Sensory analysis and Principal Component Analysis: a sustainable approach for quality control of stretch denim fabrics

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ABSTRACT – REZUMAT

Sensory analysis and Principal Component Analysis: a sustainable approach for quality control of stretch denim fabrics

This study proposes a simplified approach to optimise the portfolio of denim manufacturers by reducing the cost of unattractive or undifferentiated assortments for future consumers based on their ability to perceive and discriminate sensory comfort. A key factor in a successful textile value chain is end consumers, who can be considered naive evaluators when it comes to sensory analysis, as they tend to touch apparel fabrics to perceive the sensory comfort they feel when wearing them. In this context, 16 naive assessors were recruited to quantitatively characterise six bipolar sensory attributes as hand descriptors of an assortment of five washed stretch denim fabrics based on tactile properties. Statistical analysis of the extensive data was performed using the multivariate technique PCA. Two principal components that explained 70.46% to 76.67% of the total observed variance for the five washed denim fabrics provided an adequate summary of the sensory data reported, so relationships between sensory attributes as hand descriptors and ratings given by the 16 untrained assessors were examined. Statistical tests showed that all six bipolar attributes were important for sensory analysis and that inter-rater agreement was low. However, considering the sensory perception of the untrained evaluators (i.e., consumers), it was concluded that four of the five washed stretch denim fabrics could be an option for product portfolio diversification. Thus, from a strategic and sustainability perspective, PCA for sensory analysis may be helpful in the quality control of washed stretch denim.

Keywords: *stretch denim, sensory analysis, fabric hand, assessors, PCA, quality control, sustainability*

Analiza senzorială şi Analiza Componentelor Principale: o abordare sustenabilă pentru controlul calităţii ţesăturilor denim elastice

Acest studiu propune o abordare simplificată a unui aspect din activitatea producătorilor de țesături denim: optimizarea portofoliului și reducerea costurilor cu articole neatractive pentru viitorii consumatori, pe baza capacității acestora de a percepe și diferenția confortul senzorial al țesăturilor. Consumatorii finali, factor cheie al lanțului valoric textil de succes, pot fi considerați evaluatori naivi atunci când vine vorba de analiza senzorială deoarece au tendința de a manipula intuitiv țesăturile din produsele vestimentare, pentru a percepe confortul senzorial pe care l-ar putea simți la purtarea acestora. În acest context, 16 evaluatori fără experiență în evaluare senzorială au fost recrutați pentru a analiza un sortiment de cinci țesături denim elastice finisate și spălate, prin evaluarea cantitativă a șase atribute senzoriale bipolare – descriptori ai confortului senzorial. Analiza statistică a volumului mare de date experimentale a fost efectuată utilizând tehnica multidimensională PCA (Analiza Componentelor Principale). Contribuția fiecărui descriptor la diferențierea țesăturilor a fost sintetizată adecvat prin două componente principale care au explicat 70,46% până la 76,67% din variația totală observată pentru cele cinci țesături denim. Astfel a fost posibilă examinarea relațiilor dintre atributele senzoriale bipolare ca descriptori ai confortului senzorial și evaluările raportate de cei 16 evaluatori neexperimentați. Testele statistice au arătat că toate cele șase atribute bipolare au fost importante pentru analiza senzorială deși corelația dintre raportările evaluatorilor a fost la un nivel scăzut. Oricum, având în vedere percepția senzorială a evaluatorilor neinstruiți (consumatori obișnuiți), s-a ajuns la concluzia că doar patru din cele cinci țesături denim elastice ar putea reprezenta o opțiune pentru diversificarea portofoliului de produse. Dintr-o perspectivă strategică și sustenabilă, utilizarea PCA pentru analiza rezultatelor evaluării senzoriale poate fi de ajutor în controlul calității țesăturilor denim supuse tratamentelor de finisare-spălare în scopul diversificării gamei sortimentale.

Cuvinte-cheie: *denim elastic, analiză senzorială, confort senzorial țesătură, evaluatori, PCA, control de calitate, sustenabilitate*

INTRODUCTION

Sensory comfort is one of the most challenging and complex issues in textile quality control. It is becoming increasingly important to designers and manufacturers in the development of fabric assortments and apparel collections, primarily because it is a key factor in understanding and measuring the preferences of consumers who are willing to purchase a garment. Regardless of the source of supply or market niche, apparel consumer lifestyle surveys have shown that consumers not only follow the latest fashion trends when purchasing apparel but are also willing to pay more for comfort than any other product feature designed to meet consumer values [1–3].

The global denim market landscape has changed with the introduction of more comfortable garments made from stretch denim fabric, as this property is already considered during fabric development. Manufacturers of denim fabrics and denim clothing are therefore committed to innovating their products and adapting them to consumer needs. This strategy also includes a wide range of finishing and washing techniques used in the various stages of processing [3–7].

Due to the increasing trend of giving a special look to denim products, some studies have been conducted to investigate the effects of finishing and washing processes on the physical and mechanical properties of fabrics based on subjective evaluation [8–11]. For garments, sensory comfort is based on individual perception of textile materials and can be evaluated using sensory analysis to assess physical human interaction with fabrics, which in laboratory practice is associated with the fabric hand. This concept, used in the textile industry, refers to the sum of sensations experienced by humans when handling the fabric and perceiving its tactile properties as a sensory response. Sensory analysis is thus a science that deals with the evaluation of the physical properties of a product through the human senses [12–19]. Sensory analysis, as a subjective evaluation technique, is considered a widely used practice to assess the sensory comfort of clothing to improve the design phase for both fabrics and garments. On the other hand, when buying a garment, consumers, with or without experience with textiles, tend to hold it in their hands to get an idea of the quality of the fabric and the sensory comfort they might enjoy when wearing the garment [15, 20, 21]. In this respect, sensory analysis by default uses the human senses as a “measuring tool”, and variability in sensory responses is inherent in any group of raters participating in a sensory test, even in a homogeneous, trained panel [13, 15]. This situation can also occur with the sensory properties that are altered by the finishing and washing of denim [8, 9, 17, 18].

The planning and implementation of the sensory analysis for the perception of tactile properties must be ensured according to the standard guidelines for the field of sensory analysis, also considering the AATCC procedure for the subjective evaluation of the fabric hand. These reference documents specify the requirements and conditions under which fabrics should be evaluated for their sensory properties as descriptors of the fabric hand, including details on the selection and training of evaluators [12, 22–25].

Regarding the skills of the evaluators, the standards provide that sensory analysis can be performed by three categories: sensory assessors, selected assessors, and sensory experts. Sensory assessors may be “naive” evaluators who do not have accurate selection criteria and/or are not trained. The success of a sensory evaluation is highly dependent on the reliability of the evaluators, and this requires intensive training. However, the literature shows that sensory results reported by untrained evaluators (i.e., consumers), as opposed to those reported by evaluators with expertise, are relevant in determining actual product preferences in the marketplace [20, 21].

In evaluation trials, descriptive analysis can be used to quantitatively characterize specific sensory attributes perceived by a panel of evaluators for new product development and/or consumer testing and reported as intensity scores [15, 22–25]. In terms of constraints, it is to be expected that for certain fabrics and when looking for the effects of a variety of treatments on the fabric hand, some of the hand descriptors will be more difficult to assess and quantify by scores than others. Therefore, subjective evaluation of washed stretch denim fabrics can be very challenging for a panel of evaluators, especially naive evaluators who are considered regular wearers of denim garments. Accordingly, validation of rater performance is mandatory and involves techniques such as univariate or multivariate analysis of results reported as sensory data. As described in the literature, univariate analysis of rater performance focuses on individual attributes, while multivariate analysis focuses on the consistency of ratings within panellists and the entire set of sensory results [8, 10, 11, 17, 21]. Since it is a multivariate method to study the interaction between all sensory attributes and to highlight the similarities or differences between products, Principal Component Analysis (PCA) is recommended for descriptive analysis as one of the test methods for comparing competing products in terms of sensory differences and acceptability [23, 26, 27].

Sensory analysis of stretch denim fabrics, which now account for a significant share of the global denim market, has been studied to a limited extent. Despite the many studies on the tactile properties of fabrics, the multivariate technique based on PCA has not yet been applied to investigate the discriminative ability of a panel of naive assessors in evaluating the sensory properties of a range of washed stretch denim fabrics.

This study was conducted to establish a protocol for sensory analysis and the use of PCA as a statistical technique to support quality control of washed stretch denim fabrics and product portfolio diversification in denim companies from a strategic and sustainable perspective.

EXPERIMENTAL

Materials and methods

For this study, five stretch denim fabrics subjected to different washing treatments were blindly evaluated for their tactile sensory properties.

The 3/1 twill samples were woven on a PICANOL OMNI PLUS 800 air-jet loom using carded cotton yarns as warp threads and core-spun yarns as weft threads (with elastane as the core and combed cotton as the sheath). In the loom condition, 4 finishing treatments were conducted followed by 5 washing procedures (which are common in the denim industry) to produce an assortment of five washed stretch denims (D1 ÷ D5) [19]. The specifications of the fabric samples are listed in table 1 and the appearance of the five washed denims subjected to sensory analysis is shown in figure 1.

For this study, a group of 16 women aged 20–22 years were recruited as “naive”/untrained evaluators and participated in the subjective assessment panel. The “naive” evaluators, who had not previously participated in sensory training or sensory trials, received minimal instruction in blind manipulation of samples to quantify their perceptions by rating six bipolar attributes: stretchy/non-stretchy (St/N); soft/hard (So/H); flexible/stiff (F/S); thin/thick (T/Tk); slippery/rough (Sl/R); light/heavy (L/He).

As a principle of the scoring technique, numerical values were assigned to the two extremes of the bipolar attributes on the rating scale, quantifying the intensity of each attribute from 1 to 10 (e.g., for *soft/hard*, coded So/H: 1 for softest, 5 for medium, 10 for hardest).

Sensory analysis experiments were performed as described in previous work [19] and accordance with AATCC Procedure and current regulations [12, 22–24].

Statistical analysis of sensory data for a new quality control procedure

Following the sensory analysis experiments, the multivariate PCA technique was used to investigate the interaction between the sensory attributes indicated by the intensity ratings and to highlight similarities or differences between the five washed stretch denim fabrics as perceived by the 16 naive raters. The goal was to establish a protocol for sensory analysis and to use PCA as a statistical technique to support quality control of washed stretch denim fabrics and diversification of the product portfolio.

Given a large amount of information, this article will only address the general aspects of using PCA to analyse sensory data reported by naive assessors.

The following conventions were followed in applying the PCA algorithm:

– The intensity scores reported by the raters were observations belonging to the 16 individuals coded as E01 to E16.

– The six bipolar sensory attributes analysed as descriptors of the fabric hand were variables and were coded as St/N, So/H, F/S, T/Tk, Sl /R, L/He.

As shown in table 2, the comprehensive data processing with the PCA statistical tool consists of nine steps, each of which entails an important result [26, 27].

Table 1

STRUCTURAL PROPERTIES OF 3/1 TWILL GREIGE DENIM FABRIC

Material (%)		Yarn count (tex)		The density of yarn systems (per cm)		Mass per unit area (g/m^2)
Warp	Weft	Warp	Weft	Ends	Picks	
Cotton	98/2 Cotton/Elastane	57	63	27	20	317±16

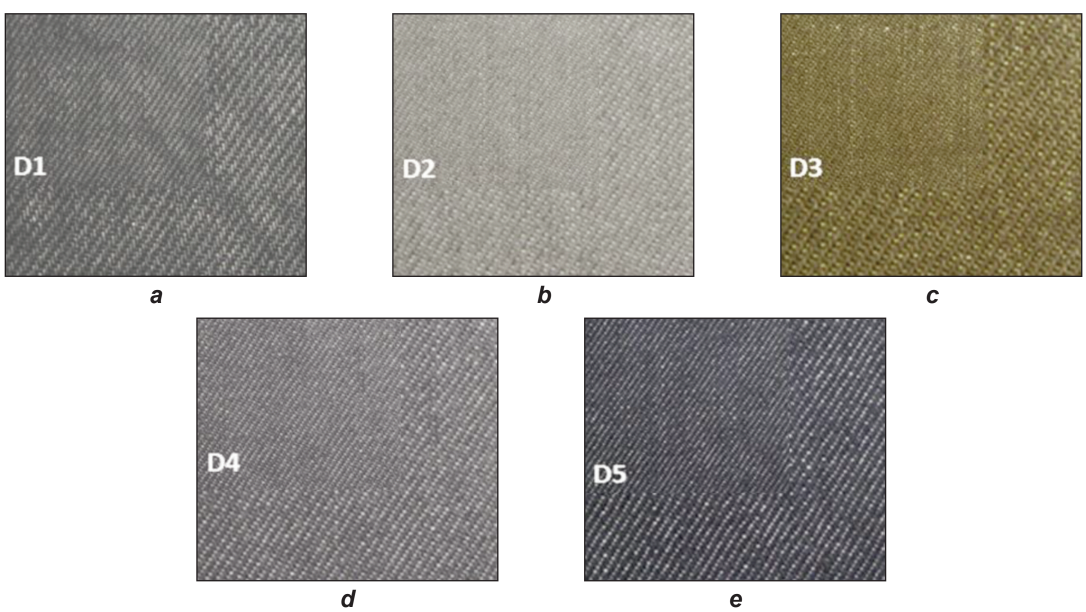


Fig. 1. Expected effects on the surface of stretch denim fabric after finishing and washing:
a – shiny for a leather look (D1); *b* – matte (D2); *c* – soft and shaded (D3); *d* – fuller and faded for a worn look (D4);
e – wrinkle-free and semi-glossy (D5)

Table 2

PCA INFORMATION FLOW FOR SENSORY DATA OF WASHED STRETCH DENIM				
Purpose	**Step**	**Item**	**Practical meaning**	**Relevant information**
Study of correlations between variables/ sensory attributes	1	*Eigenvalues*	Reflects the quality of the projection from the six-dimensional tables (for six variables) to a lower dimension by counting the total variability of the sensory data and making a quantitative assessment of how significantly a component represents the data	Assuming that there are six components/factors for six variables, eigenvalues above 1 have a larger share of the variance than any single variable, and principal components should account for more than 70% of the variance
	2	*Loading matrixes with components / factors loadings*	Understand the importance of principal components and sensory data for each variable and visualize correlations between variables and components	Note the values corresponding to the principal component for each variable with a factor loading greater than 0.4
	3	*Squared cosines of the variables*	To interpret both correctly, the representation of the variables on the coordinate axes and the correlations between the variables	The values above 0.4 confirm that the variables are well enough connected to the principal components' axis
	4	*Communalities of variables*	Highlights the ratio of the variance of each variable to the total variation	Values above 70% are considered significant
Study of correlations between observa-tions/ individuals	5	*Squared cosines of the observations*	Highlights the quality of a representation of individuals in a point cloud in the new PCA space	For each observation, values greater than 0.4 match the factor for which the squared cosine is largest
	6	*Communalities of observations*	Underlines the quality of the representation of the individuals on the coordinate axes of the principal components and the correlations between individuals and factors	The higher indicators calculated for individuals (above 70%) allow the interpretation of the visual aspect of the correlation patterns between raters
Study of correlations between variables and observations	7	*Circles of correlation of variables*	Visualizes the correlations between variables / sensory attributes and factors for each sample, using eigenvectors related to the preferred directions of the sensory data as eigenvalues that quantify the relative importance of the directions	Assuming that the principal component/factor is the direction along which the sensory data have the greatest variance, the larger the eigenvector, the greater the significance of the variable
	8	*Scatter plots of observations*	Indicates the quality of the representation of the observations/ individuals in the PCA space shaped by factors	Allows identifying the trends of the raters in the performed sensory analysis
	9	*Biplots*	Very comprehensive charts with simultaneous representations of variables and observations in PCA space, providing visual access to results	Visualizes the sensory data reported for each bipolar attribute as a complete set of variables (by eigenvectors), with the raters as individuals (by data points)

RESULTS AND DISCUSSIONS

As described in table 2, all processing steps were completed for PCA to examine correlations between variables (sensory attributes), between observations (individuals), and correlations between sensory attributes and individuals using specific plots.

In this paper, the PCA of XLSTAT® Statistical Software for Windows [27] was used and the work started with the overall presentation of the sensory data in tables for each stretch denim fabric (D1 to D5). These tables contain the intensity scores assigned by the 16 raters (E01 to E16) for each of the six bipolar attributes: stretchy/non-stretchy (St/N); soft/hard (So/H); flexible/stiff (F/S); thin/thick (T/Tk); slippery/rough (Sl/R); light/heavy (L/He).

To determine the variances and correlations in the sensory data, the Pearson correlation matrices were calculated, corresponding to the correlation coefficients for all variables. For each of the five fabrics, the relationship between every two corresponding variables was indicated and allowed estimation of the degree of redundancy between the variables. Positive and negative coefficients were identified in the matrices obtained, with no extreme values and no values that would reflect the absence of correlation. Accordingly, there was no reduction, and the number of principal components was six. Thus, in the sensory analysis of the five fabrics, all six variables proved to be important hand descriptors to highlight the sensory comfort of washed stretch denim. This situation confirmed that the list of descriptors selected for the sensory analysis experiments was appropriate for this case study.

For the entire set of sensory data, the eigenvalues and the corresponding six principal components were determined and ordered from the highest to the lowest value, as shown in figure 2 with the scree plots of the eigenvalues with the cumulative percentage of the total variance of the sensory data.

Thus, of the six potential components/factors corresponding to the six variables F1 – F6, two principal components/factors, F1 and F2, were selected to explain most of the variance in the sensory data (table 3). The first and second principal components, F1 and F2, provided a reasonable summary of the sensory data reported by the 16 naive raters and explained more than 70% of the total observed variance for each of the five samples: D1 (74.55%), D2 (76.67%), D3 (70.46%), D4 (76.63%), and D5 (75.75%).

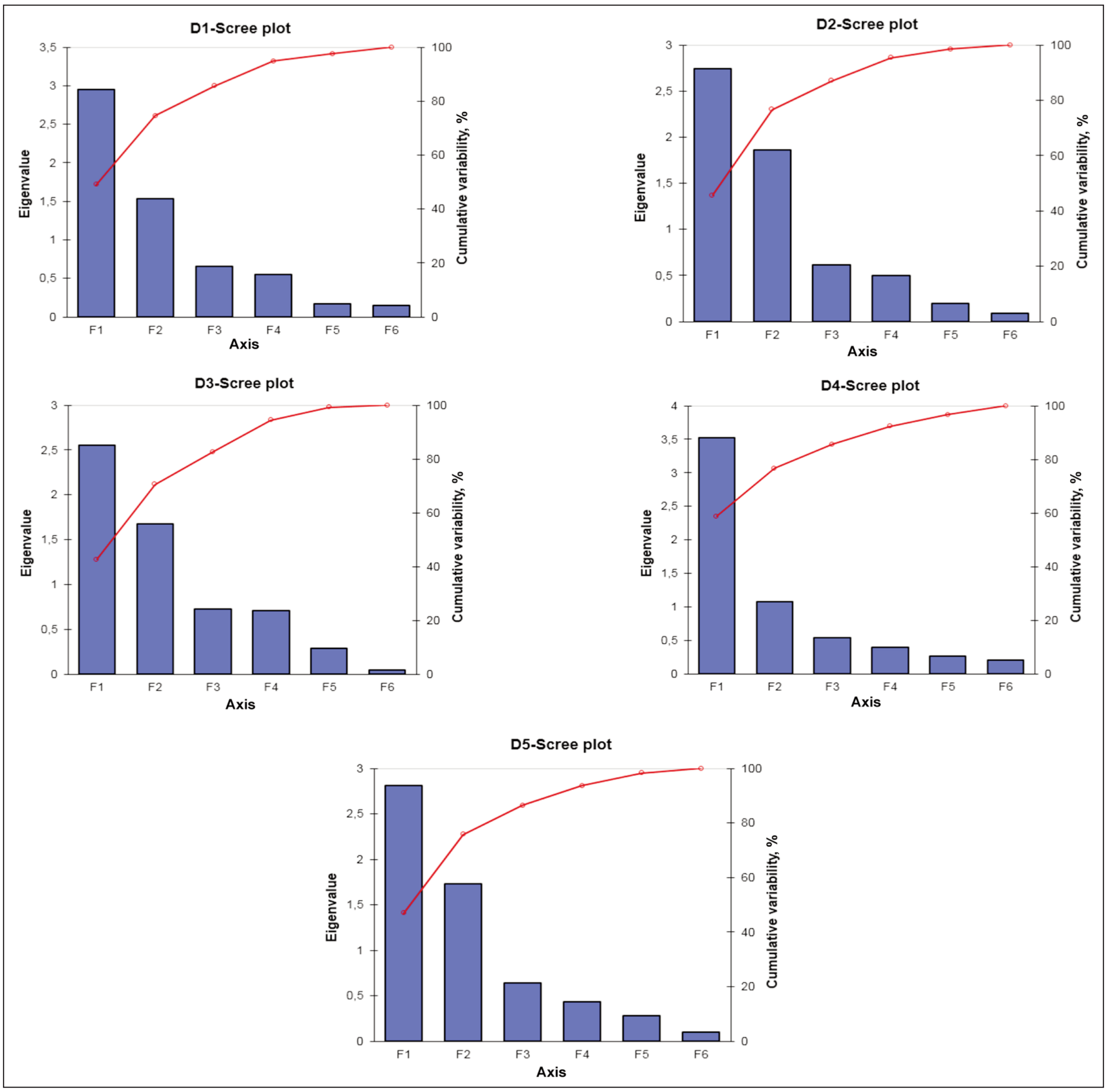


Fig. 2. PCA plots of eigenvalues to determine the number of components to keep

Table 3

PCA FOR SENSORY ANALYSIS: THE PRINCIPAL COMPONENTS REPRESENTING THE OVERALL VARIABILITY										
Principal components	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**
Washed stretch denim fabric	**D1**		**D2**		**D3**		**D4**		**D5**	
Eigenvalue	2.95	1.53	2.74	1.86	2.56	1.67	3.52	1.08	2.81	1.73
Variability (%)	49.09	25.47	45.64	31.03	42.59	27.88	58.67	17.95	46.88	28.87
Cumulative %	49.09	**74.55**	45.64	**76.67**	42.59	**70.46**	58.67	**76.63**	46.88	**75.75**

Table 4

PCA: CORRELATION BETWEEN VARIABLES AND FACTORS IN THE LOADING MATRIX											
Principal components		**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**
Washed stretch denim		**D1**		**D2**		**D3**		**D4**		**D5**	
Variables	St/N	**0.871**	–0.055	**0.676**	–0.387	**0.702**	0.378	**0.880**	0.043	0.486	**0.743**
	So/H	**0.915**	–0.192	**0.901**	–0.170	**0.680**	**0.655**	**0.824**	–0.166	0.296	**0.885**
	F/S	**0.864**	–0.093	**0.909**	–0.060	**0.642**	**0.433**	**0.713**	–0.412	**0.868**	–0.022
	T/Tk	**0.745**	0.168	**0.648**	**0.480**	**0.474**	–0.552	**0.886**	0.080	**0.697**	–0.532
	Sl/R	0.220	**0.838**	–0.189	**0.925**	**0.601**	–0.646	0.251	**0.928**	**0.703**	–0.338
	L/He	–0.006	**0.865**	**0.433**	**0.770**	**0.776**	–0.437	**0.844**	0.105	**0.870**	0.005

* The values in bold correspond for each variable to the principal component for which the factor loading is greater than 0.4 (highly positively correlations) [26, 27].

Table 5

PCA: SQUARED COSINES OF THE VARIABLES											
Principal components		**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**
Washed stretch denim		**D1**		**D2**		**D3**		**D4**		**D5**	
Variables	St/N	**0.759**	0.003	**0.457**	0.150	**0.492**	0.143	**0.774**	0.002	0.236	**0.552**
	So/H	**0.837**	0.037	**0.812**	0.029	**0.463**	**0.429**	**0.679**	0.028	0.087	**0.783**
	F/S	**0.747**	0.009	**0.826**	0.004	**0.412**	0.188	**0.508**	0.169	**0.753**	0.000
	T/Tk	**0.554**	0.028	**0.420**	0.231	0.225	0.305	**0.785**	0.006	**0.485**	0.283
	Sl/R	0.048	**0.702**	0.036	**0.856**	0.361	**0.417**	0.063	**0.861**	**0.494**	0.114
	L/He	0.000	**0.749**	0.188	**0.593**	**0.603**	0.191	**0.712**	0.011	**0.757**	0.000

* The values in bold correspond for each variable to the principal component for which the squared cosine of variables is greater than 0.4 [26, 27].

PCA to study the correlations between variables

To interpret the significance of the principal components and the sensory results about each variable and to visualize the correlations between the variables and the principal components, the loading matrices with the components (i.e., the factor loadings) were calculated. Given the significant values of the factor loadings obtained for the five stretch denim items, presenting the variables in plots with two principal components is an appropriate choice (table 4). For a proper interpretation of both the representation of the variables on the coordinate axes and the correlations between the variables, the squared cosines of the variables were calculated, as shown in table 5. As for the values calculated for the five stretch denim fabrics, most of the variables listed in the loading matrix analysis appeared to be strongly associated with the F1 and F2 axes, with a few exceptions.

The above structures led to other different structures of correlations between the variables shared by the communalities of the variables, as shown in table 6.

Table 6

PCA: COMMUNALITIES OF THE VARIABLES						
Washed stretch denim		**D1**	**D2**	**D3**	**D4**	**D5**
Variables	St/N	**0.762**	0.607	0.635	**0.776**	**0.788**
	So/H	**0.873**	**0.841**	**0.892**	**0.706**	**0.870**
	F/S	**0.756**	**0.830**	0.599	0.678	**0.754**
	T/Tk	0.583	0.650	0.529	**0.791**	**0.768**
	Sl/R	**0.751**	**0.892**	**0.778**	**0.923**	0.608
	L/He	**0.749**	**0.781**	**0.794**	**0.723**	**0.757**

* The values in bold correspond for each variable to the principal component for which the communality of variables is greater than 70% [26, 27].

Table 7

PCA: SQUARED COSINES OF THE OBSERVATIONS											
Principal components		**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**	**F1**	**F2**
Washed stretch denim		**D1**		**D2**		**D3**		**D4**		**D5**	
Naive assessors	E01	**0.707**	0.152	**0.706**	0.198	**0.413**	**0.464**	0.281	**0.428**	0.076	**0.570**
	E02	**0.363**	0.015	**0.458**	**0.493**	0.391	0.190	**0.796**	0.169	**0.910**	0.059
	E03	**0.731**	0.046	0.013	0.298	**0.468**	0.008	0.312	0.332	0.044	0.086
	E04	0.008	**0.617**	**0.521**	0.400	0.000	**0.942**	**0.731**	0.017	**0.783**	0.118
	E05	**0.736**	0.085	**0.742**	0.034	**0.737**	0.000	**0.841**	0.003	0.114	0.123
	E06	0.042	**0.734**	0.001	0.001	0.000	0.000	**0.442**	0.020	0.349	**0.593**
	E07	**0.875**	0.005	**0.912**	0.005	**0.912**	0.001	**0.928**	0.023	0.163	0.004
	E08	**0.763**	0.105	0.100	**0.806**	0.099	0.013	0.170	**0.461**	0.024	**0.453**
	E09	0.059	**0.666**	0.188	0.022	0.013	0.023	**0.691**	0.282	**0.902**	0.046
	E10	**0.869**	0.029	0.062	0.124	**0.413**	0.033	**0.460**	0.062	**0.494**	0.388
	E11	0.004	**0.872**	0.010	**0.669**	**0.804**	0.045	0.056	0.307	**0.843**	0.043
	E12	**0.515**	0.078	0.008	0.106	0.343	0.122	0.073	0.048	**0.817**	0.091
	E13	**0.493**	0.205	0.184	**0.613**	**0.485**	0.320	0.052	**0.613**	0.016	**0.880**
	E14	0.229	0.360	0.138	**0.682**	**0.713**	0.037	0.204	**0.651**	**0.436**	0.000
	E15	0.271	0.225	0.010	0.375	0.186	0.008	0.165	0.047	0.198	0.001
	E16	**0.532**	0.140	**0.739**	0.049	0.353	0.156	**0.713**	0.003	0.003	0.063

* The values in bold correspond for each observation to the principal component for which the squared cosine of observations is greater than 0.4 [26, 27].

When considering the total sensory data obtained for the five stretch denim fabrics, the interesting information was that some of the values calculated for the communality variables were below the restricted threshold of 70%, in the range of 60–70%, and cannot be interpreted as meaningful correlation patterns between the group of six variables. Consequently, the values and the representation of the squared cosines of the variables in the PCA field with F1 and F2 retrospectively required a new explanation for an important part of the variables evaluated during the sensory analysis of the five stretch denim fabrics.

PCA to study the correlations between observations

To highlight the quality of a different representation of the individuals (i.e., intensity values) from each naive rater in a scatter plot in the new PCA space, the squared cosines of the observations were calculated (table 7), representing the square of the cosine of the angle between an individual and a component.

As with the variables, the quality of the representation of the individuals on the coordinate axes F1 and F2 and the correlations between individuals and components had to be analysed based on the communalities of the observations. The correlation patterns allow interpretation for only some of the raters' observations, as in a situation with higher communality indicators for individuals (table 8).

As shown in table 8, for the higher communality indicators calculated for individuals, it is possible to interpret the visual aspect of the correlation pattern between the group of sixteen raters. The correlations between individuals and components and the common variation of the components with the given observations allow us to highlight the quality of the sensory results and consequently the quality of the evaluation panel.

Table 8

PCA: COMMUNALITIES OF THE OBSERVATIONS						
Washed stretch denim		**D1**	**D2**	**D3**	**D4**	**D5**
Naive assessors	E01	**0.859**	**0.904**	**0.877**	**0.709**	0.645
	E02	0.378	**0.951**	0.581	**0.965**	**0.968**
	E03	**0.778**	0.311	0.477	0.644	0.129
	E04	0.625	**0.921**	**0.942**	**0.747**	**0.901**
	E05	**0.821**	**0.776**	**0.737**	**0.843**	0.237
	E06	**0.776**	0.003	0.000	0.463	**0.941**
	E07	**0.880**	**0.917**	**0.913**	**0.952**	0.167
	E08	**0.868**	**0.906**	0.112	0.630	0.477
	E09	**0.725**	0.210	0.036	**0.973**	**0.948**
	E10	**0.897**	0.185	0.446	0.522	**0.882**
	E11	**0.876**	0.680	**0.848**	0.363	**0.886**
	E12	0.594	0.114	0.465	0.121	**0.907**
	E13	0.697	**0.797**	**0.806**	0.664	**0.897**
	E14	0.589	**0.820**	**0.750**	**0.856**	0.437
	E15	0.496	0.385	0.194	0.212	0.199
	E16	0.672	**0.788**	0.509	**0.716**	0.066

* The values in bold fit for each observation to the principal component for which the communality of the observations is greater than 70% [26, 27].

PCA biplots to study the correlations between variables and observations

To determine the links between the hand attributes and the ratings, the information from the separate correlation circles between the variables and the components and the scatter plot of the observations can be combined into corresponding PCA biplots. Table 9 summarizes the final PCA results using biplots generated for the sensory data of the 16 naive raters for the five washed stretch denim fabrics: the loading of each variable was plotted on the first component F1 in the horizontal dimension and on the second component F2 in the vertical dimension.

For the following discussions, it should be noted that the discriminatory attributes to be considered in this study were not always six. Considering the information in table 2, some calculated values of the communalities were smaller than the restricted limit and the interpretation of the squared cosines of these variables was limited. As with the variables, the observations reported by some assessors had lower values for the communality of the observations, which limited the interpretation of the squared cosine values calculated for these scattered individuals.

In addition to PCA, Kendall's concordance coefficient (W) was calculated to assess the extent to which the 16 naive assessors ranked the five stretch denim fabrics separately for each bipolar sensory attribute as a hand descriptor for fabrics. According to the results of the Chi-Squared significance test comparing the calculated values with the critical value, the concordance coefficients were found to be statistically significant at the 95% confidence level only for the bipolar attributes flexible/stiff ($W_{F/S}$ = 0.210) and slippery/rough ($W_{Sl/R}$ = 0.207). However, there is insufficient evidence to support the hypothesis that there is significant agreement between the sixteen raters on the two bipolar sensory attributes. This detail is somewhat consistent with the information previously obtained in the interpretation of the PCA results (table 9).

Considering the expected effects on the surface of stretch denim fabrics after washing (figure 1) and the PCA results (interpreted in table 9) for the sensory

Table 9

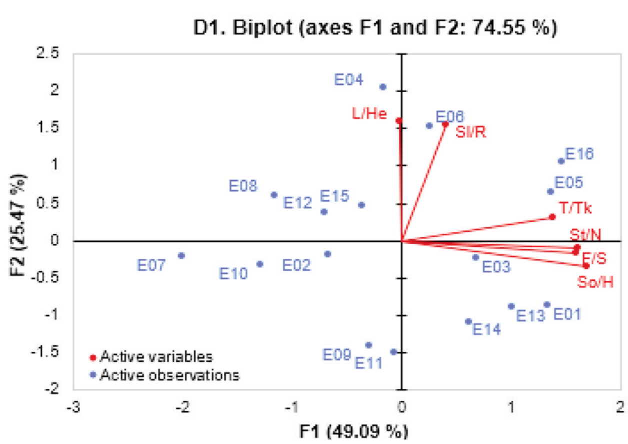
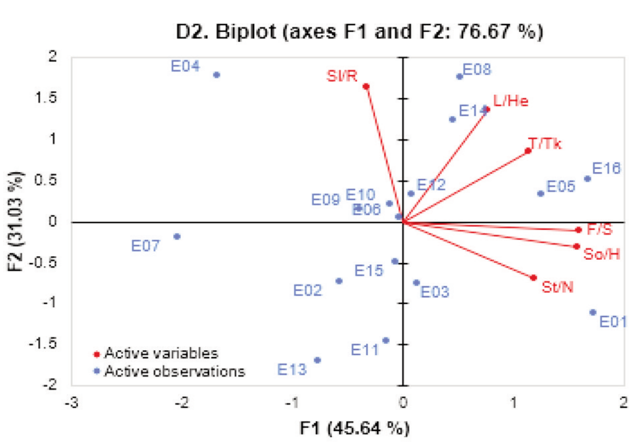
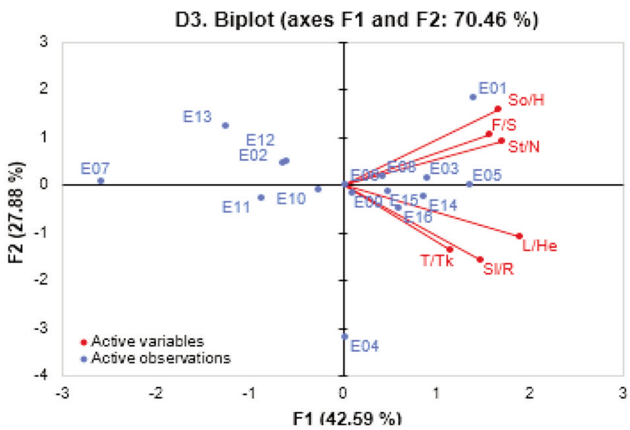
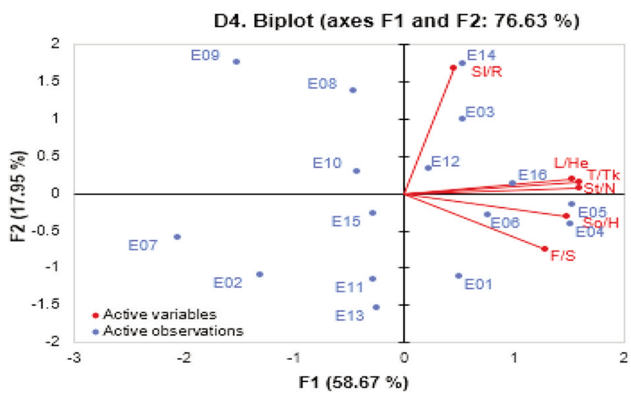
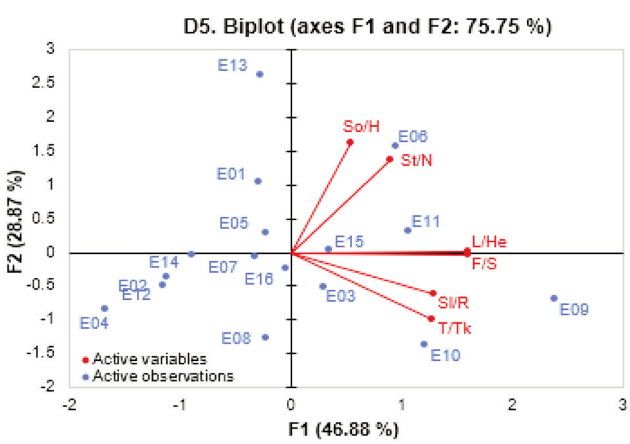
PCA BIPLOTS FOR A COMPREHENSIVE OVERVIEW OF SENSORY DATA CORRELATIONS REPORTED BY NAIVE RATERS FOR THE WASHED STRETCH DENIM RANGE	
PCA biplot of each washed stretch denim sample	**Discussions for the five fabrics (D1-D5)**
	The biplot for the washed stretch denim D1 represents 74.55% of the total variance of the sensory data and shows the following correlation patterns: the attributes stretchy/non-stretchy, soft/hard, and flexible/stiff, which seem to be strongly associated with the axis of the first component F1; for the attributes slippery/rough, light/heavy, which seem to be strongly associated with the axis of the second component F2. The variables St/N, So/H and F/S are strongly positively correlated with the observations of evaluators E01, E03 and E05, while the variables Sl/R and L/He are strongly positively correlated with the observations of evaluators E04 and E06. In the study of the influence of washing treatments on the sensory comfort of D1 stretch denim, the naive assessors rated only 5 of 6 attributes, and there were only 5 of 16 raters whose tactile perceptions were strongly correlated with bipolar sensory attributes.
	The biplot for the washed stretch denim D2 represents 76.67% of the total variance of the sensory data and shows visual correlation patterns: for the soft/hard and flexible/stiff attributes, which seem to be strongly associated with the axis of the first component F1; for the slippery/ rough and light/heavy attributes, which seem to be strongly associated with the axis of the second component F2. At the same time, the variables So/H and F/S are strongly positively correlated with the observations of assessors E01, E05 and E16, while the variables Sl/R and L/He are strongly positively correlated with the observations of assessors E08 and E14. The discriminative attributes to be considered regarding the influence of washing treatments on the sensory comfort of D2 stretch denim were only 4 out of 6, and there were only 5 out of 16 assessors whose tactile perceptions correlated strongly with bipolar sensory attributes.

Table 9 (*continuation*)

PCA biplot of each washed stretch denim sample	Discussions for the five fabrics (D1-D5)
	The biplot for the washed stretch denim D3 represents only 70.46% of the total variance of the sensory data, and a visual correlation pattern emerges for the light/heavy and slippery/ rough attributes, which appear to be strongly associated with the axis of the first component F1. At the same time, the variables L/He and Sl/R are strongly positively correlated with the observations of assessor E14. The visual correlation pattern relates to only 2 of 6 variables, and at the same time, it was only one assessor out of 16 whose tactile perceptions when handling sample D3 were strongly correlated with bipolar sensory attributes.
	The biplot for the washed stretch denim D4 represents 76.63% of the total variance of the sensory data and shows visual correlation patterns: for the attributes stretchy/non-stretchy, soft/hard, light/heavy, and thin/thick, which seem to be strongly associated with the axis of the first component F1; for the attribute slippery/rough, which seems to be strongly associated with the axis of the second component F2. The variables St/N, So/H, L/He and T/Tk are strongly positively correlated with the observations of evaluators E04, E05 and E16, while the variable Sl/R is strongly positively correlated with the observations of assessor E14. Among the discriminative attributes to be considered about the influence of washing on sensory comfort in the D4 sample, there were 5 out of six and only 4 out of 16 raters whose tactile perceptions were strongly correlated with bipolar sensory attributes.
	The biplot for the washed stretch denim D5 represents 75.75% of the total variance of the sensory data and shows visual correlation patterns: for the attributes flexible/stiff, light/heavy, and thin/thick which seem to be strongly associated with the axis of the first component F1; for the attributes stretchy/non-stretchy and soft/hard, which seem to be strongly associated with the axis of the second component F2. The variables F/S, L/He and T/Tk are strongly positively correlated with the observations of evaluators E09 and E11, while the variables St/N and So/H are strongly positively correlated with the observations of evaluator E06. In the study of the effect of washing on sensory comfort of D5 stretch denim, naive evaluators rated 5 of 6 attributes, and there were only 3 of 16 assessors whose tactile perceptions correlated strongly with bipolar sensory attributes.

data perceived by the 16 untrained assessors (i.e., consumers) about the six bipolar attributes of the fabric hand, we can conclude the following: denim D3 can be excluded from the portfolio because its relevance to a potential customer, who will certainly handle the fabrics to perceive the sensory comfort he/she might feel when wearing a garment made of denim, is questionable compared to other four fabrics subjected to sensory analysis. To diversify the appearance of stretch denim fabrics through washing processes, only four stretch denims (D1, D2, D4 and D5) can remain reliable options for the manufacturer's portfolio.

Although the evaluation showed lower agreement among naive panellists, as inexperienced evaluators, this study can be the starting point for providing a readily available method to help denim manufacturers select the optimal wash treatment, which is undoubtedly important for future market success.

CONCLUSIONS

This study proposes a simplified approach to optimise the portfolio of denim manufacturers by reducing the cost of unattractive or undifferentiated assortments for future consumers based on their ability to perceive and discriminate sensory comfort.

Therefore, a quantitative descriptive sensory evaluation method was used to investigate six sensory properties of washed denim and interpret the comfort perceptions of untrained evaluators (i.e., consumers).

The use of descriptive analysis as one of the test methods for comparing competing products in terms of sensory differences and acceptability involved the multivariate statistical technique Principal Component Analysis (PCA) for sensory data processing. When using the PCA technique to examine sensory data reported by a group of 16 naive assessors in blind ratings of washed stretch denim fabrics, good agreement was found for only a few raters and only for certain bipolar attributes as fabric hand descriptors. Overall, the results showed that the raters were sufficiently able to distinguish between the sensory properties of different denim fabrics, as the different washing processes had an impact on the perceived ratings.

Considering the observations of atypical individuals, who could be consumers without background knowledge of textiles, a procedure should be initiated by denim manufacturers to establish a sensory analysis program for the quality control strategy even closer to reality: to ensure that the expected effects of washing processes on stretch denim fabrics are perceived by potential customers, otherwise, a restriction of the offer is recommended. Of course, the PCA approach to sensory analysis can also be used to improve the quality control strategy with a panel of experts or selected assessors. It should be noticed that the relevance of sensory analysis in the quality control strategy to be applied alongside existing practices has been ensured by the publication of the first edition of the international standard ISO 20613:2019.

Washing processes add value to stretch denim fabrics and are important for designers and manufacturers looking to diversify their fabric offering and improve sensory comfort, as these are key factors in the market success of any garment. On the other hand, the issue of sustainability is becoming more acute in the textile industry today and requires a new approach to new product development and quality control. A strategy aimed at reducing the fabric assortment and producing only what is perceived as specific sensory comfort by a larger mass of consumers can also help reduce the carbon footprint. The carbon footprint of textiles is critical to the management of environmental pollution, making sustainability an important issue of our time. In this context, reducing the environmental impact of washing stretch denim fabrics is an important step for 3 R.

Ultimately, in addition to improving quality control, the interest of denim manufacturers in developing a product portfolio should not focus on an oversized fabric range, but on choosing optimal washing treatments in line with a sustainable policy: less waste of resources is more valuable for all.

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