Elastic or Stiff? Light or Heavy? Pseudo-Haptic Photograph Interaction for Fabric Perception

Marina Ricci, Sylvia Pont, Gijs Huisman, *Member, IEEE*, and Maarten Wijntjes

***Abstract*—Online retail is still mostly limited to the visual channel despite haptic interface technology advances. One potential strategy for overcoming the lack of touch in online retail is using pseudo-haptics: illusory haptic sensations resulting from manipulating the visual feedback of mouse or touchscreen interactions. Previous research used computer-generated graphics for pseudo-haptic experiences, while online retailers rely heavily on accurate photos of their products. Therefore, our study proposes a novel approach to designing pseudo-haptics using interactive photograph series together with mouse cursor gain modulations, called Pseudo-Haptic Photograph Interaction (PHPI). Unlike prior approaches that rely on simulated or stylized imagery, PHPI introduces pseudo-haptic effects through real photographic sequences of fabric motion, bridging the gap between visual realism and interactive haptic simulation. We conducted user studies on the perception of stiffness and weight to validate our approach. In experiment 1, we investigated the relation between the perception of weight and stiffness and increased or decreased gain of mouse movement. The study reveals a strong relation between mouse gain and perception. To test whether this corresponded to pseudo-haptic sensations, we performed experiment 2, in which actual fabrics had to be matched with those displayed through PHPI. We found a correlation between the haptically perceived weight and stiffness of fabrics, and their digital surrogate mediated by visual cues, confirming the potential of PHPI for multimodal experiences in online retail and other photographic presentations.**

***Index Terms*—Design, fabrics, haptics, pseudo-haptics, interaction design, perception.**

I. Introduction

THE sense of touch enables humans to explore and interact with the world around us, enabling us to gather information, make judgments, and form emotional connections [1]. While touch has long been recognized for its importance in basic survival functions and social interactions, its impact on specific areas of modern human life, such as shopping, has gained considerable attention only in recent years [2]. In clothes shopping especially, multi-sensory perception plays an important role; for example, consumers use multiple senses in evaluating fabrics and garments, including vision, touch, sound, and even smell [3]. Although the perception of fabrics incorporates several sensory modalities, visual and tactile sensations are predominantly influential. That is consumers "view" and "feel" fabrics [4]. However, a large percentage of clothes shopping now occurs online [5], and online stores have been hindered by the impossibility of physically providing consumers with the opportunity to touch and handle the products they are interested in. Another resulting issue is certainly that of excessive returns [6]. According to Forrester, in 2021, the average return rate of garments purchased online rose to 30% . This alarming statistic means that almost a third of all clothing items sold online are returned, posing a significant challenge to the profitability of fashion e-commerce companies [7] and causing consumers to exhibit reluctance to purchase clothing online. This emphasizes the need to involve the sense of touch in e-commerce [8]. While this issue has been acknowledged in the scientific literature, practical solutions have remained limited [9]. It is currently difficult to communicate their distinctive tactile qualities for complex materials of a wide variety, such as fabrics [10].

Although haptic interface technology has advanced tremendously over the past decades, it cannot accurately simulate the rich haptic experience of fabrics. Moreover, such advanced technology is not available to most home users. Hence, it is worthwhile to investigate vision as a sensory substitute to convey the haptic material properties. Our research builds upon studies that have demonstrated that it is possible to use visual stimuli to simulate the experience of touch [11]. The current study investigates pseudo-haptic contributions [10] to photographic presentations. Pseudo-haptics relies on altering the visual feedback of motor actions (mouse movement in our case) in visual interactive interfaces [12].

Previous experimental studies into pseudo-haptics have only been conducted using static images [13], computer-generated images [14], [15], [16] or videos [11]. These approaches may not be compatible with online shopping environments or lack the visual detail necessary to successfully communicate detailed material properties of complex materials, such as the surface structure and dynamics under manipulation of fabrics. Therefore, we investigated interactive images, also known

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the TU Delft Human Research Ethics Committee (HREC) (approval granted on 13 January 2023) and was conducted in accordance with the TU Delft ethical guidelines for research involving human participants.

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as Shoogles [17], which are image-based animations. The advantage of using images over computer rendering is that the complexity of optical and mechanical characterization of fabrics is bypassed: the veracity of a photo is inherently higher than a computational replica.

At the same time, high-fidelity photographic realism is not an unequivocal advantage. Real fabric images contain visual cues such as wrinkles, specular highlights, and texture, which may suggest stiffness or elasticity independently of mouse-gain manipulation. These cues could potentially conflict with the intended pseudo-haptic effect and undermine the illusion. Unlike simplified visuals, where motion cues dominate, photographs present rich information that could either reinforce or interfere with pseudo-haptic perception. It is therefore not trivial to assume that pseudo-haptic effects will persist under photographic conditions.

Our central motivation is thus to verify whether pseudo-haptic effects remain robust when presented through photographic sequences that include such complex visual information. Demonstrating their persistence under these conditions is essential for establishing the feasibility of photographic pseudo-haptics as a reliable design tool. Therefore, we introduce the novel concept of Pseudo-Haptic Photograph Interaction (PHPI), which combines an animated sequence of photographs with pseudo-haptic effects. We carried out two user studies focusing on the haptic material properties of stiffness and weight to test and validate our approach and investigate whether it can effectively convey the psychophysical dimensions of fabrics, enabling users to experience a "visualized touch." Thus, we want to address the following Research Questions (RQs):

- RQ1 - To what extent is there a correspondence between the displayed pseudo-haptic effects and the perceived degrees of weight and stiffness? (Experiment 1).
- RQ2 - To what extent is there a correspondence between fabrics' actual weight and stiffness and the simulated properties via PHPI? (Experiment 2).

The contribution of this work is to demonstrate that pseudo-haptic illusions can be systematically elicited even with photographic stimuli, where additional visual cues might otherwise interfere. This confirmation establishes the robustness of pseudo-haptic effects in ecologically valid conditions and opens new opportunities for applying them in realistic digital material experiences.

The remainder of this paper is structured in five sections. The first describes the state-of-the-art related to pseudo-haptics for fabric perception by focusing on the stiffness and weight properties. The second describes the methodology behind our PHPI approach. The third and fourth present, respectively, Experiment 1 and Experiment 2. The fifth presents a general discussion about the experiments in relation to our research questions. Lastly, we report our conclusions and future work.

II. Pseudo-Haptics for Fabric Perception

About twenty years ago, user interface researchers experimented with an alternative means to reduce system and device complexity while still providing a rich haptic sensation [18] by utilizing pseudo-haptics [19]. Lécuyer (2009) defines pseudo-haptic feedback as "a technique meant to simulate haptic sensations using visual feedback and properties of human visuo-haptic perception" [20]. Pseudo-haptic feedback can be used in order to simulate haptic sensations. We focus on studies involving pseudo-haptics without using any external haptic device, with input based on a mouse cursor (for desktop displays) or fingers (for handheld displays).

For instance, by modifying the mouse cursor's control-display ratio (C/D ratio) when exploring a 2D image, Argelauget et al. demonstrated that it is possible to simulate stiffness [14]. Costes et al. (2019) proposed an alternative approach called "Touchy" for improving touchscreens, in which a symbolic cursor is introduced beneath the user's finger, undergoing alterations in its shape and motion on handheld displays, to elicit different haptic properties. This novel metaphor enabled the exploration of four distinct perceptual dimensions: hardness, friction, fine roughness, and macro roughness. Seven visual effects based on cursor alterations were compared with actual texture samples in a study involving 14 participants. The findings indicated that Touchy could evoke clear and distinguishable haptic properties, including stiffness, roughness, relief, stickiness, and slipperiness.

The material properties we selected for our first studies are stiffness and weight since both properties have been previously investigated from the pseudo-haptic perspective on desktop displays [14], [21].

Only one study has examined both properties within the same paper. Although Ban and Ujitoko (2018) [22] focused on friction rather than stiffness and used a handheld device instead of a desktop display, the overall task was comparable. Their user study with twelve participants investigated whether a virtual string—visually representing a connection between the user's finger and the object—would enhance the pseudo-haptic effect for weight and friction. Participants lifted an object under a pseudo-gravitational force and dragged it along a surface where a pseudo-frictional force was applied to a specific section. Their results showed that the "Break effect" significantly increased perceived weight and friction, despite a constant C/D ratio. A plausible explanation is that participants saw the object come to a stop during dragging, which led to a perception of a pseudo-force opposing the motion.

A. *Stiffness*

The haptics community has widely studied the perception of stiffness of real and virtual objects, usually aiming to measure the capacity of humans to perceive different levels of stiffness using a dedicated haptic device or well-characterized physical stimuli [23], [24], [25].

In the existing literature, only one study uses mouse-based input (on a desktop display) to create a pseudo-haptic effect of stiffness without the need for dedicated hardware [14]. Argelaguet et al. (2013) presented "elastic images," a pseudo-haptic feedback technique that allows users to perceive the local stiffness of images without the need for any haptic device on desktop displays [14]. The proposed approach focuses on the ability of visual feedback to induce a feeling of rigidity when the user interacts with an image using a standard mouse. The user deforms the image locally by clicking on an 'elastic image.' Because of the viewpoint (top-down view on a horizontal surface), the image deformation is attributed to the haptic interaction with the stimulus. To reinforce the effect, they also proposed the generation of shadows and folds to simulate the compressibility of the stimulus and different mouse cursor substitutions to enhance the perception of pressure and rigidity. The results showed that users could recognize up to eight different stiffness values and confirmed that it provides a perceivable sensation of stiffness. Potential applications of the proposed approach range from pressure sensing in product catalogs and games to usage in graphical interfaces to enhance the expressiveness of widgets.

B. Weight

There are various studies on weight perception using pseudo-haptics, but these works focused mainly on VR environments by using a hand-held controller [26], [27], [28], [29]. These works explored how weight can be conveyed by manipulating the CD ratio.

Our study differs from the previous literature since we explored the weight perception on desktop displays. Only in one paper, Kawagishi et al. (2023) proposed a method combining pseudo-haptics, tensile illusion, and asymmetric vibration. This enhanced the pseudo-force sensation, which could be presented without a force feedback device, by simulating the interaction with objects with different masses and weights [21].

Considering the above literature, we observe that there is a research gap concerning studies that simulate fabric properties with actual images of the fabrics rather than computer-generated images and prerecorded manual interaction that does not rely on real-time image rendering (such as in the case of Argelaguet [14], through deformation of top-viewed surfaces).

Compared to previous pseudo-haptic approaches, our method (PHPI) is novel in that it applies gain manipulation not to synthetic or deformable virtual objects, but to photographic sequences of real fabrics, capturing real-world visual cues such as folds, wrinkles, and gloss. Unlike Argelaguet et al. [14], who applied pseudo-haptic effects on top-down 2D images with simulated deformations, our approach uses real photographs captured during actual fabric manipulation, without requiring dynamic rendering or artificial cues like shadows or cursor morphing. Similarly, studies such as Ban and Ujitoko [22] or Kawagishi et al. [21] introduced enhancements like break effects or vibration, but either relied on stylized visuals or specialized setups. To our knowledge, no previous work has evaluated pseudo-haptic feedback using real photographic image sequences of fabrics, nor examined how the manipulation of mouse gain interacts with high-fidelity visual realism to simulate material properties.

III. Pseudo-haptic Image Interaction Approach

Therefore, we present PHPI, a novel approach that exploits a combination of alterations of the mouse cursor gain and animated sequence of photographs to generate pseudo-haptic sensations and reproduce and simulate the behavior of real fabrics as closely as possible to reality.

The main novelty we introduce in our study is the first-time use of pseudo-haptics with real images, rather than virtual ones, to convey these properties. This choice does not stem from the belief that real images are inherently better than virtual images in absolute terms, but rather from the specific context for which our PHPI approach is designed—e-commerce. Indeed, there are several reasons why we consider real images of fabrics to be more suitable than virtual images in an e-commerce setting.

First, fabrics' acquisition, simulation, and rendering are highly complex tasks due to their extremely diverse geometric and optical characteristics. As a result, complex and irregular textures and reflectance functions can be generated [30], [31]. Even when starting from high-resolution scans, randomness arises that is difficult to model [32], in addition to leading to errors (and visual distortions) if the models are not sufficiently detailed [31].

Moreover, virtual fabric-based solutions in e-commerce systems can cause user disorientation and difficulty in making purchasing decisions. In an online shopping study, Kim and Forsythe (2008) show that virtual representations are not always convincing to consumers, who may feel less confident about their purchase [33]. Although their work focuses on "virtual try-on," it highlights how low visual fidelity of virtual fabrics and materials can generate doubts and lead to shopping cart abandonment. Consequently, if users do not perceive the fabric (both visually and through "virtual touch") as realistic, their trust in the product decreases, hindering the purchasing decision [34].

In contrast, real images of fabrics constitute a tool more closely aligned with user needs, owing to greater visual accuracy, material rendition, fidelity to reality, and more plausible sensory correspondence [35]. In our PHPI approach, the set of images considered refers to the physical interaction of a real hand with an actual piece of fabric, along with the changes the fabric undergoes during this interaction. Previous research has shown that both real images and videos depicting physical manipulation of the fabric achieve higher realism by displaying folds, reflections, and shape changes more intuitively, while at least visually simulating the missing "tactile" dimension. For instance, although Yoo and Kim (2014) do not directly address fabrics, they explain that, in online shopping contexts, real images promote greater trust due to the presence of "human" factors and physical product manipulation (such as a hand touching the fabric), which enhances perceptions of authenticity [36]. Wijntjes et al. (2019) also discuss the positive effects (i.e., reduced disorientation, and increased trust) resulting from images or videos in which a user's hand physically manipulates the fabric [37].

To this aim, we captured sequences of pictures that simulate fabric stretching and lifting interactions. Therefore, progressions of pictures ($\sim$24) were taken with a professional photographic setup (See Fig. 2) to capture the material movement frame-by-frame.

From the pseudo-haptics point of view, we exploit the cursor gain technique with an adjustment direction parallel to the direction of the mouse movement [38], [39], [40], [41], [42].

Although the cursor gain technique is easy to implement, it only works when the user moves the mouse and is limited to the direction of the user's movement.

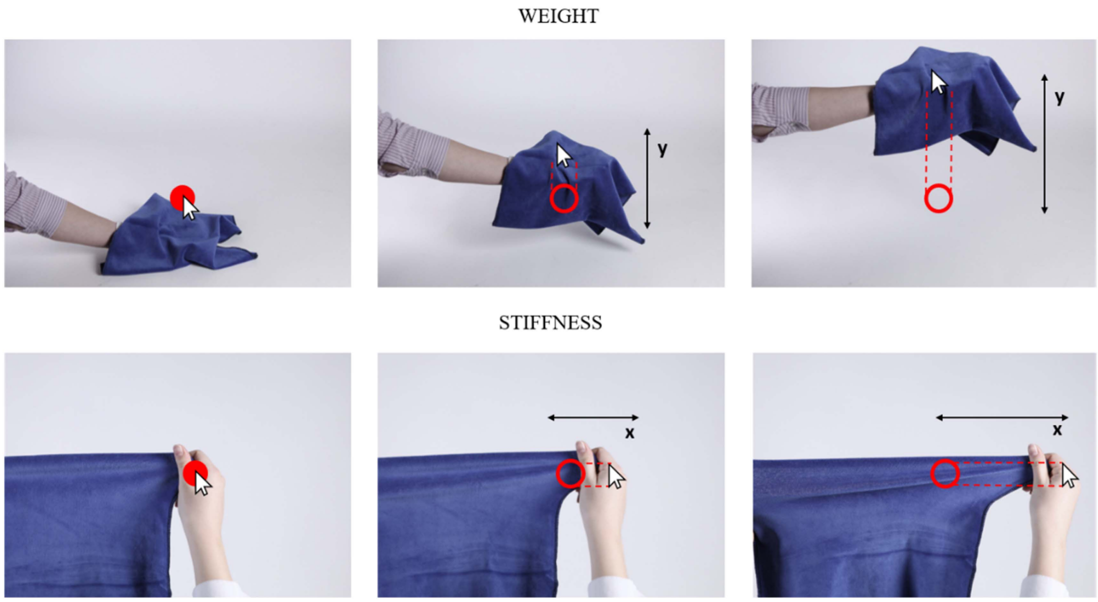

Fig. 1. PHPI for provoking pseudo-haptic effect on mouse cursor movement through a disk as a signifier. In the pictures, the disk is represented through a red circle, the auxiliary lines represent the displacement of the cursor, and the mouse cursor is the actual position of the mouse. Please note the distance between the mouse cursor and the photographed hand/fabric, indicating the effect of gain on the relationship between mouse movement and visual presentation. Top-Left: The weight PHPI at first frame; Top-Middle: The weight PHPI after user manipulation (heavier weight; gain = 2); Top-Right: The weight PHPI after user manipulation (lighter weight; gain = 05). Bottom-Left: the stiffness PHPI at first frame; Bottom-Middle: The stiffness PHPI after user manipulation (high stiffness; gain = 4); Bottom-Right: The stiffness PHPI after user manipulation (low stiffness; gain = 025).

Fig. 2. Photographic setup consisting of two LS-1200 LED Panels for bright, homogeneous lighting, a Canon EOS 5D Mark II camera on a tripod, a white paper backdrop, and a blue velvet fabric (32 x 46 cm).

The coded gain formula was:

$$virtual\ position = actual\ cursor\ position * gain$$

When the gain is set to 1, each transition from one frame to the next occurs every 10 pixels of mouse displacement along the designated axis (x for stiffness, y for weight). As the image sequence contains 24 frames, a total displacement of approximately 230 pixels is required to navigate the entire sequence. This mapping is scaled proportionally by the gain factor: for example, a gain of 2 requires only ∼115 pixels, while a gain of 0.5 requires ∼460 pixels to reach the final frame. The system dynamically computes the visual frame index based on the displacement from the initial mouse position, which is reset at the moment of interaction onset.

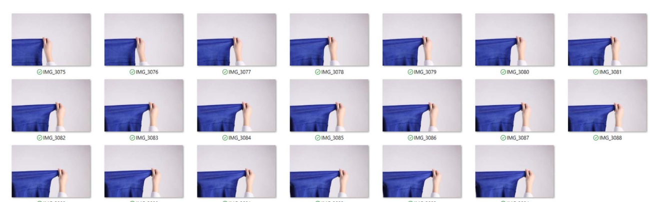

Fig. 3. Stiffness PHPI design: Sequence of pictures taken in sequence to capture hand motion and fabric movement before being embedded in JavaScript's p5 library code.

To ensure consistent and linear mapping across participants and systems, mouse acceleration was explicitly disabled on all experimental devices. This prevented any nonlinear scaling of cursor displacement due to hardware or OS-level mouse settings.

The previously taken pictures were used in a visual interaction implemented using p5.js, a JavaScript library based on the Processing programming language (See Fig. 3).

The interaction occurred on a desktop display using the mouse. By interacting with the fabric through the mouse cursor, the PHPI will slow or speed up the movement of the visuals.

For our user studies, we selected the properties/stimuli of stiffness and weight, recreating the following fabric interactions:

- Lifting gestures to reproduce weight perception [43], [44].
- Stretching gestures to reproduce stiffness perception [45].

Also, we designed a "signifier" within the PHPI [46], represented by an animated white transparent disk (See Fig. 1), which moved in a loop (on the x-axis for stiffness and the y-axis for weight) to signal to the user in which direction to move the cursor to experience the stimulus. After the user clicks on it, the cursor disappears, and the user is free to move the cursor. We also added clarifying texts for weight: "Hold the mouse and drag the cursor to the top," and for stiffness, "Hold the mouse and drag the cursor to the right".

IV. Experiment 1

In the first experiment, we used a rating task to measure the observers' ability to perceive different displayed stiffness/weight levels.

We hypothesized that the user ratings and the displayed properties of the fabrics managed in the coding phase through the variable "gain" might correspond.

Considering the prior scientific literature and RQ1, we hypothesized

- H1 - There is a negative correlation between mouse gain and weight perception (amplified mouse movement results in a lighter perception).
- H2 - There is a negative correlation between mouse gain and stiffness (amplified mouse movement results in a more elastic, less stiff perception).

A. Methods

1) Stimuli: The task in the first study was to rate the perceived stiffness and weight (on a 7-Point Likert Scale) by interacting with the PHPI. We tested five stimulus levels corresponding to 5 levels of mouse gain.

For stiffness, we asked to rate perceived stretchiness or compliance, which is the opposite, but seemed to us more intuitive. The rating data ("1" corresponded to "rigid," and "7" to "elastic") was then converted to stiffness = 8-rating, i.e., an elastic rating of 7 corresponds to a stiffness rating of 1. For the weight scale, "1" corresponded to "light," and "7" to "heavy. The five gain levels were selected to span a broad and approximately logarithmic range of perceived interaction speeds, while remaining perceptually distinguishable based on pilot testing and pseudo-haptic literature [14], [18]. For the stiffness condition, gain values were: 0.25, 0.5, 1, 2, and 4, representing increasingly stiffer feedback. For the weight condition, we used gains of 0.5, 0.59, 1, 1.43, and 2.

We chose to design the stimuli using only one material sample to systematically test and isolate the effect of gain without material type as a confounding factor. In this way, users could only distinguish the different properties of the material once they interacted with it, as each stimulus presented a different gain value while displaying the same fabric. The fabric sample measured 32 × 46 cm and weighed 32.1 g as determined with a Kern 572 precision balance. Its stiffness was evaluated by applying a 1 kg weight (force $F = 9.81$ N) to one end of the diagonal while the opposite end was fixed. The resulting displacement was 12 cm (0.12 m), yielding a stiffness value of approximately 81.75 N/m, calculated using the relation F = kx.; the observed displacement was 12 cm.

2) Procedure: Observers first received written instructions (together with the consent form), followed by a brief video demonstration of the general procedure. Stimuli were presented randomly to avoid possible biases, e.g., learning and order effects. Participants used their mouse to interact with the visualized fabrics and to rate them.

The participants had to rate the haptically perceived stiffness and weight of the fabrics using the bipolar semantic differential (SD) scales (heavy-light, elastic-stiff).

3) Participants: Forty-one subjects were recruited at TU Delft and participated voluntarily. Participants signed an informed consent sheet and received monetary compensation for their time. The study was approved by the ethics committee of TU Delft and by the Declaration of Helsinki.

The experiment was conducted in a university laboratory. 15 males and 26 females participated, with 14 participants aged 18-24, 24 participants aged 25-34, 1 participant aged 35-44, and 2 participants aged 45-54.

Thirty-five subjects have more than three years of experience using online shops to purchase clothes; only three have experience between one and two years, one has less than one year, and two only buy clothes in physical stores.

Each participant completed 5 trials per condition, one for each gain level (i.e., 5 for weight and 5 for stiffness), resulting in a total of 10 trials per participant. No repetitions of the same gain value were presented. The gain levels were randomized within each condition to control for order effects. Participants took an average of 42 seconds per trial to explore the fabric before giving their evaluations. The total duration of the experiment averaged approximately 8 minutes per participant.

4) Data Analysis: The gain is defined as the amplification factor of the mouse movement:

$$interaction\ motion = gain * mouse\ motion$$

To quantify the relation between gain factor and perception, we fitted polynomial models of increasing order to the data, starting with a zeroth-order model (no effect), then first-order (linear effect), and second-order (quadratic effect).

We used the logarithmic values of the gain on the x-axis. The Akaike Information Criterion [47] was used to determine the best-performing model, and adjusted R^2 was computed to quantify how well the models explained the variance.

B. Results

In Fig. 4, it can be seen that a linear decrease in the logarithmic gain value predicts the perceived weight. The Akaike Information Criterion for the Zeroth order model was 818.506, first order 663.319, and second order 664.955. The adjusted R^2 for the winning (linear) model was 0.53. To ascertain the validity of the first-order model, we conducted an ANOVA on the second-order model. We indeed found that the contribution of the quadratic factor was not significant ($F(1202) < 1$).

In Fig. 5, the result for the stiffness is shown. Again, the linear model best explained the data, as the AIC values were

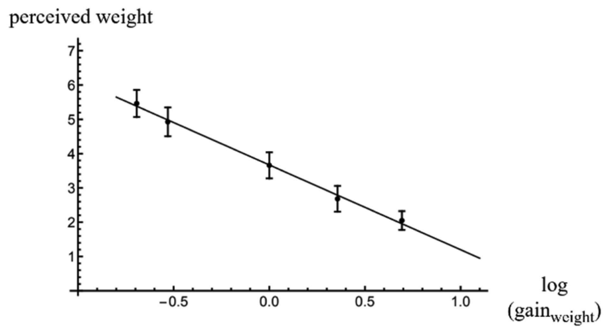

Fig. 4. Akaike model related to Experiment 1 (weight).

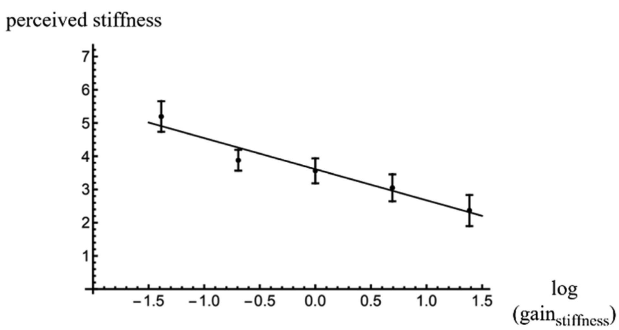

Fig. 5. Akaike model related to Experiment 1 (stiffness).

783.858, 706.712, and 706.828 for the zeroth, first, and second-order models, respectively. Again, we conducted an ANOVA to verify that the contribution of the quadratic factor was not significant ($F(1202) = 1.8778$, $p = 0.17$). However, the model explained less variance for stiffness (adjusted $R2 = 0.32$) than the weight data.

Fig. 6. The user interacts with fabric C to perceive the stiffness of the sample, as shown in Experiment 2.

Fig. 7. User interacting with fabric B to perceive the weight within Experiment 2.

C. Discussion

We found a clear pseudo-haptic effect of mouse gain for both material properties. However, we also found some interesting differences between the two material properties. For perceived weight, the explained variance of the linear model was about 1.7 times higher than for stiffness. This could be attributable to a seemingly visible nonlinearity observed in Fig. 7: the lowest gain value seems to show a relatively strong inelastic percept. One possible explanation for this is a ceiling effect: at low gain values, the interaction becomes barely perceptible, which might lead participants to interpret the material as purely inelastic. A key question is why this effect was more prominent for stiffness than for weight. Given that both weight and stiffness involve pseudo-haptic perception through altered movement dynamics, one might expect the barely moving interaction to impact both properties equally. However, previous research on pseudo-haptic illusions suggests that weight perception is primarily influenced by force resistance and cursor displacement over time (e.g., [48]), whereas stiffness perception is more dependent on perceived deformation and return dynamics [14]. When gain is extremely low, cursor motion is significantly reduced, which likely disrupts the perception of an elastic response more than the perception of weight, as stiffness relies on relative displacement and restoration forces. In contrast, weight can still be inferred from minimal movement under effortful control. Additionally, low gain may exaggerate haptic ambiguity, where users struggle to distinguish between proper stiffness and an artificially induced constraint on movement. This aligns with findings in prior work suggesting that haptic ambiguity in virtual environments can lead to nonlinear effects in perception [49]. Thus, our results may exemplify a boundary in pseudo-haptic effects where extreme constraints on movement disproportionately affect stiffness perception due to its reliance on dynamic interaction cues.

Although the data reveal a strong relation between mouse gain and perception, the question remains whether observers truly experienced a pseudo-haptic effect. Without reverting to introspection, we conceived that matching a pseudo-haptic stimulus to a touched stimulus could answer this question. Therefore, we designed a second experiment in which we used the mouse gain as a dependent variable (as opposed to being an independent variable in Experiment 1) and physical fabric stimuli with varying weight and stiffness as independent variables.

TABLE I
FABRICS REAL PROPERTIES

Fabric		Weight (grams)	Stiffness (N/m)
A	linen (knitted)	22,0 g	981 N/m
B	denim+ elastane (woven)	38,4 g	327 N/m
C	jersey (woven)	49,6 g	122.6 N/m

V. EXPERIMENT 2

In the second experiment, the task was to adjust the displayed stiffness/weight to match the perceived weight and stiffness of the physical stimuli fabrics. We hypothesized, considering the prior scientific literature and results of the first experiment, and answering RQ2:

- H1 - Lighter fabrics will be matched to lower gain and heavier fabrics to higher gain.
- H2 - More elastic fabrics will be matched to lower gain, and stiffer fabrics to higher gain.

A. Methods

1) Stimuli: To evaluate whether PHPI indeed induced pseudo-haptic effects, we designed three conditions.

The fabrics measured 32 x 46 cm. In terms of weight, the fabrics were weighed using a precision balance Kern 572 and had the following values: fabric "A" weighed 22g, fabric "B" weighed 38.4 g, and fabric "C" weighed 49.6 g, as shown in Table I.

To quantify their stiffness, for the sake of simplicity, we regarded the fabrics as linear springs, with the spring constant characterizing stiffness. If force is kept constant, the displacement is the determining linear variable of the spring constant. Thus, the stiffness of the fabric was characterized by measuring the deformation resulting from applying a 1 kg weight (force $F = mg = 9.81N$) to one side of a diagonal, while keeping the other side fixed. The measured displacements were 1 cm, 3 cm, and 8 cm for fabrics A, B, and C, respectively. By applying the relation $F = kx$ with x expressed in meters (0.01 m, 0.03 m, 0.08 m), one obtains: for fabric A, k = 9.81 N/0.01 m ≈ 981 N/m; for fabric B: k = 9.81 N/0.03 m ≈ 327 N/m; for fabric C: k = 9.81 N/0.08 m≈122.6 N/m.

From the perspective of material characterization, fabric "A" was linen, fabric "B" was denim containing elastane, and fabric "C" was Jersey.

2) Procedure: In experiment 2, we performed a match-to-sample task related to the three fabrics. For this, participants had to adjust the mouse gain value using an on-screen interface to adjust the pseudo-haptic perception of stiffness and weight to the perceived stiffness and weight of the three fabrics.

Participants had to interact with the three fabrics differing in stiffness and weight (See Figs. 8 and 9), first with the physical fabrics and then the photographed fabric on the screen. For this, they had to adjust the mouse gain value using an on-screen interface to adjust the pseudo-haptic perception of stiffness and weight to the perceived stiffness and weight of the three fabrics. This matching task was specifically designed to avoid reliance on introspection and instead focus on an objective behavioral measure. Rather than asking participants to verbalize or rate their perceptual experience—an approach that can introduce cognitive biases—the task required them to actively adjust a controllable parameter (mouse gain) until it perceptually matched a reference physical stimulus. This method leverages participants' implicit perceptual-motor adjustments, thereby reducing the risk of subjective biases and increasing the ecological validity of our findings.

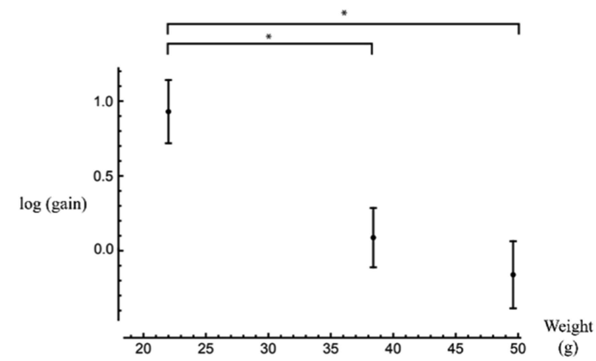

Fig. 8. Subjective gain settings as a function of weight in Experiment 2. Error bars denote 95% CI, horizontal bars denote significant pairwise comparisons.

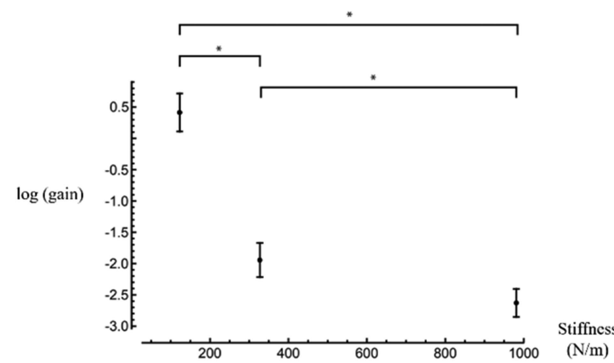

Fig. 9. Subjective gain settings as a function of stiffness in Experiment 2. Error bars denote 95% CI, horizontal bars denote significant pairwise comparisons.

Furthermore, this approach aligns with established methodologies in pseudo-haptic research, where perception is inferred through action-based responses rather than explicit introspection [18]. By using physical fabric stimuli as reference points, Experiment 2 ensures that pseudo-haptic effects are assessed about real-world material properties, strengthening the study's validity and its contribution to the understanding of pseudo-haptic illusions.

Users had to use the "W" key to increase stiffness and weight, and the "S" key to decrease them. The stepsize of the adjustment scale was defined by gain = 2^i with i = { …,-1,-0.50,0.51, … }. After each trial, the experimenter recorded the gain value, which was not visible to the participant.

3) Participants: The same participant pool was recruited for both experiments to ensure comparable sample characteristics, but the rating (Experiment 1) and matching (Experiment 2) tasks were analyzed independently without direct comparison between them (see Figs. 6 and 7)

Each participant completed 3 tasks per stimulus, one per material. Participants took an average of 108 seconds per task to explore the interaction before deciding the final gain. The total duration of the experiment averaged approximately 11 minutes per participant.

B. Results

Because there was only one independent variable (fabric), with three levels, we decided to perform repeated-measures ANOVAs instead of linear regressions. Any second-order polynomial would fit the data perfectly and may also falsely suggest a local minimum instead of a monotonically decreasing function. Mean values and pairwise comparison significance is shown in Figs. 8 and 9.

For weight, the ANOVA was significant ($F(2, 80) = 44.92$, $p < .001$, $\eta^2 2 = 0.529$) and Bonferroni corrected pairwise comparisons show difference between the lightest and the medium and heaviest fabric ($t(40) = 7.332$, $p < 0.001$ and $t(40) = 8.276$, $p < 0.001$, respectively).

For stiffness, the ANOVA was also significant ($F(1.614, 64.570) = 174.773$, $p < 001$, $\eta^2 = 0.814$) which was Greenhouse-Geisser corrected due to sphericity violation. All pairwise comparisons were significant ($t(40) = 12.651$, $p < 001$, $t(40) = 15.667$, $p < 0.001$ and $t(40) = 5.588$, $p < 0.001$).

C. Discussion

Experiment 2 reveals a clear, systematic relation between the levels of the independent variable and the gains that participants selected to match them. This negative, monotonic trend supports our hypotheses and shows that users may predictably exploit PHPI's gain modulation to recreate real-world impressions of weight and stiffness.

Experiment 2 allowed participants to actively adjust the gain themselves, offering a more direct and ecologically valid measure of how pseudo-haptic perception maps onto real-world material properties. By comparing participant-adjusted gain values across different fabric materials, Experiment 2 further clarified the role of movement constraints in pseudo-haptic weight and stiffness perception, reinforcing the robustness of the observed effects while addressing potential boundary limitations identified in Experiment 1.

While the weight data display a slight non-linearity, the function is strictly monotonic; participants can therefore map mouse-gain changes onto real-world material differences in a consistent fashion. The lack of statistical difference between the medium and heaviest fabrics is likely due to their proximity in weight.

Stiffness, however, does seem to show non-linear behavior, which is consistent with previous work showing that the perception of stiffness arises from complex interactions between optical, shape, and motion cues, and does not scale linearly with physical stiffness [50]. Horizontal brackets mark Bonferroni-corrected pairwise comparisons.

Colour can influence perceived weight and, by extension, stiffness [51], [52]. All stimuli in Experiment 2, therefore, shared the same colour and derived from the identical photographic sequence used in Experiment 1, isolating the variables of interest. Nevertheless, the fabric category, which often covaries with colour, also carries expectations about material properties [53]. Systematically disentangling colour, category, and gain manipulation remains an open avenue for future research.

Collectively, these results show that our PHPI technique can reproduce meaningful variations in perceived weight and stiffness, paving the way for realistic digital-material interactions in domains such as online retail and design.

VI. General Discussion

Our study builds upon previous research in pseudo-haptics, extending it to an animated sequence of photographs for a more realistic representation of fabric properties. Traditional approaches using static images, computer-generated graphics, or videos may not adequately convey detailed, complex characteristics of material properties, especially for fabrics. Our novel approach, PHPI, utilizes sequences of actual photographs and modulates the alterations of the mouse cursor gain to address this gap and provide a more accurate representation. This study focused on the haptic material properties of stiffness and weight.

Findings from Experiment 1: gain–perception relationship: We confirm that both hypotheses for each of the two experiments were tested and validated. On the one hand, Experiment 1 revealed a strong relationship between mouse gain and the perception of weight and stiffness, answering RQ1. Interestingly, the explained variance for perceived weight was higher than for stiffness. This could have been caused by potential non-linearities in the relationship, possibly influenced by a ceiling effect. The results imply that lower gain values produced greater impressions of weight and stiffness, while higher gains produced lighter, more compliant impressions, showcasing the effectiveness of our PHPI approach.

Although pseudo-haptic modulation of stiffness and weight has been studied before, particularly through cursor manipulation or synthetic visuals, our first experiment validates that such effects persist - and remain measurable - even when real photographs of fabrics are used as the visual medium. This is non-trivial, as real fabric images contain complex visual cues that may interact with gain-induced perceptions in ways not previously explored. Our findings show that these potential conflicts did not undermine the illusion: pseudo-haptic effects remained systematic and measurable even in the presence of wrinkles, highlights, and other photographic cues. This robustness highlights that photographic realism does not weaken, but rather coexists with, gain-based manipulations. Therefore, Experiment 1 serves a dual purpose: first, to verify that pseudo-haptic illusions can be elicited through photographic media; and second, to establish a baseline for interpreting how gain variations influence the perception of physical material properties in a realistic visual context. Unlike prior work that used simple or stylized images [14], [18], [21], [22], our findings show that photography-based pseudo-haptics can evoke similar perceptual effects, thereby opening new design opportunities for realistic digital material experiences.

It is worth noting that prior work, such as Atkinson et al. [45], which explored tactile perceptions of digital textiles through "shoogles," did not implement gain modulation to alter material perception in the way pseudo-haptics does. In their study, finger motion and image motion were directly linked via touchscreen interaction, making gain manipulation inherently more difficult to achieve. By contrast, our mouse-based approach takes advantage of the lack of absolute mapping between user input and visual feedback, which enables gain manipulation as a perceptual design tool. This distinction highlights an important advantage of mouse-based pseudo-haptics in enabling the modulation of material impressions without direct 1:1 visuomotor coupling, as would be the case with touchscreen interaction.

Findings from Experiment 2: correspondence with real fabrics: In Experiment 2, we further validated our approach by assessing the correspondence between the three fabric levels (independent variable) and the gains that participants selected through PHPI, answering RQ2. The findings supported our hypotheses, indicating that participants associated heavier and stiffer fabrics with lower adjusted gains. This non-linear but monotonic relationship between mouse gains and actual material characteristics shows that our PHPI version successfully elicits material perception variations comparable to those experienced in real life. Importantly, the use of photographic images may have contributed to this effect by providing high-fidelity visual cues that enhanced the realism of material perception. Unlike computer-generated textures, which often simplify surface details, images of real fabrics retain subtle variations in reflectivity and texture that might interact with pseudo-haptic feedback. Additionally, the limited number of frames at the highest stiffness and heaviness levels may have influenced these results, a limitation that deserves further investigation. This may explain why, despite the non-linearity observed in some conditions, the overall trend remained monotonic, reinforcing the robustness of the pseudo-haptic illusion. This insight suggests that the fidelity of visual stimuli plays a crucial role in shaping the efficacy of pseudo-haptic illusions, which deserves further investigation in future research.

Methodological considerations and limitations: In our study, we used 24 photographs to represent sequential motion. This choice was made to balance smooth visual perception with computational efficiency. Our experimental code loads each image separately, without using video compression, where subsequent frames can be optimized to reduce file size. Future research should investigate how these noticeable frame jumps are related to mouse interaction, as it is possible that visuomotor coupling induced a smooth visual experience (similarly to what happens in proprioception).

Additionally, qualitative feedback from users did not indicate perceptible discontinuities in motion. However, we acknowledge that motion smoothness may depend on the user's specific interaction pattern, and we are certainly motivated to include this as follow-up research.

While real images of fabrics offer high visual realism, their use in pseudo-haptic feedback generation presents certain challenges and limitations. One key limitation is the static nature of photographs, which may restrict the ability to simulate material properties such as stiffness or fine deformations dynamically. Unlike computer-generated models that allow real-time adjustments, photographic sequences rely on pre-recorded images, meaning that the number and variety of captured frames constrain the haptic illusion. Additionally, ensuring lighting consistency during image acquisition is crucial, as variations in lighting conditions could lead to perceptual inconsistencies [54], potentially affecting the intended pseudo-haptic effect. Another challenge is the trade-off between smooth visual transitions and computational efficiency: increasing the number of frames enhances the perception of continuity but also raises storage and processing demands. Despite these limitations, our results indicate that photographic images remain a viable and effective medium for pseudo-haptic feedback, especially in applications where preserving the authentic appearance of materials is essential. We cannot predict whether PHPI is viable in online retail practice, and how it relates to its virtual counterpart, but we did show that it is feasible.

One important limitation of our approach is that all visual stimuli across experiments were derived from a single sequence of photographs of the same fabric sample. This choice was deliberate, aiming to isolate and evaluate the impact of gain manipulation on perceived material properties without introducing visual confounds. However, we acknowledge that this introduces a degree of perceptual inconsistency: while gain changes simulate different levels of weight and stiffness, the visual cues - such as wrinkles, gloss, and deformation patterns - remain constant. This may limit the ecological validity of the illusion, as real fabrics with different physical properties typically exhibit distinct visual behaviors. From this perspective, the current implementation of PHPI shares similarities with other pseudo-haptic techniques that manipulate motion cues over static or visually invariant inputs [14], [18], [20], [42]**.** Future work should explore the use of fabric-specific image sequences, aligned with real physical properties, to determine how visual consistency can further enhance the realism and fidelity of pseudo-haptic experiences.

Another one of the study's main limitations is that PHPI was validated for only two properties, stiffness and weight, and only two gestures, stretching and lifting. Indeed, in our future work, we will investigate other properties such as softness and roughness and explore other gestures (e.g., rub, stroke) to broaden the testing and validation of PHPI.

Another limitation related to Experiment 2 is that the independent variable (fabric) was defined only through physical parameters, rather than perceptual scales. Future studies should anticipate creating perceptual scales, for example, using Thurstonian scaling [55] or MLDS [56] to better understand the non-linear relationship we found.

A further methodological consideration concerns the use of a fixed starting gain value in the adjustment task of Experiment 2. In our design, the gain always started at a neutral value of 1 for all trials. While this ensured consistency, it may have introduced order effects or anchoring biases, as adjustment methods typically benefit from varied starting points (both high and low) to minimize such effects. Although the final gain values showed consistent trends across participants and materials, suggesting the results are robust, future work should adopt counterbalanced or randomized initial gains to confirm the absence of such biases.

Future research directions: By exploiting photographs, the proposed PHPI approach can be adapted to various types of e-commerce products, expanding and customizing image sequences to meet user needs (e.g., multiple angles, simulations of different deformations, fabric customization). In our prototypes, we considered only one possible movement during the interaction (on the x-axis for the stiffness and on the y-axis for the weight), but multiple movements can be envisioned.

Future research directions could explore the applicability of PHPI to other material properties and expand the scope to different products and industries. Additionally, refining the understanding of the non-linear relationships between mouse gains and perceived material properties will contribute to optimizing the PHPI technique for broader use. An important consideration in our study is the potential influence of fabric-specific visual cues [54], such as texture, sheen, and weave patterns, on pseudo-haptic perception. Unlike computer-generated representations, real fabric images inherently carry detailed visual properties that may contribute to the perception of material properties, particularly in a pseudo-haptic interaction context. While our study primarily focused on pseudo-haptic perception driven by gain manipulation, these fabric-specific visual cues likely contributed to the participants' overall perception of material properties. Within the field of visual material perception, various visual cues have been proven to be diagnostic for properties like gloss [57], translucency [58], transparency [59], roughness [60], stiffness [50], etc. Photographs are a powerful medium to convey these cues that naturally arise in the optical process of capturing, although light has an additional influence [61].

By incorporating real fabric images, our study offers a more ecologically valid pseudo-haptic experience that aligns more closely with real-world material interactions. However, further research is needed to disentangle the extent to which specific low-level visual properties contribute to pseudo-haptic material perception and whether these properties interact with gain-based manipulations to shape the strength of the illusion.

Practical implications for online retail and design: Our motivation is to understand the potential of pseudo-haptics for haptic simulation and enrich visual communications, specifically photography. Our study lays the foundation for advancing the integration of pseudo-haptic technologies in enhancing on-screen sensory experiences using photographic visuals, e.g., for online shopping. Indeed, by incorporating pseudo-haptic feedback into online shopping platforms, we could bridge the sensory gap between physical and digital experiences. This enhancement could enable customers to virtually feel textures, weight, and other properties of products, leading to more informed purchasing decisions. Furthermore, by offering a more immersive and tactile online shopping experience, companies could increase customer satisfaction and reduce product return rates. This reduction in returns not only minimizes the high costs associated with reverse logistics but also decreases the environmental impact caused by excessive packaging waste and additional transportation emissions. Ultimately, this approach could drive sales while fostering brand loyalty more sustainably.

The PHPI approach offers significant potential for enhancing online shopping experiences, particularly in sectors where material appearance and behavior are crucial, such as fashion, interior design, and upholstery. By using real fabric photographs instead of virtual fabrics, PHPI ensures that users can interactively explore fabric properties such as stiffness, weight, roughness, and more, under different conditions. For instance, in online clothing stores, customers could visualize how a fabric responds to movement or folding before making a purchase, helping them better assess material properties. Similarly, in furniture and home decor e-commerce, PHPI could allow users to see how different upholstery materials behave when applied to cushions, sofas, or curtains, providing a more accurate representation of their look and feel. Moreover, PHPI can facilitate fabric customization by enabling users to switch between different fabric types, colors, and patterns while maintaining realistic physical properties.

However, acknowledging the inherent trade-off between photographic and computer-generated approaches is critical: while renderings offer greater flexibility in adjusting visual properties, photographs capture subtleties that enhance realism. Our study contributes by designing a photographic equivalent of the well-known computer-rendered version, helping practitioners weigh design freedom against the fidelity of the representation. These possible applications highlight the advantages of PHPI over conventional static images and 3D-rendered models, making it a valuable tool for improving product visualization and user engagement in e-commerce.

VII. Conclusion

The paper presents a novel approach, PHPI, outlining the methodology, presenting the results of user studies by exploiting PHPI to convey some tactile properties, i.e., stiffness and weight, and discussing the implications and potential applications of our findings.

PHPI was shown to have the potential to enhance the user experience from a multisensory perception point of view. It simulates variations in real-life hand interactions with fabrics by altering the coupling between the on-screen fabric and hand-mouse movement based on a gain value.

Our research demonstrates that PHPI is a promising tool for simulating tactile sensations in online shopping environments. The strong relationships between perceived and simulated material properties support the effectiveness of our approach. PHPI's potential applications extend beyond online shopping, offering a pathway for a more immersive and realistic user experience in various domains. Importantly, our study demonstrates that pseudo-haptic effects remain reliable even with high-fidelity photographic stimuli that introduce complex visual cues. This confirmation establishes the robustness of PHPI under ecologically valid conditions and strengthens its potential for real-world applications.

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