dispersion of the results for consistent visuo-haptic deformation perception in the preliminary study (results from all trials).

Regarding scale, the minimum for small objects and large objects seem similar. Using the first increment (Increment 1 = 6 N/cm, see Figure 4), small and large objects both provide a consistent rendering for 18.3 N/cm (resp. 95CI = 5.9 N/cm and 5.7 N/cm). A small difference can be observed for their maxima both at the first and last increments (6 N/cm to 1 N/cm), when the thresholds are being refined, with small objects thresholds going from 47.1 N/cm (95-CI = 6.9 N/cm) to 45.3 N/cm (95-CI = 8.4 N/cm) and large objects thresholds going from 53.9 N/cm (95-CI = 6.6 N/cm) to 51.8 N/cm (95-CI= 8.6 N/cm).

4.4.5 Findings & Discussion

H1 This preliminary study enables us to define the stiffness range to test in order to estimate the visuo-haptic consistency range and refine the proposed stiffness in the subsequent experiment. Our minimum and maximum thresholds barely overlap - therefore these results suggest that a wide range of compliance can indeed be explored using a single non-compressible object. We learnt from this study that stiffness up to 10 N/cm or beyond 65 N/cm do not require a large increment for our point of subjective consistency estimation; as well as values between approximately 25 N/cm to 45 N/cm.

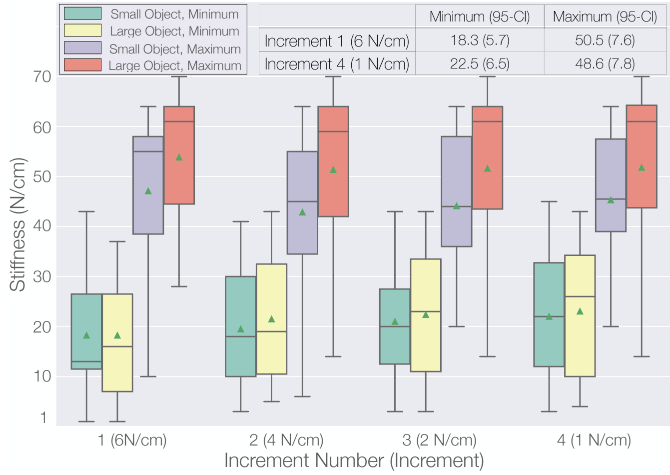

Fig. 4: Boxplot of Thresholds in N/cm per object scale and increment number. After each couple of trials, the increment reduced for the thresholds to get refined. Table indicates mean thresholds and their respective 95-confidence interval (95-CI) for the first/last reversal.

H2 Regarding object's scales, results show that the mean for both the small and large objects' minimum thresholds are around 20 N/cm (respectively 20.2N and 21.3N) while their maximum threshold means differ slightly more (respectively 44.9N and 52.2 N). These differences seem to differ at large stiffnesses; we thus further investigate the impact of objects' scales in the user experiment to verify our hypotheses.

H3 In this study, users had to reach a force threshold for the object to become green. Qualitative feedback made us believe that this threshold (18 N) was too high. They actually did not perceive that this threshold was stable - they felt it was lower for compliant objects and higher for stiff objects.

Other Findings Our results also open up an interesting discussion regarding pseudo-haptics' efficiency. The maximum threshold is indeed surprisingly low. While we expected users to refine their minimum thresholds for obvious over-compliance, participants also believed that the virtual and physical deformation rendering of a stiffer rigid object (at 70 N/cm) did not seem consistent. This is surprising as the object is not deforming - the effect of pseudo-haptics seemed to alter the real perception of tangible objects. Participant P2 instinctively said that he did feel a discrepancy as he was applying a tremendous effort to deform the object and make it visually green (the threshold was defined as 18N) - he expected that with such an amount of force, the object would eventually deform. Even though rigid objects do exist in the real environment, we are not used to compress them with a large force. We therefore keep values from the "inconsistent range" and propose an additional task in the subsequent experiment; we further investigate the task effect and the amount of force provided to widen pseudo-haptics efficiency. We believe this effect might also be due to the staircase design, where participants directly compared conditions. We remove this bias by randomizing the subsequent experiment.

4.5 Experiment Design

4.5.1 Participants

Fifteen participants (10 male, 5 female) aged from 23 to 37 (mean = 27, std = 4.3) were recruited among our institution for this experiment. Five participants (33%) were beginners in VR, seven (47%) were intermediate and three (20%) were experts. Among the participants, 87% (13/15) had never been exposed to pseudo-haptics or visuo-haptic illusions in VR, 13% (2/15) had performed under 5 experiments involving pseudo-haptics.

4.5.2 Procedure

Participants were first informed of the aim of the study. Unlike participants from the preliminary study, they were not aware that the objects were not being changed between the trials, and were only told that their perception of stiffness was evaluated using objects of different sizes and stiffness. The total duration of the study was approximately 30 minutes (std = 6 min).

4.5.3 Tasks and Stimuli

Similarly to the preliminary study, the scene was designed on Unity3D, and consisted in the same virtual experimental room. The main difference was in the answer panel - but the virtual keyboard, objects and arrows were not changed. Moreover, in this experiment, participants were first subject to an introductory scene, to get acquainted with the physical elements in the scene. In this scene, they learnt how to use the keypad to select their answer or confidence level, press next or reset.

4.5.4 Conditions

We controlled a factor related to SCALE and one related to the force input (TASK). Participants manipulated objects of various STIFFNESS. The two same objects SCALES from the preliminary study are kept in this experiment.

We proposed two TASKS for force input: Compress and Squeeze. Users are told either to *Compress the cube until it gets green* (force control condition) or to *Squeeze the cube as much as [they want]*. We also used qualitative feedback from the preliminary study to reduce the force control condition (originally established at 18N) to 13 N. We extracted the results from the preliminary study to define variable increments in the STIFFNESS range, and refined them between [10 N/cm - 25 N/cm] and [45 N/cm - 65 N/cm]:

- 5 N/cm increment from 1 N/cm to 10 N/cm;
- 2 N/cm increment from 10 to 25 N/cm;
- 5 N/cm increment from 25 N/cm to 45 N/cm;
- 2 N/cm increment from 45 N/cm to 65 N/cm;
- 5 N/cm increment from 65 N/cm to 75 N/cm.

4.5.5 Design

We used a within-subject design. The order of each condition was randomised. Each object (SCALE, STIFFNESS) appeared randomly on the table. Each participant performed 2 SCALES × 2 TASKS × 27 STIFFNESSES = 108 CONDITIONS.
The global experiment design was 15 PARTICIPANTS × 108 CONDITIONS = 1620 TRIALS.

4.5.6 Measures

At each trial, participants were subject to a 2-Alternative Forced Choice (*2AFC*), being:

The Physical and Virtual deformations are *Similar* **or** *Different*.

After answering the question, they had to answer to a 5-point Likert scale to convey their confidence in their answer (1: Not sure at all; 5: Absolutely sure). We recorded the 2AFC answer and the associated confidence level. In the first task (*Compress until it gets green*), participants could not answer prior to have applied the requested force (13 N). We also recorded the maximum force they applied at each trial to investigate the effect of force input (**H3**).

5 RESULTS

We aim to find the point of subjective visuo-haptic consistency for which pseudo-stiffness starts being consistent. As per our experiment design, we reflect on the 2AFC results, as well as the participants confidence in their answers. In the following, we consider a confident answer to be strictly above 3 on the 5-point Likert-scale. We gathered the 2AFC data as *Similar = 1* and *Different = 0*, and thus define 0.5 as more than 50% *Similar* answers. This corresponds to the Point of Subjective Visuo-Haptic Consistency, defined in the Related Work section (Section 2.1) as the lowest intensity (threshold) for which 50% of the answers are perceived as *Similar*. We also assign the letter k to display stiffness.

5.1 Quantitative Results

Note: As opposed to conventional pseudo-haptics studies where features such as weight [39] or sizes [9] are compared around a reference value, and differentiated in a 2AFC containing “less" or “more" choices, we are using a non-deformable non-compressible object. Therefore, our results will not be displayed using traditional psychometric curves, as our physical baseline can only provide a single side of these curves (“same" or “different").

5.1.1 Global Results

Confidence Results. Global results show that more than 50% of the answers were given with confidence for all stiffness but $k = [16N/cm, 20N/cm, 22N/cm]$. Among these results, more participants voted *Similar* with confidence starting from $k = 14N/cm$ (21/37 *Similar*). Though, the first stiffness for which more than 50% of the global votes were *Similar* with confidence is $k = 24N/cm$ (38/60 *Similar*). In Figure 5, participants answers with confidence levels are represented with variations of colors.

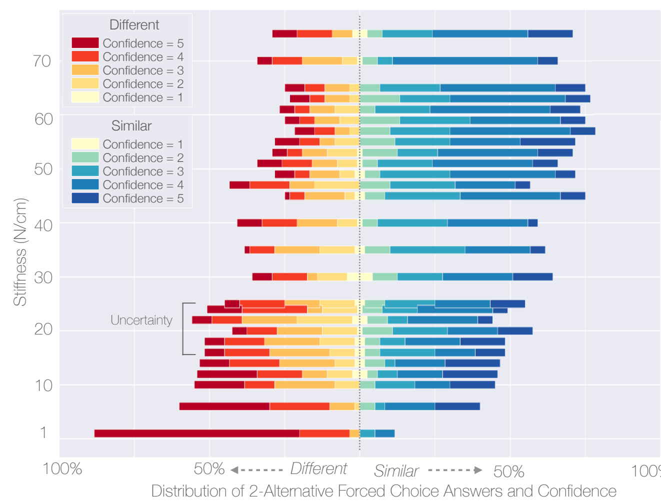

Fig. 5: Stacked Barplot of the UX answers. Red: *Different* on 2AFC; Blue: *Similar* on 2AFC. Color gradient represents participants' confidence in their answer. Dotted line represents low confidence (Confidence = 1). Results show uncertainty between 16 N/cm and 24 N/cm. Results are above 50 % similar at $k = 24N/cm$.

Point of Subjective Visuo-Haptic Consistency. We analyse the mean answers from the 2AFC. Results are between 0.45 and 0.55 between $k = [16N/cm - 25N/cm]$. As seen in Figure 5, the answers are indeed split between *Similar* (blue) and *Different* (red) in this range. They reach 0.57 (i.e. more than 50% votes *Similar*) for $k = 20N/cm$ (95-CI = 0.1), 0.43 for $k = 22N/cm$ (95-CI = 0.1), and are above 0.5 for the rest of the stiffness range ($k \geq 24N/cm$, 95-CI = 0.1). We therefore define the **point of subjective visuo-haptic consistency** as $k = 24N/cm$, though we believe this threshold could probably be extended to $k = 21N/cm$.

5.1.2 Scale Impact

Confidence Results. Confidence was in average similar for both small and large objects (17 confident votes / 30 total). Among answers with confidence, small objects started to be perceived as similar from $k = 14N/cm$, with 10/19 votes; large objects started to be perceived as similar from $k = 18N/cm$, with 10/16 votes.

Point of Subjective Visuo-Haptic Consistency. The threshold for which small objects are perceived as similar with more than 50% of the votes (including non-confident ones) is for $k = 24N/cm$ (score = 0.53, 95-CI = 0.2, 20/30 votes), while the one for large objects is for $k = 25N/cm$ (score = 0.57, 95-CI = 0.1, 15/30 votes). Note that we extract the thresholds from which all mean results are above 0.5 in the remaining of the tested stiffness.

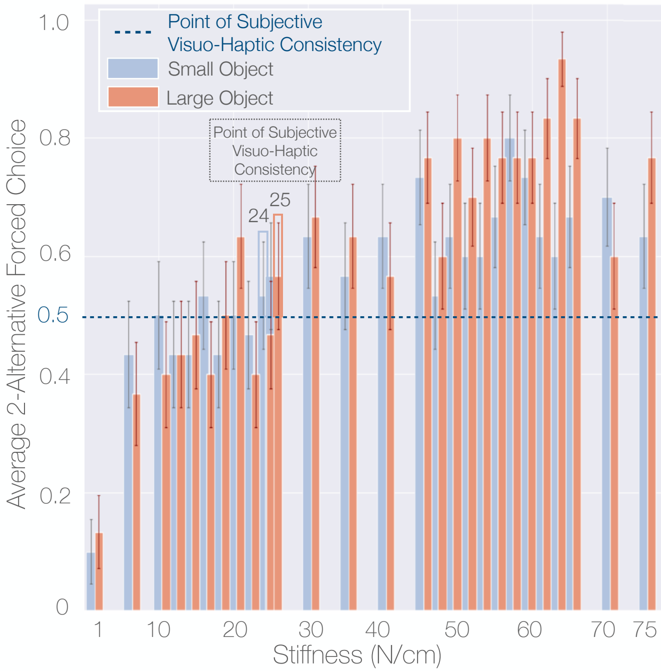

Fig. 6: Barplot of the 2AFC results per scale, as a function of stiffness (N/cm). Dotted line shows the point of subjective visuo-haptic consistency. Small and Large points of subjective visuo-haptic consistency are respectively 24 N/cm and 25 N/cm. Error bars indicate 95-Confidence Interval (95-CI).

Ranges of Stiffness Results. When interacting with low stiffness (up to 40 N/cm), results for both small and large objects are similar (see Figure 6). They differ a little when the stiffness increases. For instance, the mean for small objects for $k \in [35-75]N/cm$ is 0.65 (95-CI = 0.2), while the one for large objects is equal to 0.75 (95-CI = 0.2).

5.1.3 Force Impact

Maximum Force Applied. In average, participants applied $F = 19N$ (95-CI = 1.8 N) for the Squeeze task, and $F = 19.8N$ (95-CI = 1.3 N) for the Compress task. These forces were quite constant with no regards with the virtual object's stiffness. Up to $k = 35N/cm$, the respective averages were then $F = 18.6N$ and $F = 19.6N$. From $k = 35N/cm$, the average applied forces were respectively $F = 19.2N$ and $F = 19.9N$.

Confidence Results. Participant's confidence in their answers did not vary as a function of the performed task (Squeeze = 17/30, Compress = 18/30). Among answers with confidence, the Squeeze task was perceived as believable with a stiffness $k = 25N/cm$ (10/17, average force = 18.6N); the Compress task stiffness threshold was $k = 22N/cm$ (10/15, average force = 19.9N).

Point of Subjective Visuo-Haptic Consistency. The point of subjective visuo-haptic consistency for the Squeeze task is $k = 25N/cm$ (score = 0.59, 95-CI = 0.2, average force = 18.6N). Though, we note that the results were above 0.5 from $k = 12N/cm$ (score = 0.52, 95-CI = 0.2), except $k = 24N/cm$ (score = 0.41, 95-CI = 0.2). The Compress task's one is $k = 18N/cm$ (score = 0.67, 95-CI = 0.2).

5.1.4 Scale × Force Impact

Maximum Forces Applied. Participants significantly applied more force on large objects ($F = 21.1N$) than on small ones ($F = 17.7N$). For large objects, the amount of force did not vary as a function of the performed task (both equal to $F = 21.1N$); for small objects, more force was applied for the Compress task ($F = 18.5N$) than for the Squeeze task ($F = 16.9N$) (see Figure 7).

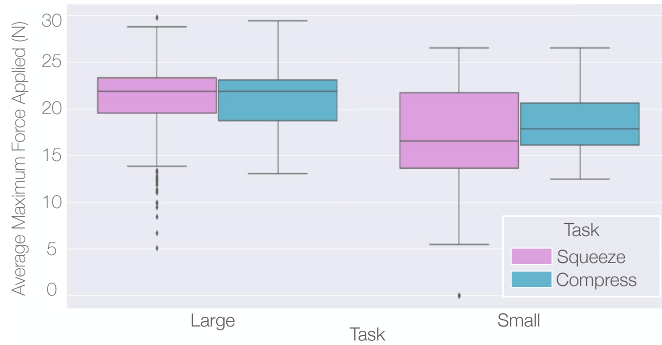

Fig. 7: Boxplot of the average Maximum force applied (N) as a function of Scale (Large, Small) and Task (Squeeze, Compress).

Confidence Results. Participants were in average confident in their answers for Large objects no matter the performed task (8/15 for each task), similarly to small objects (8/15 for squeeze, 9/15 for compress). Among the confident answers, the small object deformation was perceived as consistent for $k = 24N/cm$ for both tasks with 8/15 votes. The large object deformation was perceived as consistent for $k = 25N/cm$ on the Squeeze task, and for $k = 24N/cm$ on the Compress task, both with 8/15 votes.

Point of Subjective Visuo-Haptic Consistency. As expected according to the previous results, the small object point of subjective visuo-haptic consistency was found for $k = 24N/cm$ for both tasks (score = 0.53, 95-CI = 0.2). When the large object is being Squeezed, the threshold was $k = 25N/cm$ (score = 0.53, 95-CI = 0.2); when being Compressed it was $k = 24N/cm$ (score = 0.53, 95-CI = 0.2).

Object Visual Deformation. Visual deformation is defined as $\Delta D = F/k$. At the point of subjective visuo-haptic consistency, the small object was deformed of 14% of its original size, while the large object was deformed of 9.3% of its original size (see Table 2).

	Small	Small Squeeze	Small Compress	Large	Large Squeeze	Large Compress
Absolute Threshold (N/cm)	24	24	24	25	25	24
Force max (N)	18.5	18.9	18.9	19.8	21.1	20.8
Deformation (% of Object's Size)	14	14.4	14.2	9.3	9.9	10.2
Deformation (cm)	0.77	0.79	0.78	0.79	0.84	0.87

Table 2: Point of subjective visuo-haptic consistency (N/cm) per Scale, Task, and Scale × Task, with their associated average Maximum Forces (N) and Deformation (% of object's size and cm).

Ranges of Stiffness. Visuo-haptic consistency ranges are similar with no regards to the performed task or object's size. Though, we note that these factors impact the results for the rest of the stiffness range (see Table 3). Indeed, and as per our increment ranges in the experiment design, we note that results are consistent when $k \in [25-45]N/cm$, but they reveal high scores for larger stiffness. We note that Large objects deformation and compress task deformation are really believable for larger stiffness ($k \in [45-65]N/cm$). They also show results around 0.8 when being coupled at high stiffness (Large × Compress with $k \in [45-75]N/cm$).

Score (95-CI): Score < 0.4 | 0.4 ≤ Score < 0.5 | 0.5 ≤ Score < 0.65 | 0.65 ≤ Score < 0.75 | 0.75 ≤ Score

Conditions / Stiffness Range (N/cm)	Small	Large	Squeeze	Compress	Large Squeeze	Large Compress	Small Squeeze	Small Compress
1 - 10	0.34 (0.24)	0.30 (0.16)	0.32 (0.23)	0.32 (0.19)	0.29 (0.23)	0.31 (0.12)	0.36 (0.23)	0.33 (0.26)
10 - 25	0.49 (0.03)	0.47 (0.05)	0.50 (0.04)	0.47 (0.05)	0.46 (0.06)	0.49 (0.08)	0.53 (0.04)	0.44 (0.04)
25 - 45	0.63 (0.06)	0.64 (0.07)	0.61 (0.06)	0.65 (0.07)	0.59 (0.07)	0.69 (0.09)	0.64 (0.07)	0.61 (0.06)
45 - 65	0.65 (0.05)	0.78 (0.05)	0.69 (0.05)	0.75 (0.04)	0.73 (0.07)	0.82 (0.05)	0.64 (0.05)	0.66 (0.05)
65 - 75	0.57 (0.04)	0.73 (0.14)	0.66 (0.08)	0.74 (0.04)	0.69 (0.12)	0.78 (0.17)	0.62 (0.04)	0.71 (0.09)

Table 3: Average Results and 95-CI per Condition and Stiffness range (N/cm). The color gradient indicates the score range: the brighter, the higher the score. We note that Large objects, Compress task, and Large $\times$ Compress show results above 0.75.

5.2 Qualitative Results

Globally, all participants' answers were consistent with the preliminary study but two: P10 believed everything was consistent, while P12 only found large stiffness deformations consistent. Nonetheless, **all** participants (including P12) felt that the stiff objects were harder to compress to eventually make green. They were therefore really surprised to learn that the threshold was the same (13N) all along the experiment.

Perception-wise, at least three participants asked if they had performed multiple blocks of the same stiffness. Their perception was quite similar for $k \in [20-25]N/cm$ and $k \in [45-55]N/cm$; they thought they were testing the same stiffness multiple times.

After the experiment, participants removed the HMD and saw the setup: only two non-hand-compressible objects with sensors. Most of the participants were really surprised that all of the stiffness could be simulated using these two cuboids. They then manipulated the cuboid to ensure that it was not compressible and felt impressed. They tried to find reasons for their stiffness perception: three participants mentioned that the spread of their finger's skin over the cuboid surface might have played a role in their answers, as they truthfully felt a physical deformation. This phenomenon is investigated in [31] and is a plausible theory, as it does induce an artificial variation of compliance perception. Pseudo-stiffness therefore potentially benefits from this finger pad deformation.

As participants were mostly beginners or intermediate in VR, they really appreciated manipulating tangible objects, especially while seeing their real hands. As the hand representation was consistent with the object's deformation, they believed they were performing the deformation - which positively altered their stiffness perception.

As a side note, We noticed that participants directly pressed the objects when the task was COMPRESS - to eventually make it green; as they were doing "dynamic squeeze" gestures with the SQUEEZE task. They were indeed keeping their fingers on the object and making small subsequent deformations.

5.2.1 Findings & Discussion

H1 From this experiment, we verify our first hypothesis. Quantitatively, a stiffness from $24N/cm$ to at least $75N/cm$ can be elicited on a rigid non-compressible object. Qualitatively, participants felt that objects with larger stiffness were harder to deform, even though the force applied was relatively similar ($F = 19.1N$ up to the point of subjective visuo-haptic consistency, $F = 19.6N$ beyond it).

H2 → H3 We hypothesised that object's scales impacted the pseudo-stiffness perception. While this factor does not impact the point of subjective visuo-haptic consistency, it indeed does enhance the efficiency of pseudo-stiffness in large stiffness deformation, with over 75% of *Similar* answers, and around 60% on small objects. While large objects show better results than small objects (**H2**), the force applied on large objects during the user experiment was significantly higher than for small objects (**H3**) (see Section 5.1.4). We therefore cannot decorrelate scales from user input force in this hypothesis.

H3 Regarding the amount of induced forces, participants did apply more force for the "Compress" task than the "Squeeze" one, as expected (1.6N higher in average). We note that "Compress" results are higher (over 75%, $F = 19.8N$ in average) than "Squeeze" (between 65 and 75%, $F = 18.9N$ in average). Both small and large objects see their scores enhanced when being "compressed", i.e. when more force is applied on the object (see Table 3).

The "Squeeze" task shows better results at low stiffnesses than the "Compress" task. We note that apart from $k = 24N/cm$, the "Squeeze" task reached over 50% of *Similar* answers from $k = 12N/cm$. Therefore, a free deformation can potentially be implemented for a low stiffness ($k \approx 12N/cm$). Reciprocally, the "Compress" task shows better results thank the "Squeeze" task in large stiffness ranges.

As opposed to our preliminary study surprising results, we do not find a *maximum* threshold for pseudo-stiffness efficiency. We logically find that results are better for large stiffness ranges. In these ranges, the more force applied, the better the results. The best results are even achieved for Large Objects being Compressed, with even 100% *Similar* answers for $k = 60N/cm$. We believe that the results from the preliminary study are due to its staircase design - as our global experience uses a randomised within-design and therefore removes biases and direct comparisons between conditions. As a conclusion, user input force therefore does not impact the point of subjective visuo-haptic consistency of pseudo-stiffness (see Table 2), but it enhances its efficiency in larger stiffness ranges.

5.3 Comparison with Everyday's Objects

Material stiffness is usually expressed through *elasticity*, using Young's modulus. To compare our pseudo-stiffness point of subjective visuo-haptic consistency findings with common everyday's objects, we therefore translate stiffness into E, elasticity coefficient.

$$E = \frac{F \times L_0}{\Delta D \times A} = k \times \frac{L_0}{A} \tag{1}$$

where E is Young's modulus (Pa); k is the stiffness (N/m); L_0 is the object's length (m); A is the object's cross-section (m^2).

As Young's modulus is a function of the original length of the object, the smaller and larger objects therefore show different results. At $k = 24N/cm$ (point of subjective visuo-haptic consistency), we therefore have $E_{small} = 0.13MPa$ and $E_{large} = 0.19MPa$.

In terms of materials, these Young's moduli are comparable to **silicons** and **rubbers**. In terms of everyday's objects, these results are in between **gummy bears** ($E = 0.07MPa$) and **raisins** ($E = 0.22MPa$), w.r.t to their original sizes [48]. In our user experience, we did not go beyond $k = 75N/cm$. This translates into $E_{small} = 0.40MPa$ and $E_{large} = 0.61MPa$. These results can be respectively comparable to a dried raisin ($E = 0.43MPa$) and between a dehydrated to a dried apricot ($E = 0.49MPa$ and $E = 0.99MPa$) [48]. Objects between these extrema include dried gummy bears and prunes [48].

6 Future Work

6.1 Widening Haptic Properties of Passive Props

Using passive props is shown to improve the user experience, though it is limited a certain amount of props. We believe that our results can be used to widen the intrinsic haptic properties of these props.

As future work, we propose to investigate the ranges of pseudo-stiffness that can be induced on soft objects as well. While rigid objects can mimic both rigid and soft objects, it would be interesting to define if soft objects can simulate both stiffness above our point of subjective visuo-haptic consistency ($k = 24N/cm$) and large ones (over $k = 75N/cm$). The aim of this future work is to enable wider ranges of haptic properties by leveraging users' vision.

In these regards, we also propose to investigate coupling different visuo-haptic illusions techniques. For instance, our pseudo-stiffness study could be intertwined with *Resized Grasping* [9] and *Haptic Retargeting* [5]. In this configuration, a single object could simulate 1) N objects, 2) of M sizes and 3) L stiffness.

6.2 Coupling with Robotic Shape Displays

Shape-changing interfaces such as [19, 42] can potentially be used for edition tasks and deformations in VR [13]. We propose to study the extent of a physical deformation intertwined with pseudo-haptic illusions. Using a rigid surface, we simulate a 24 N/cm stiffness; it would be interesting to understand if a rigid surface coupled with a small physical displacement can go beyond this threshold, and simulate really soft objects.

On another perspective, Abtahi et al. investigated the effect of visuo-haptic illusions to tackle their robotic shape displays limitations (resolution, size, speed) [1]. We believe that our results can be exploited to reduce the complexity of interfaces and mitigate their current "failure modes" [11]. On the one hand, encountered-type haptic devices leveraging the use of real passive props such as [12] can benefit from our results to provide various stiffness properties. On the other hand, encountered-type haptic devices reconfiguring themselves to provide haptic feedback such as [42] and shape-changing interfaces often suffer from this reconfiguration phase [11]: modifying a physical object structure can be difficult due to tracking issues. We believe that pseudo-haptics can either simulate these deformations, or scale their real physical amount up; and eventually extend their compliance range [15].

6.3 Scalability & Linearity of Pseudo-Stiffness

Participants used their thumb and either only index, only middle, or index and middle, or index-middle-ring etc. As future work, an analysis on the impact of the grasp configuration on pseudo-stiffness efficiency could be interesting. In the same line of observations, we could potentially extend this study to link the induced input force to the biomechanics of the hand. Indeed, while we noted that larger objects showed better results than smaller ones, along with significantly higher forces, we believe this might be due to the hand configuration. The grasp over larger objects probably enables more applied force than on smaller objects. Reciprocally, these results are entitled to a limit: significantly larger objects cannot allow for grasps as consistent as the ones we studied, and therefore users cannot exert large forces. Future work can include a study of this maximum size threshold for pseudo-stiffness.

Finally, we simulated a linear deformation in our study. Though, some materials have non-linear deformations. We propose as future work to study different material and texture renderings using non-linear deformations, to understand their impact on user's perception. Similarly, future work includes the perception of breakage, whenever elastic deformation becomes plastic. This deformation is then *irreversible*. While the virtual objects were changing back to their original sizes in our user experience, it would be interesting to have some insights on the perception of this irreversible deformation.

7 Conclusion

In this paper, we evaluate whether compliance can be induced in a rigid passive prop using pseudo-haptic techniques in VR, and to which extent. We provide (1) a method to induce compliance into rigid objects and (2) empirical contributions: our results show that a stiffness beyond 24 N/cm ($k \geq 24N/cm$) can be perceived using pseudo-stiffness. This point of subjective visuo-haptic consistency is not impacted by the virtual object's scale or the user input forces, yet we do show a correlation between objects' scales and user input force: the larger the object, the higher the force. Similarly, pseudo-stiffness is enhanced by this exerted user input force in large stiffness ranges: the more force applied, the more believable and consistent the deformation. Our contributions offer novel opportunities to reduce future haptic systems' complexity and to widen the extend of intrinsic haptic properties of passive props in VR.

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