Multimodal perception of digital protective materials

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ABSTRACT – REZUMAT

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The online clothing industry has gained popularity among consumers, and the perception of materials and equipment plays a crucial role in their purchasing decisions. Therefore, accurately representing their appearance in real-time is essential. This study aimed to subjectively evaluate 20 protective textile materials by translating their tactile characteristics into virtual prototypes. This was accomplished by scanning physical materials with an x-Tex scanner and processing them in KeyShot rendering software. Consequently, four scenarios featuring digital materials were created: S1-image, S2-video animation, S3-3D object, and S4-physical materials. Digital visual subjective evaluations were conducted for sensory analysis. Participants were asked to assess four visual and seven tactile characteristics using a seven-point Likert scale. Statistical analysis was employed to evaluate the sensory data collected through subjective testing. The results indicated that agreement values for the four scenarios ranged from 1.25 to 7.0, as illustrated in boxplot diagrams representing the subjects' agreement with the perceptual attributes.

Pairwise comparisons of the S4-S1, S4-S2, and S4-S3 scenarios concerning the difference in means revealed that attributes FR with values of 0.045 (S1), RM with values of 0.063 (S1), CR with values of 0.028 (S1), CR with values of 0.039 (S2), and 0.052 (S3) are closely aligned with the actual values, as the values obtained from these scenarios closely approximate 0. In contrast, the values of the remaining attributes were close to 1, indicating the difficulty of translating these attributes into digital format and achieving accurate perception. Assessing textile material properties through digital images remains a challenging task that requires in-depth subjective analysis.

Keywords: *scanning, digitization, rendering, subjective perception, tactile attributes, visual attributes*

Percepția multimodală a materialelor textile digitale cu rol de protecție

Industria de îmbrăcăminte online a câștigat popularitate în rândul consumatorilor, iar percepția materialelor și echipamentelor utilizate în transpunerea caracteristicilor acestora joacă un rol crucial în deciziile de cumpărare a potențialilor clienți. Prin urmare, reprezentarea cu acuratețe a aspectului materialelor textile în timp real este esențială. Acest studiu și-a propus să evalueze subiectiv 20 de materiale textile cu rol de protecție, prin transpunerea caracteristicilor tactile în prototipuri virtuale. Acest lucru a fost realizat prin scanarea materialelor fizice cu scanerul x-Tex și procesarea digitală a acestora cu software-ul de randare KeyShot. În consecință, au fost create patru scenarii de reprezentare a materiale digitale: S1-imagine, S2-animație video, S3-obiect 3D și S4-materiale fizice. Au fost efectuate evaluări subiective vizuale digitale pentru analiza senzorială. Participanții la experiment au fost rugați să evalueze patru caracteristici vizuale și șapte caracteristici tactile folosind metoda de evaluare Likert cu șapte puncte. Analiza statistică a fost folosită pentru a evalua datele senzoriale colectate prin testare subiectivă. Rezultatele au indicat că valorile de acord pentru cele patru scenarii au variat de la 1,25 la 7,0, așa cum este ilustrat în diagramele boxplot, reprezentând acordul subiecților cu caracteristicile perceptuale.

Comparațiile în perechi ale scenariilor S4-S1, S4-S2 și S4-S3 cu privire la diferența de medii au arătat că anumite caracteristici FR cu valori de 0,045 (S1), RM cu valori de 0,063 (S1), CR cu valori de 0,028 (S1), CR cu valori de 0,039 (S2) și 0,052 (S3) sunt strâns aliniate cu valorile reale, deoarece valorile obținute din aceste scenarii sunt aproximativ 0. În schimb, valorile caracteristicilor rămase au fost apropiate de valoarea 1, indicând dificultatea de transpunere a acestora în format digital și de a obține o percepție exactă a caracteristicilor materialelor. Evaluarea proprietăților materialelor textile prin intermediul imaginilor digitale rămâne o sarcină provocatoare care necesită o analiză subiectivă aprofundată.

Cuvinte-cheie: *scanare, digitizare, randare, percepție subiectivă, caracteristici tactile, caracteristici vizuale*

INTRODUCTION

Due to the urgent necessity for a sustainable environment, all companies are striving to find the most efficient process for production optimization [1]. Different strategies must be applied to achieve a smooth transition to a sustainable textile industry [2]; in this regard, the textile industry must have a robust digital arsenal [2]. In their creative endeavours, companies have embraced the concept of Digital Product Creation (DPC), which streamlines the prototyping process through virtual 3D simulations [3], enabling compliance with increasingly stringent environmental standards. By using digital galleries of textile materials in the DPC process, a sustainable future is supported by reducing waste through the elimination of physical materials [4–6]. To support a sustainable textile industry, the adoption of digital technologies has posed several challenges to material digitalization [7]. There is still a gap in translating the appearance from visual and tactile qualities into a digital environment and their physical counterparts [8, 9].

Standardized methods for representing materials in a digital format, even when based on images, are still lacking. Consequently, the investigation of existing databases is approached through subjective evaluation to enhance the quality of these databases [10]. Regarding the perceptual evaluation of material appearance, numerous studies have focused on analysing the perception of smart materials [11], such as knitwear made of wool, cotton, or synthetic fibres [12, 13], as well as functional textiles [14, 15]. Only a limited number of reference papers have provided concise information on the subjective appearance evaluation of protective materials. Research in the evaluation of protective textile materials has primarily centred on evaluating their comfort properties [16]. In this paper, we aim to investigate the disparity in appearance between digitized protective materials and their physical counterparts by assessing how perceptual material information is transmitted through tactile and visual stimuli. Additionally, it's important to note that current databases cover only a limited range of isotropic and anisotropic materials [17–19], and there are only a few databases specifically focusing on protective textiles [20]. This research assesses twenty digital protective textile materials obtained through scanning [21]. Our proposal suggests a standardized set of procedures for analysing materials using different techniques to conduct perceptual quality ratings across 11 selected attributes. The proposed method for evaluating protective materials is an extension of the research work conducted by Martin et al. [22]. The evaluation of digital materials' appearance is based on spatially varying BRDFs when compared to physical materials at the perceptual level, utilizing various stimuli.

The human brain has the innate ability to recognize materials and their properties merely by visual observation [23], without the need for physical contact [24]. This theory forms the basis for the evaluation proposed in this research, involving the examination of rendered materials as images on a screen in scenario S1. Motion is considered a crucial aspect in the perceptual evaluation of digital material surfaces [25, 26], which led to the creation of video animations in scenario S2. When it comes to testing protective materials, advanced evaluations can be conducted by simulating them on specific three-dimensional shapes. This process heavily relies on perceiving the fabric's properties to accurately assess their effectiveness. According to Xiughui Dong's study [27], subjects can perceive the textures of digital materials more easily when allowed to increase the resolution of objects. Therefore, scenario S3 was created to present materials as three-dimensional interactive objects, allowing for object rotation and resolution enhancement to improve texture visualization. Studies on the subjective analysis of textile materials suggest that visual and tactile senses play a crucial role in describing their properties [28]. To address this, scenario S4 was introduced, enabling subjects to interact with physical materials and answer the same questions as in the digital material evaluation scenarios (S1–S3). This paper aims to expand on the reference works by combining the main methods of subjective evaluation of textile materials. Starting with the multi-modal digital representation of materials in scenarios S1–S3 and having scenario S4 as a reference, we seek to answer the key question of whether subjects can obtain sufficient information to perceive the real characteristics of materials in digital format.

MATERIALS AND METHODS

Materials

In this paper, twenty textile materials were subjected to a subjective evaluation. These materials were chosen by the standards governing industrial products crafted from specialized fabrics, as dictated by European and national legislation. Among the materials examined, fourteen fall under the category of protective textile materials, specifically designed for waterproof equipment intended to shield against various environmental conditions, including precipitation in the form of rain or snow. These materials adhere to the ISO EN 343 standard and find utility as both inner and outer layers of protection in various sectors, encompassing roles such as firefighting, traffic policing, and hunting. Furthermore, one material was assessed for its suitability in the production of ballistic protection equipment, aligning with European regulations such as Standard EN166. Additionally, four materials were analysed in terms of their appropriateness for the manufacturing of protective equipment used in forestry applications, in compliance with standards including EN 381, EN ISO 20471, and EN 343. Lastly, a textile material intended for military product manufacturing was also included in the evaluation. The following protective materials, each characterized by its composition, were evaluated in this paper: 100% Polyester + 100% Polyurethane (film layer); 100% Polyamide + 100% Polyurethane (film layer); 32% Polyamide + 68% Polyester + 100% Polyurethane (film layer); 100% Nylon + 100% Thermoplastic Polyurethane (film layer); 100% Polyester; 45% Polyamide + 55% Polyester; 100% Polyester; 45% Polyamide + 55% Polyester; 32% Polyamide + 68% Polyester; 60% Polyamide + 32% Polyester + 11% Elastane; 100% Polyurethane; 89% Polyester + 11% Elastane. This paper provides a comprehensive evaluation of these materials within the scope of the research.

Method of scanning and digitizing materials

The scanning procedure for the twenty protective material samples was conducted using the x-Tex system, developed by Vizoo. Each fabric was scanned using the x-Tex [29] system, resulting in the acquisition of a synthetic SVBRDF (Spatially Varying Bidirectional Reflectance Distribution Function) dataset comprising six uniform texture maps: Base Colour, Normal, Volumetric, Metallic, Opaque, and Rough. The output format is compatible with rendering applications such as Key Shot [30] software, which was employed to generate four scenarios utilized in this study, namely S1-image, S2-video animation, S3-3D object, and S4-physical materials. The geometry of the materials was approximated from the set of photographic texture maps within a virtual scene, using an illumination algorithm. For scenario S1, the output format was JPEG, with an image size of 2560 pixels in width by 1440 pixels in height, and a resolution of 300 dpi. In scenario S2, which involved an animated scene, the camera was rotated at –45 degrees, the camera focus distance was set to 800 mm, and the scene was rendered at 60 FPS (frames per second) to create a clip lasting 15 seconds, with a resolution of 2560 pixels by 1440 pixels. For scenario S3, the materials were rendered as interactive 3D objects, with the following settings: 26 frames of horizontal rotation and 16 frames of vertical rotation, resulting in a total of 416 frames for each 3D object, with a zoom factor of 200%. The results of the three scenarios used in the subjective evaluation are depicted in figure 1.

Visual and tactile attributes of materials for evaluation

To ensure the feasibility of this study, the primary objective was to analyse the key characteristics of protective materials. The selection of visual characteristics was based on relevant literature, encompassing a set of attributes focused on recognizing and perceiving material qualities, particularly those related to general text attributes. The descriptive attributes for visual properties of materials included gloss, colour, roughness, and transparency/opacity [31–37]. Similarly, the tactile attributes encompass softness, drape, elasticity/stretch properties, abrasion, thermal sensation, and moisture sensation/hygroscopicity [38–46].

Questionnaire evaluation

The subjective evaluation of protective fabrics was conducted using visual assessment techniques within digital/rendered scenarios. The assessment involved 24 subjects from Romania, comprising 6 males and 18 females, whose ages ranged from 22 to 59 years. All participants have higher education and extensive professional experience in the textile industry, which made them more critical and objective in their evaluation of textile materials. Before the assessment commenced, the subjects received instructions on the assessment procedures and processes. For data collection, a questionnaire based on a Likert scale was utilized [47]. This method was chosen because it is widely regarded as the most effective approach for assessing data in product analysis,

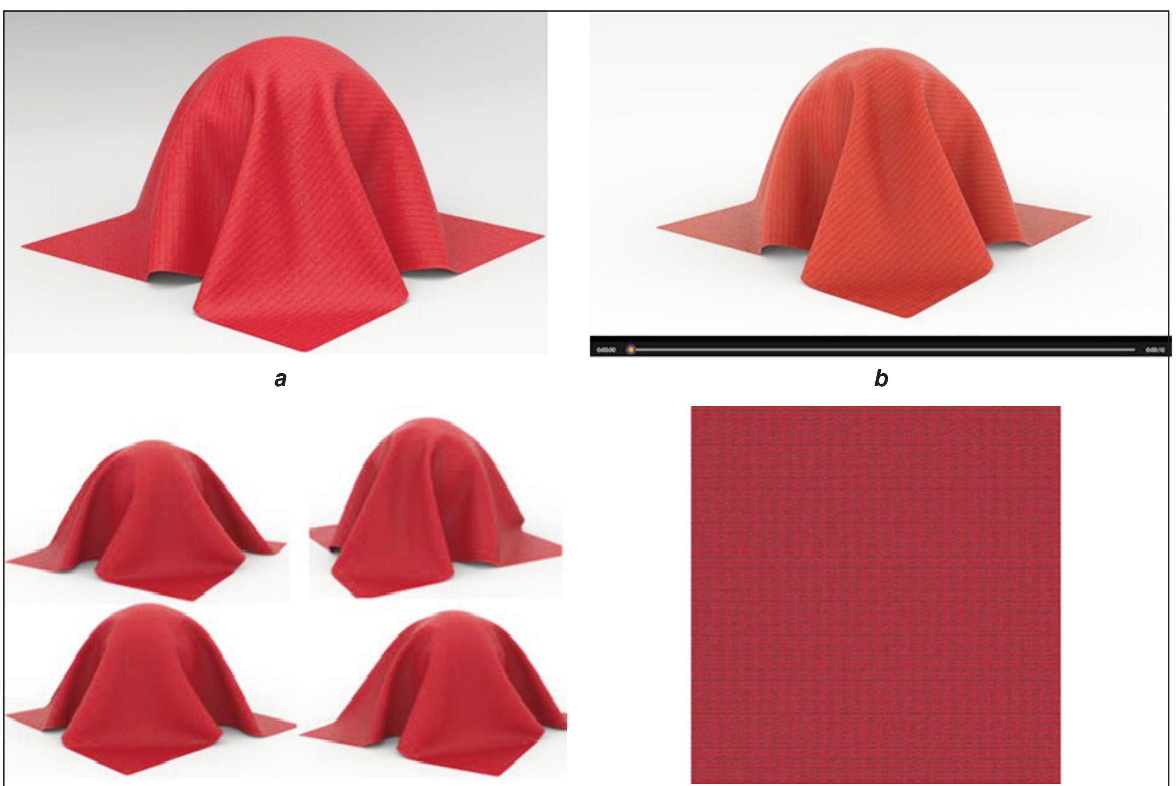

Fig. 1. Evaluation scenarios for the subjective evaluation of scanned textile materials:
a – S1 – image; *b* – S2 – video; *c* – S3 – 3D object; *d* – S4 – physical material

service evaluation, and the perception of specific products [37]. The subjects' task was to evaluate each digital representation of materials displayed on a monitor. The monitor used had a resolution of 3840 × 2160 pixels. To maintain consistency with the perception of potential buyers of textile protective materials or products made from these materials, the monitors were deliberately not calibrated. A total of twenty rendered protective textiles were assessed, employing a seven-point Likert rating scale, as detailed in table 1, where 1 indicated the lowest intensity and 7 represented the highest intensity of the attributes in question. This design was applied consistently across rendered images (S1), video (S2), 3D objects (S3), and physical materials (S4). To ensure that subjects did not experience confusion regarding the authenticity of digital materials in the first three scenarios, they were not permitted to touch or view the physical samples until scenario S4. Materials were to be evaluated solely within the digital context. After evaluating the first three digital scenarios, subjects were allowed to physically touch and examine the materials. They were then asked to respond to the same set of questions as in the previous three scenarios. A complete evaluation session for each corresponding scenario lasted approximately 4 hours and 30 minutes per person.

RESULTS AND DISCUSSIONS

The applied statistical analyses

In this research, boxplot diagrams were employed to assess the subjects' level of agreement regarding the perception of material characteristics. Additionally, the Friedman test was applied to evaluate and compare the perception across the three digital scenarios with the perception of physical materials in the fourth scenario. The final phase of the study involved establishing correlation coefficients to observe the associations between the scenarios.

Subjective evaluation of the perception of bipolar attributes regarding experts' degree of agreement

Subjective judgments involving human experts were employed to conduct sensory evaluations of the protective materials. All data obtained through the visual subjective evaluation technique were analysed using the statistical analysis software XLSTAT, a statistical tool integrated into Excel designed for sensory and visual analysis. The subjective evaluation of bipolar attributes, in relation to the degree of agreement among the experts, included the calculation of statistical indicators to measure the variation of textile material attributes. These indicators were then visually presented using boxplot diagrams. When considering the distribution of minimum and maximum values, the highest degree of agreement was observed in scenario S4 (8 out of 11 attributes), followed by S1 (8 out of 11), while the lowest degree of agreement was found in scenario S2 (6 out of 11). Regarding the symmetry of the distribution, a high level of agreement among the subjects was evident for attributes ML, UM, and NA (asymmetric to the right), as well as for attribute TO (asymmetric to the left). In the case of the remaining attributes, the distribution was approximately central. As for the height of the box, it appeared reduced for most bipolar attributes across all four scenarios, indicating that responses tended to cluster around the median. The results indicated that agreement values for the four scenarios ranged from 1.25 to 7.0, as represented in the boxplot diagrams, which illustrate the subjects' agreement with the perceptual attributes. Minimum agreement values were found in S1 for attribute NA, while the maximum agreement value was observed for attribute TO. This disparity suggests varying levels of agreement among subjects regarding the perception of attributes. Figure 2 depicts the boxplot diagram illustrating the subjects' level of agreement on the perception of the analysed materials, along with the minimum and maximum values obtained for all scenarios.

Table 1

QUESTIONNAIRE STRUCTURE REFERRING THE VISUAL AND TACTILE ATTRIBUTES

Abr.	Evaluated attributes	1	2	3	4	5	6	7
ML	Gloss	Mat						Glossy
UM	Colour	Uncoloured						Multi-coloured
RM	Roughness	Rough						Silky
TO	Transparency	Transparent						Opaque
FR	Softness	Flexible						Rigid
GU	Drape	Heavy						Easy
ER	Elasticity	Elastic						Rigid
SG	Thickness	Thin						Thick
AA	Friction	Slippery						Adherent
CR	Thermal sensation	Warm						Cold
NA	Hygroscopicity	Non-absorbent						Absorbent

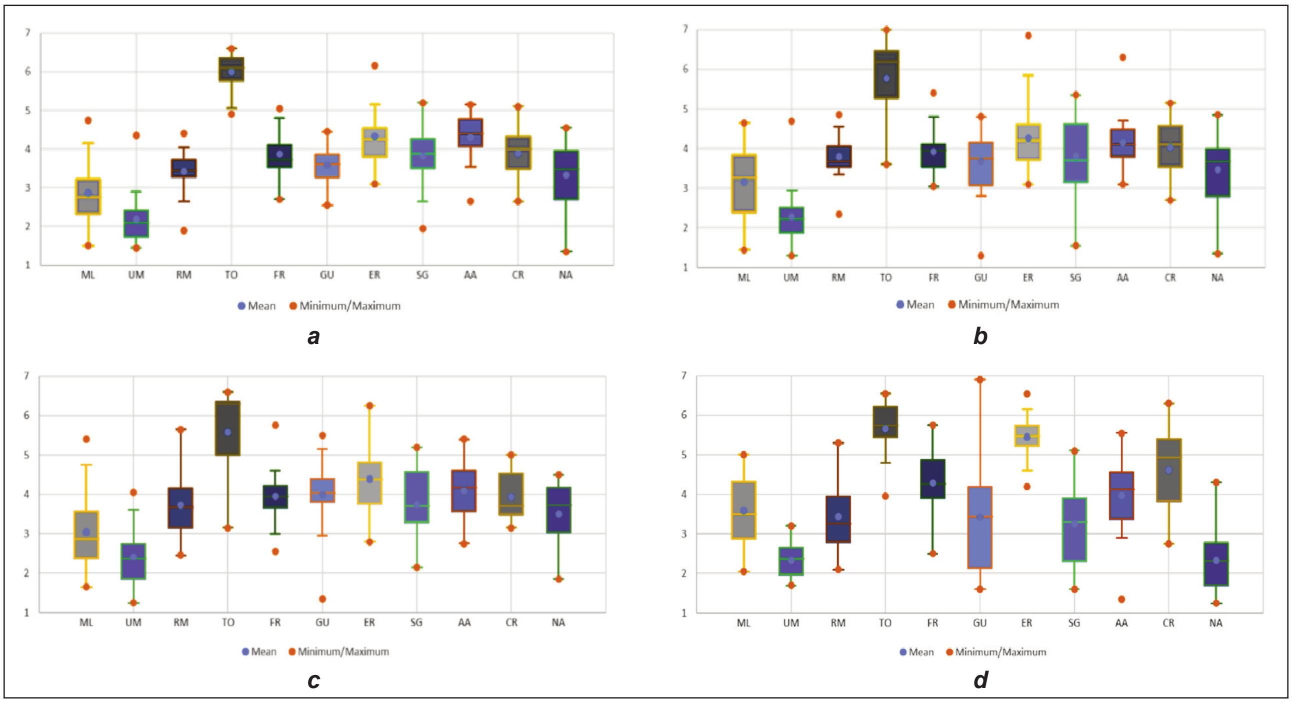

Fig. 2. Boxplot diagram on materials properties perception in scenario S1, S2, S3, S4: *a* – S1 Min = 1.35 (NA), Max = 6.6 (TO); *b* – S2 Min = 1.3 (UM,GU), Max = 7 (TO); *c* – S3 Min = 1.35 (GU), Max = 6.6 (TO); *d* – S4 Min = 1.25 (NA), Max = 6.9 (GU)

Comparative analysis between scenarios of the bipolar attributes

The subsequent phase of this study involved an analysis of scenarios, specifically a comparison between scenarios S1, S2, and S3, representing digital materials, and scenario S4, featuring physical materials. This analysis aimed to elucidate the differences in perception between digital and physical materials. The Friedman test was employed to evaluate and compare the four scenarios. All data analyses for all materials were conducted in pairs, with S4 serving as the reference scenario. The closer the difference in means is to 0, the more closely aligned the S1–S3 scenarios are with the S4 scenario. The results are presented in table 2, with significant differences from the S4 scenario highlighted in bold. The pairwise comparison of the S4–S1, S4–S2, and S4–S3 scenarios, concerning the difference in means, reveals that attributes FR with values of 0.045 (S1), RM with values of 0.063 (S1), CR with values of 0.028 (S1), CR with values of 0.039 (S2), and 0.052 (S3) closely approximate the truth. This is evident as the values obtained for these scenarios closely approach the value of 0. Conversely, the values for the remaining attributes were closer to 1, underscoring the challenge of translating these attributes into digital format and perceiving them accurately.

Table 3 presents a comparison of pairs of scenarios, namely S4–S1, S4–S2, and S4–S3, concerning the p-values. The closer the "p" values are to 1, the more closely aligned the S1–S3 scenarios are with S4. Significant differences from the S4 scenario are highlighted in bold in the results.

The challenge in translating attributes like ML, FR, ER, SG, CR, and NA may be attributed to technical scanning and rendering conditions. The disparities in ER, SG, AA, and NA attributes underscore the complexity of translating tactile attributes into a digital format. For ML and FR attributes, significant differences are observed in scenario S1 only. These differences indicate that the representation of static three-dimensional materials in scenario S1, as opposed to scenarios S2 and S3 where materials are depicted in three-dimensional motion, didn't allow for the identification of the degree of material transparency. In the case of attributes UM, RM, and GU, significant differences are evident in scenarios S1–S3 when compared to scenario S4. Additionally, for attributes UM, RM, and GU, significant differences are highlighted between scenarios S1–S2–S3 compared to scenario

Table 2

COMPARING SCENARIOS BASED ON THE MEAN DIFFERENCE

Attribute	Scenario	Mean difference		
		S1	S2	S3
ML	S4	0.917	0.583	0.833
UM	S4	0.646	0.333	0.104
RM	S4	**0.063**	–0.542	–0.188
TO	S4	–0.729	–0.458	–0.479
FR	S4	**0.045**	0.208	0.230
GU	S4	–0.250	–0.500	–0.750
ER	S4	1.583	1.958	1.458
SG	S4	–1.083	–0.938	–0.729
AA	S4	–0.563	–0.479	–0.458
CR	S4	**0.028**	**0.039**	**0.052**
NA	S4	–1.125	–1.229	–1.313

Table 3

COMPARISON BETWEEN SCENARIOS BY REFERENCE TO "P" VALUES				
Attribute		**"p" value**		
	Scenario	**S1**	**S2**	**S3**
ML	S4	0.069	0.400	0.117
UM	S4	0.309	**0.808**	**0.992**
RM	S4	**0.998**	0.467	**0.958**
TO	S4	0.208	0.609	0.573
FR	S4	0.045	0.208	0.230
GU	S4	**0.908**	0.537	0.186
ER	S4	0.000	<0.0001	0.001
SG	S4	0.021	0.060	0.208
AA	S4	0.433	0.573	0.609
CR	S4	0.028	0.039	0.052
NA	S4	0.015	0.006	0.003

S4. Concerning the UM attribute, the results are similar for scenarios S2 and S3, with a value close to 1, indicating a similar perception of material colour in both digital representation scenarios. Regarding the GU attribute, the values are similar and close to 1 in scenario S1, with lower values in scenarios S2 and S3. This reflects the challenge of conveying the draping of materials through a static image. Finally, for the RM attribute, the values are similar and close to 1 in scenarios S1 and S3, but significant differences are observed in scenario S2, indicating that roughness was harder to perceive in scenario S2.

Calculating correlation coefficients to observe the associations between scenarios

Correlation coefficients were calculated to observe the associations between scenarios S1, S2, and S3 in relation to scenario S4. The resulting data are presented in table 4. Upon reviewing the data in the table, it becomes apparent that there are no very high correlations for the UM attribute in scenario S1, the TO attribute in scenario S3, and the SG, AA, and CR attributes in scenario S2. Instead, medium correlations are observed for the ML attributes in scenario S1, RM and NA in scenario S3, ER in scenario S2, as well as the UM and FR attributes in scenario S2. In contrast, only low and very low correlations are found for the S3 scenario. The majority of statistically dependent bipolar attributes concerning S4 are found in the case of scenario S2.

Table 4

CORRELATION COEFFICIENTS BETWEEN SCENARIOS			
Attribute	**Scenarios**		
	S1–S4	**S2–S4**	**S3–S4**
ML	0.350	0.220	0.041
UM	**0.539**	–0.170	0.055
RM	0.147	0.138	0.320
TO	0.106	0.188	**0.562**
FR	–0.137	–0.107	0.146
GU	0.042	0.139	–0.119
ER	0.062	0.254	–0.050
SG	0.291	**0.585**	0.225
AA	0.176	0.478	0.330
CR	0.194	**0.516**	0.105
NA	–0.035	–0.030	0.207

Correlation coefficients intervals interpretation:
- 0.0 < 0.1 – very low correlation
- 0.1 < 0.3 – low correlation
- 0.3 < 0.5 – average correlation
- 0.5 < 0.7 – high correlation
- 0.7 < 1 – very high correlation.

CONCLUSIONS

Research on the perception of protective textile fabrics has been extended through the use of subjective fabric assessment. This method is considered non-traditional due to the absence of established standards for deviations in textile perception in digital images. Interpreting and predicting the exact margin of error for these deviations has proven challenging. The questionnaire on the characteristics of protective textile materials aimed to assess the following bipolar attributes: Gloss (matt-glossy), Colour (unicolour-multicolour), Roughness (rough-matt), Transparency (transparent-opaque), Softness (flexible-rigid), Drape (heavy-light), Elasticity (elastic-rigid), Thickness (thin-thick), Friction (slippery-sticky), Thermal sensation (warm-cool), and Hygroscopicity (non-absorbent-absorbent). The complexity involved in transposing textiles into a digital format is evident in the results obtained from the bipolar attribute evaluation experiment. The results display a wide distribution for all attributes represented digitally. As expected, the subjects exhibited the highest level of agreement when assessing materials' physical and tactile attributes in the S4 scenario, where they could see and touch the physical sample. The highest degree of agreement was found in the case of the S4 scenario (8 out of 11 attributes). Surprisingly, an equal number of agreements (8 out of 11 attributes) were obtained from scenario S1 (rendered image). The lowest agreement was observed in the case of the S2 scenario (6 out of 11). In the comparative analysis between scenarios for the bipolar attributes, significant differences were noted for the ML, ER, SG, and NA attributes in all three scenarios (S1-S3) compared to scenario S4. These differences underscore the difficulty of translating these attributes into a digital format. The challenge in translating the ER (elastic-rigid) attribute, a tactile attribute, may be attributed to certain technical factors influencing its digital representation. This is compounded by variations in subjects' interpretations, often influenced by diverse prior experiences related to material perception. Similar difficulties were encountered with the SG (thin-thick) and NA (non-absorbent-absorbent) attributes. The data obtained significantly deviates from the truth concerning the S4 scenario, indicating the complexity of perceiving these characteristics. Furthermore, numerous challenges in multimodal perceptions of protective materials remain to be addressed, emphasizing the need for further research in this direction.

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