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Development and evaluation of a methodology to integrate technical and sensorial properties in materials selection

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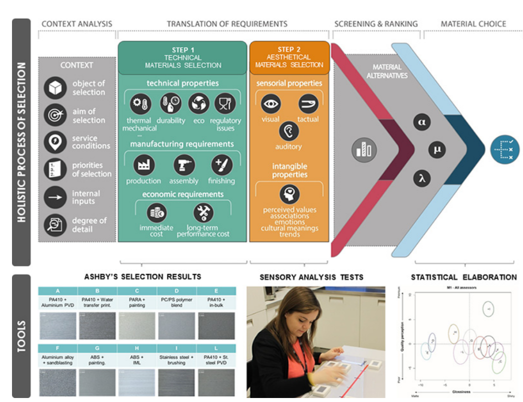
In the materials selection process, the use of different tools, languages and perspectives frequently causes dis-agreement between engineers and industrial designers.
The aim of the paper is to define an integrated method for materials selection that provides industrial designers with measurable data to support and explain aesthetic decisions on materials.
A new method for materials selection consisting of multiple tools structured in a two-step framework is pre-sented. The method is tested through a case study of professional kitchen appliances where metal components are replaced with polymers. The first step involved the application of an established technique to identify poly-meric bulk solutions, based on their technical properties. The second step employed a sensory analysis test to choose suitable finishes. Thirty-seven individuals performed the test: the subjects highlighted their main percep-tions of metal and metal-look polymer finishes.
The research demonstrates that the proposed method is suitable for the evaluation of both technical and sensorial properties of materials. In particular, Mapping test represents a rapid, low cost and effective tool to help industrial designers justify Colour Materials and Finish (CMF) choices with quantifiable information.

Keywords: Materials selection, Sensory perception, Human factors, Aesthetics, Product design, Metal replacement

HIGHLIGHTS

- A new approach to material selection that integrates technical and aesthetic decisions is proposed in a two-step framework.
- Sensory Analysis is integrated within the traditional Ashby's selection process.
- A case study on aesthetic components describes the applicability of the method in the New Product Development process.
- The reconciliation of material languages among designers and engineers helps reaching a mutual appreciation of diverse material properties.

GRAPHICAL ABSTRACT



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1. Introduction

Materials selection plays a central role in defining the design and aesthetics of products [1]. In new product development [2,3], materials selection is the result of a multidisciplinary decision-making process that typically involves several departments of a company, particularly the design and product engineering departments [4,5]. Moreover, material and finishing choices are determined by a considerable number of variables related to aesthetics and design including: the product's technical configuration, manufacturing constraints, operating conditions and environment stresses, designers' expertise and sensitivity to certain styles, colour and material trends, usability issues, and brand identity [6–14].

For this reason, materials selection is usually a complex and iterative process of design formalisation, which starts from the first phases of concept development. Fig. 1, elaborated from a typical model [15], describes the main stages of the product development process, highlighting the company departments generally involved and the decisions to be made in the steps of "Screening" and "Design", in which the activity of materials and finishes selection is predominantly performed.

As illustrated in Fig. 1, different professionals are involved in the materials evaluation process, according to their know-how. Engineers and technicians (i.e. Product Engineering) typically deliberate on technical decisions based on quantitative data, namely technical properties, and manufacturing and economic requirements [11,12]. In the last fifty years, several methods and tools have been developed to guide "engineering" materials selection [16,17]. Among them, Ashby's method [10,12,13,18–20] is widely implemented in the industry [21–24], providing a useful support (i.e. material indexes and properties charts) to compare different material properties since early stages of product design. From the perspective of evaluating material performance in technical applications, materials selection can, therefore, be considered a mature discipline [25].

On the other hand, industrial designers (i.e. Industrial Design) mainly focus on Colour, Material and Finish (CMF) selection to characterise the identity, perception and aesthetic appearance of products [26–29]. In describing aesthetic decisions about materials, finishes and textures, industrial designers generally use qualitative criteria, expressed as intangible and sensorial characteristics [30–34] by descriptors or adjectives [16,31,35–37]. Mood boards [38] and physical material collections, inspired by product and material trends, are non-verbal qualitative tools used to express a specific aesthetic and expressive effect on a product's surface. The need for integrating expressive-sensorial characteristics of materials has gained increasing attention in the last thirty years, especially in the academic field. Theoretical design-based methods [14,31,39,40] and practical tools have been developed [36–38,41–43]. Among them, the Expressive-Sensorial Atlas [43], a collection of sensorial maps that link technical properties of materials with the sensorial ones in a linear scale, can be recognised as one of the first tools focused on visual and tactile properties with a design educational perspective. From a general observation of the approaches for materials selection currently employed by industrial designers, emerges the intention of quantifying aesthetic attributes of materials correlating sensorial and physical properties [31,36,41,43,44], by involving evaluators. Moreover, they provide a large set of materials aesthetic and perceived attributes that are generally used among designers [37,39,45,46]. However, there is no evidence to indicate that such design-based methods fit with real industrial needs. In addition, these approaches are not correlated with any standard procedure, which are established in the industrial field. Standards, indeed, provide step-by-step instructions, accessible to different users, to select the appropriate experimental design and panel of assessors, and to analyse data based on appropriate statistics.

Engineering and design approaches to materials selection differ in terms of tools, languages and perspectives [16]. Different ways of interpreting and communicating material surface properties often cause discontinuity and disagreement along the materials selection process [47]. The epistemology contrasts among engineers, who tend towards propositional knowledge, and designers, who are more familiar with experiential learning (empirical knowledge), has been investigated in depth in the materials teaching context [49,50]. In the manufacturing industry, engineering rationale is generally considered more robust and reliable than the design one. This because engineering rationale is based on propositional knowledge, funded on analysis and investigation to satisfy "the truth of what is believed and the justification of what is believed" [51]. Compared with engineering, we can envision design epistemology as a method for subjective expression and materials manipulation [52]. Even if it is not possible to fully rationalise aesthetic decisions, industrial designers are increasingly called to justify their materials choices [53]: a possible way is to qualify aesthetic attributes with

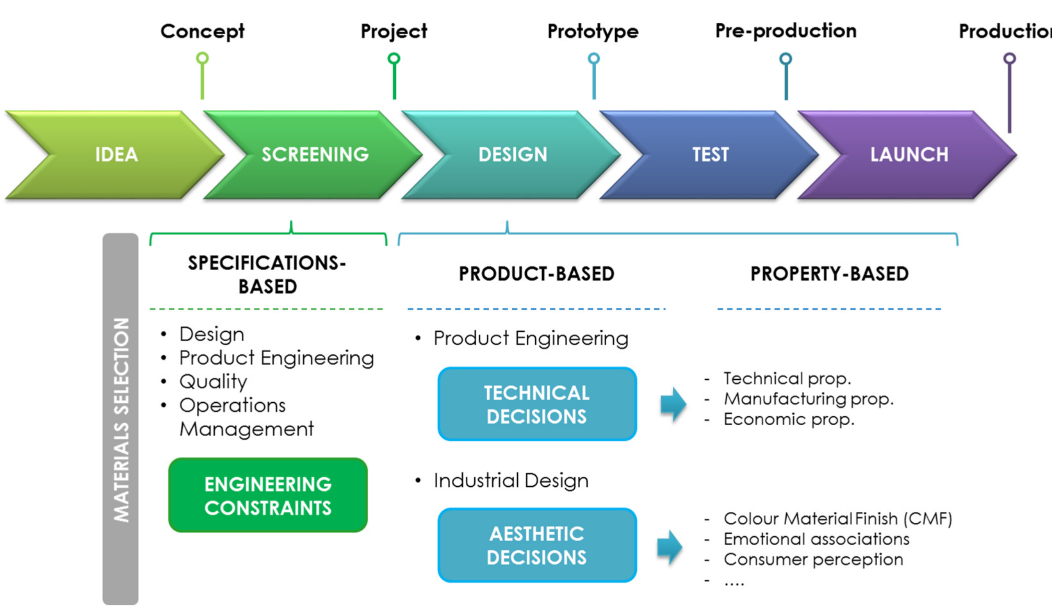

Fig. 1. Materials selection in new product development (NPD) (2-column).

quantifiable parameters [54] in order to increase the consensus among all the subjects involved in material selection.

The aim of the current study is to define an integrated method to select materials and finishes based on technical properties and sensory criteria, providing industrial designers with measurable data to support and explain the practical reasons behind their decision-making [48]. Taking advantage of a collaboration with a leading company in the production of professional kitchen appliances, a motivating example is used to describe the proposed method.

2. Motivating example: aesthetical components in professional appliances

The "aesthetic components" of professional kitchen appliances offer a compelling case to investigate the evaluation of aesthetic and technical features of materials. These components, whose primary function is manual handling, are among the most used parts of a kitchen and can be compared to the steering wheel and the gearshift of an automotive vehicle. In the design of such components, the technical (e.g., mechanical and thermal resistance, and durability to chemicals) and aesthetic properties of the proposed materials must be considered. For this reason, materials and finishes have to be selected based on both performance and aesthetic criteria [16]. As these components embody valuable aesthetic details of professional products, industrial designers have to pay special attention to the definition of their chromatic and tactile identity. In particular, they consider stainless steel finishing as the best solution to communicate robustness, elegance and premium quality [49–51]. Despite this, there are issues associated to the employment of metals in the aesthetical components of professional appliances. When dealing with complex and/or organic shapes in the professional industry, the use of traditional metal manufacturing processes (e.g., casting, forging, machining) becomes a limiting factor due to the high manufacturing costs [52]. At last, in the kitchen environment, metallic handling components tend to heat up, with evident limits in terms of usability.

With reference to these aspects, metal replacement could bring several advantages in manual handling components. High performance polymers have been proven to replace and outperform traditional metal counterparts providing good chemical resistance, and flexibility in the production process of complex shapes [53]. Because of their intrinsic thermal and electrical insulation, the use of reinforced plastics could guarantee operative and safety requirements from the early stages of design [54]. Despite these advantages, replacing metal components with polymers might affect the overall perception of food service professional equipment since in this industrial context polymeric solutions are generally perceived as "toy-like" materials [30]. Thus, it is necessary to search for polymeric alternatives characterised by adequate mechanical and durability performances, and that can be perceived as being most similar to stainless steel in terms of aesthetic properties.

3. Research approach and questions

In this paper, we focus on the development of an integrated method for the evaluation and integration of technical and sensorial properties of materials. A two-step framework for materials selection has been proposed. The Technical Materials Selection (TMS) step, following the main steps identified by Ashby (*Translation*, *Screening*, *Ranking* and *Choice*), aims at choosing a raw material taking into consideration the desired technical properties. The Aesthetical Materials Selection (AMS) step aims at examining sensorial and intangible properties and translating them into quantitative data in order to select materials and finishes. To achieve this, traditional tools were used together with new ones, which have been developed according to the constraints of the specific industrial sector analysed (Fig. 2).

3.1. Technical materials selection

The method developed by Ashby [10,11] and the CES Selector software [17] are used to provide an overview of the raw materials suitable for a specific component. The TMS consists in the application of the selection phases identified by Asbhy [55,56], due to the diffusion of this approach in engineering industrial practice. The constraints of the investigation are translated into material specifications (*Translation of requirements*). After a first investigation of the different material options, the CES Selector is used to filter records based on the constraints identified through the "limit stage" (*Screening*). The performance function (Z_{perf}), based on the alpha coefficients [10], is then used to generate a ranking of the alternatives, and bar charts and bubble charts support the selection taking into consideration the particular properties explored (*Ranking*). Finally, the optimal material solutions for the given application are chosen according to the ranking elaborated. In order to accelerate the first phases of the selection, a new tool has been developed and integrated. The "Context Analysis Datasheet" (Annex I) permits to systematize the collection of case study's specifications, and prioritizing the properties that should be taken into consideration [47]. This tool provides a structured approach for sharing quantitative and qualitative data (e.g., failures or testing results on currently employed materials, material supplier recommendations, etc.) about the component examined.

3.2. Aesthetical materials selection

This step is built on traditional [31,35,43,57,58] and non-traditional methods [59,60,64,69], which are used to investigate sensorial and

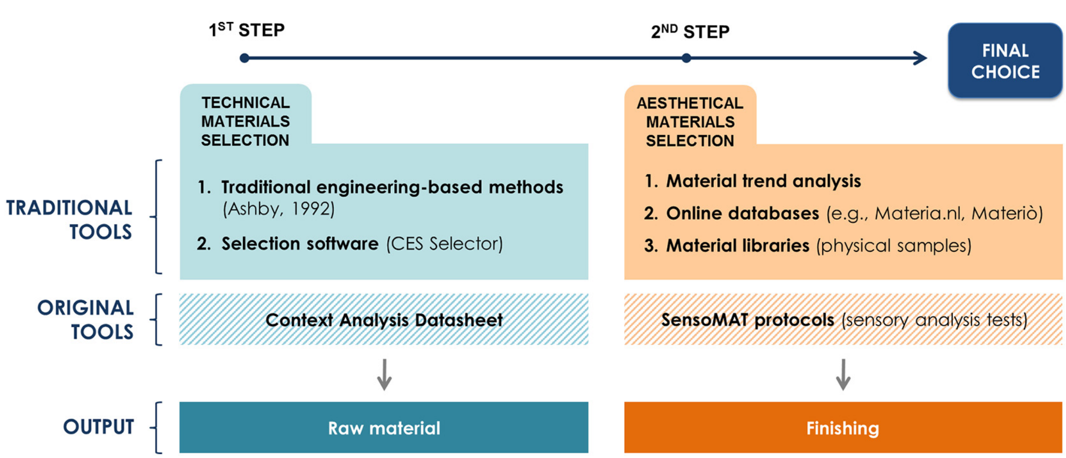

Fig. 2. Steps of the integrated materials selection process (1.5-column).

intangible properties of materials. The process of integrating user perceptions and associating them with numerical variables is completed through a series of sensory evaluations. Sensory Evaluation Analysis, or sensory analysis tests, have been introduced in the food and cosmetic industry from the 1950s, and have been recently applied in the materials science field to measure and interpret the user-material perception process focusing on visual and tactile properties of materials [59,60].

Sensory tests are distinguished in three main categories: discrimination tests, descriptive analysis, hedonic or affective tests. Discrimination tests are used to examine materials and products similarities or differences, descriptive analysis attempt to characterise qualitatively and quantitatively sensory attributes of a sample, while consumers' preferences are assessed by hedonic tests [61,62]. One test from each category has been selected to be integrated in this step of the framework [16,63], and adapted to translate sensorial and intangible properties in numerical variables. Among discrimination techniques, Paired-comparison test [64] was selected as a quick methodology that permits to involve a limited number of untrained assessors to evaluate whether exists a perceptible difference between two materials or finishes samples concerning a given attribute. Despite this, the test does not give any indication of the extent of such differences and, concerning the evaluation of aesthetical properties of materials, paired-comparison test could be applied only on relatively homogeneous specimens [65].

The Napping® test [60], not currently defined by technical standards (e.g., ISO, AFNOR, etc.), allows to describe the sensorial dimension of a large set of samples (at least 10) by their mutual distance on a two dimensional map [66,67]. During the test, the trained panellist is asked to express his perception about samples by associating a textual description on the map [67]. This method enables the identification of a complete qualification of a product by the generation of specific terms that fits with the real perception of the assessors themselves. In industrial contexts, due to limited time constraints, the panellist training, the collection and elaboration of this great amount of information represents a limitation for the integration of the method [68].

Ranking tests [69] is a simple and rapid procedure of ordering a set of samples on a line according to the intensity of a specific attribute or scaling from the least liked to most liked for consumer acceptance. Despite providing essential information that can be easily elaborated, it is difficult to combine data from different rankings, and the information contained in the data is limited. Moreover, from the test it is difficult to get a representative panel [70]. In the integrated method of selection, these testing procedures have been named as “SensoMAT protocols” (Fig. 2), in order to be easily recognised in the industrial context of reference.

3.3. Research questions (RQs)

According to the different selection steps, the main research questions explored were:

RQ1: Are the method and tools employed in the TMS appropriate for comparing and selecting different material alternatives based on technical properties?

RQ2: Aiming to choose finishing based on sensory criteria, are sensory tests suitable to measure user-material perceptions and to correlate them with technical parameters?

RQ3: To what extent do experience of users influence how they perceive and evaluate a material?

Looking at the motivating example presented, the general RQs have been specified:

RQ1*: Which polymeric bulk materials could be employed in substitution of metal alloys in aesthetical components of professional appliances?

Technical Materials Selection is performed to find polymeric bulk alternatives to metal alloys counterpart focusing on their technical and manufacturing properties. The purpose of this paper is not, however, to present the steps of traditional process of selection, but to describe the novel approach that follows the selection of the finishes to be applied on the raw materials.

RQ2*: Considering an application on aesthetical components of professional appliances, which is the best alternative material to stainless steel?

This is the central question of the paper, aiming at identifying the most similar finishing to stainless steel based on the evaluation of sensorial and intangible properties by sensory analysis test. In the current study, the Mapping test will be presented and evaluated as the process through which this is determined.

RQ3*: Does users' experience in the product context or in materials influence their perception of the metal-look alternatives proposed?

Assessors who participated to the sensory test were selected depending on their experience on the industrial context and on materials.

4. Materials & methods

4.1. Stimuli

Following Ashby's method, the bulk polymeric solutions resulted from the Technical Materials Selection phase[1] are polyamide (PA) and acrylonitrile butadiene styrene (ABS), commonly used in the automotive and consumer goods sector for both aesthetical and functional components. The commercial solutions selected for the replacement case study have been selected according to the company's potential material suppliers (*RQ1**).

The metal-look finishes to be applied on the raw materials have been selected according to economical and manufacturing constraints and the aesthetical requirements from the Design department of the company.

Fig. 3 shows the ten metal-look finishes materials used as the stimuli in this study (*RQ2**). All the material samples have been shown in standard shape conditions [59] and isolated from the background. For this reason, 3D printed rectangular white boxes have been designed to contain the flat material samples (55 × 35 mm display). The samples have been named and marked with an alphabetical code in order to facilitate the data collection.

Looking at the metals selected, stainless steel (I) represents the reference material to be substituted, while aluminium (F) was included in the metal replacement case study as already employed in aesthetical components of small professional appliances. In the same way, aluminium-based painting finishing on polyarilamide (PARA) (C) and a blend of polycarbonate/polystyrene (PC/PS) adhesive film (D) are examples of metal-look polymer finishes already employed in the industrial context. From explorative interviews with experienced users (3 chefs and 3 designers), emerged that C and D samples presented some limitations in terms of aesthetical properties as they were characterised by low quality and low elegance.

The specimens have been characterised by physical and optical measurements (Annex II). The colour of the samples was measured using a spectrophotometer (Konica Minolta CM-2600d, light source: D65), while gloss measurements were collected by a glossmeter (Minolta Multi-Gloss 268) (Annex II, Table A1). The measurements were expressed in accordance with the CIELAB colour system, developed by the Commission Internationale d'Eclairage for characterizing colours based on human perception [71,72]. The three coordinates of CIE LAB colour model (L^*, a^* and b^*) represent the lightness of the colour ($L^* = 0$ yields black and $L^* = 100$ indicates diffuse white), its position between red/magenta and green (a^*, negative values indicate green while positive values indicate magenta) and its position between yellow and blue (b^*, negative values indicate blue and positive values indicate yellow). Polar

[1] The properties evaluated in the TMS phase are: mechanical (i.e., Tensile strength (MPa), Flexural Modulus (GPa)), thermal (i.e., Max service temp (°C), Heat Deflection Temperature (°C)) and dimensional stability (Linear mould shrinkage (%), Thermal expansion coefficient (µstrain/°C)).

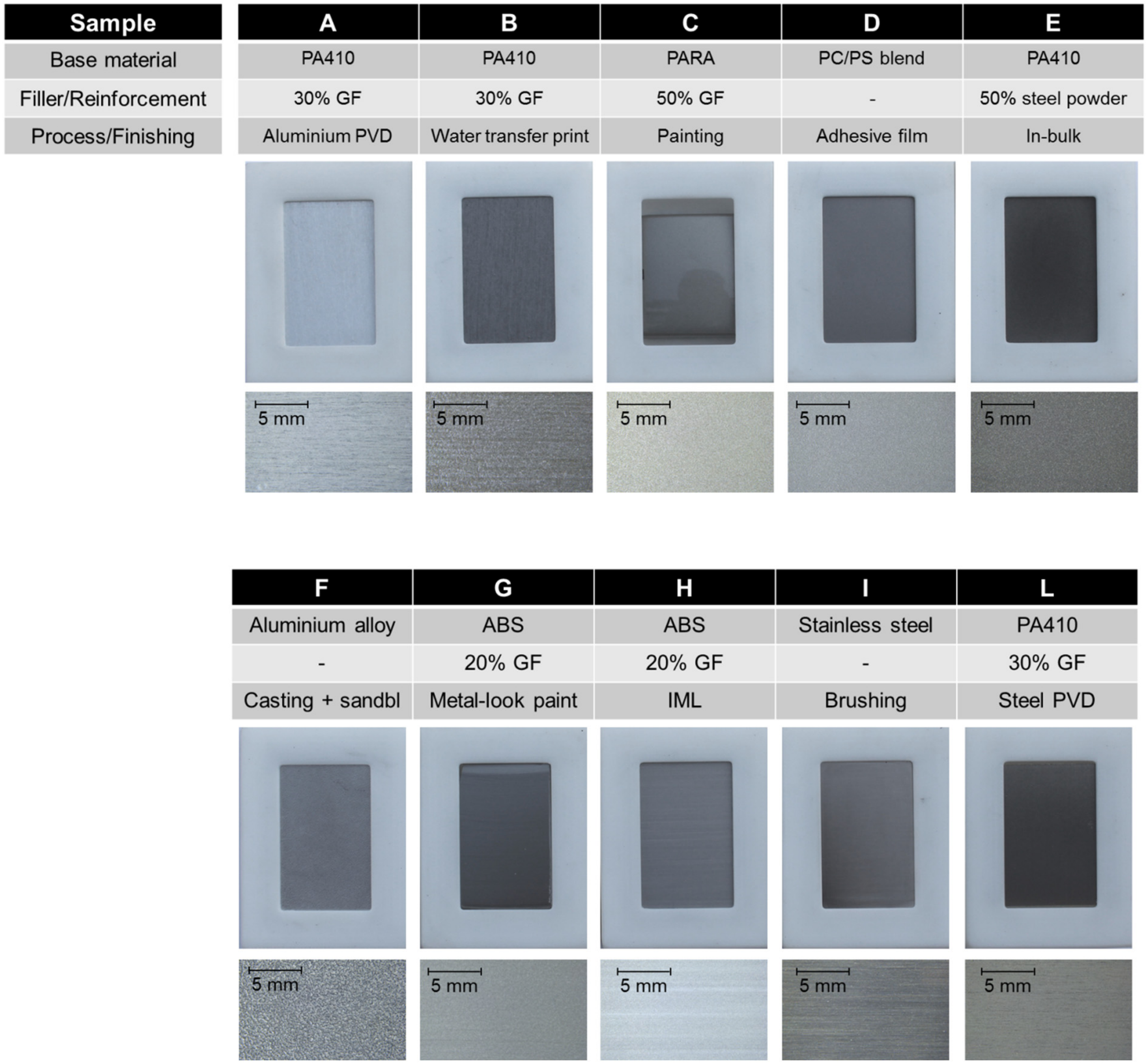

Fig. 3. Sample displays used in the Mapping test (2-column).

coordinates at constant lightness describe colour hue (h), as angular coordinate, and chroma (C) as in-plane saturation [73]. The samples' surface roughness was measured using a laser profilometer[2] (UBM Microfocus, 5600). Two profile measures were conducted on different areas of each sample (Annex II, Table A2).

4.2. Sensory analysis: mapping test

When the aim of the selection is not to describe the sensorial dimension of different finishes, but to evaluate them based on specific sensory criteria indicated by the designers, Ranking test could be performed. Even though, if the objective is also to study the possible correlation among the relevant descriptors in a specific context, a hybrid methodology is needed. Developed to fit better the professional appliances industry needs, the Mapping test represents an adaptation of the Napping® and the Ranking test. Mapping test permits to evaluate two descriptors per each session which are directly panel leader.

The aim of Mapping test, indeed, is to study the perception of materials and finishes and their correlation on a sensory space (map) defined by two specific attributes (axes) (Fig. 4). The closer the material samples are placed, the more similar they are concerning the two qualitative properties identified.

4.2.1. Participants

Thirty-seven volunteers (21 males and 16 females), with a mean age of 31 years old (SD = 6.7), took part in this study. The majority of the participants were native Italians (54%), followed by 19% who were English, and the remaining assessors had another nationality. In order to study if the experience on the industrial context and on materials could influence the perception of non-trained assessors, the results of Mapping test were elaborated across four different panel categories (RQ3*). All subjects gave informed consent prior to their participation in the study.

A1) Assessors with experience in the industrial context (EP)

[2] Sample A, B, C, E, G, H, L,: measurement length of 4.00 mm, with a point density of 500 points mm-1, cut off wavelength of 0.80 mm and a 75% damping. Sample D, F: measurement length of 12.50 mm, with a point density of 150 points mm-1, cut off wavelength of 2.50 mm and a 75% damping. Sample I: measurement length of 1.25 mm, with a point density of 1400 points mm-1, cut off wavelength of 0.25 mm and a 75% damping.

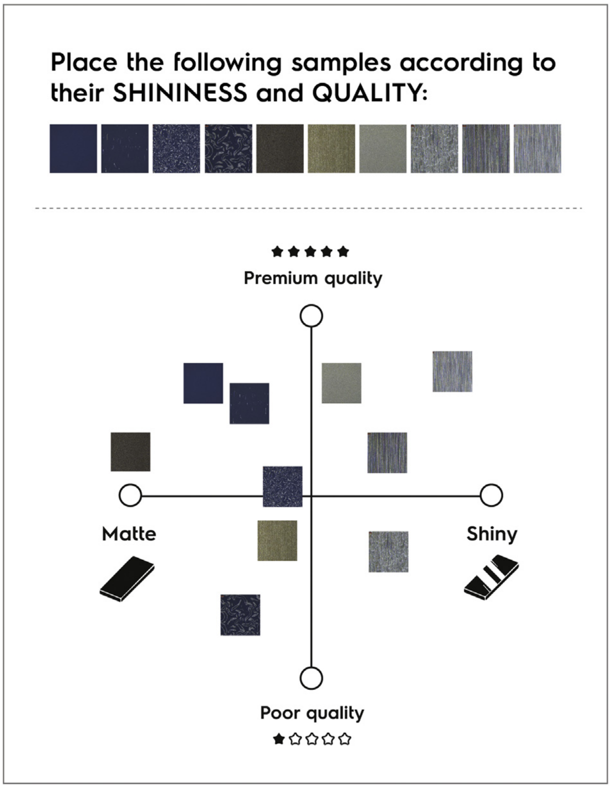

Fig. 4. Mapping test example (single-column).

19 assessors (6 F, 13 M) were professionals in the company including designers and other professionals. 32% of the panel has >5-years' experience in the industrial product context, 54% of them work in the professional kitchen appliance field from 1 to 5-years, while 16% of them has <1-year experience with the design and use of professional appliances.

A2) Non experience in industrial product context (NEP)

18 volunteers (10 F, 8 M) have been recruited as non-experienced user of professional kitchens.

B1) Experience in materials (EM)

Among the 37 assessors, 20 people (7 F, 13 M) are designers and material experts, meaning that they could perform a materials selection. The evaluators with experience in materials have different background of study: design (25%), design engineering (30%), materials engineering (20%) and the remaining part has another engineering-related background. Even if they were non-trained sensory analysis evaluators, these professionals based their perception about aesthetical properties of materials on a basic common knowledge on material classes, material technical properties, etc.

B2) Non-experience in materials (NEM)

17 assessors (9 F, 8 M) are professionals with no particular experience on materials evaluation. Their background of study is various: from the engineering field (mechanical and electrical engineering, 35%), to the humanities (18%); from the natural sciences (physics, mathematics, and computer science, 24%), to food technology (12%). This category represents naïve assessors: they would evaluate aesthetical properties of materials based on everyday experience, guided by personal preferences and cultural behaviours.

Table 1
Sensory descriptors' list for aesthetic components.

Modality	Property	Descriptor (English)	Descriptor (Italian)
Visual	Glossiness	Shiny – Matte	Lucido – Opaco
	Surface evenness	Uniform - Non uniform	Omogeneo - Disomogeneo
	Colour intensity	Intense - Light	Acceso - Sbiadito
	Transparency	Transparent – Opaque	Trasparente - Opaco
Tactual	Roughness	Rough – Smooth	Ruvido – Liscio
	Warmth	Warm – Cold	Caldo – Freddo
	Stickiness	Sticky - Not sticky	Appiccicoso – Non app.
	Softness	Soft – Hard	Morbido - Duro
Intangible	Quality	Premium qual. – Poor quality	Alta qualità – Bassa qualità
	Elegance	Elegant – Non elegant	Elegante – Non elegante
	Innovation	Modern - Traditional	Moderno – Tradizionale
	Cost	Expensive – Cheap	Costoso - Economico
	Pleasure	Like - Dislike	Piace – Non piace

4.2.2. Descriptors

Participants were asked to evaluate the material based on different sensorial and intangible characteristics. The sensory descriptors that could be used in evaluating aesthetic components of professional kitchen appliances have been selected from literature together with the company's designers [25,30,50,57,58,74–78]. Table 1 describes the list of sensory descriptors.

- *Glossiness/Shininess*: the visual property that indicates how well a surface reflects light in a mirror-like direction.
- *Warmth*: the property that permits to distinguish metals and polymers by touch. The perception is based on our ability to produce and transmit heat through our skin and on two physical properties of materials: thermal conductivity and heat capacity.
- *Perceived quality*: an intangible property that could be significantly different from metals to polymers. This judgment is usually formulated through multimodal evaluation (sight and touch) comparing different materials, and it is correlated with the absence of defects, and the ability to fulfil expectations.
- *Elegance*: an intangible property that is not discriminant to identify metals or polymers. It can be associated with the concept of superior, graceful, polished and refined.

4.2.3. Procedure

Participants were invited to partake in the study through an email explaining the requirements. The test took place in two different locations according to the groups of assessors recruited: at the company's location (Pordenone, Italy) and at the Design Engineering Department of Imperial College (London, UK).

A panel leader that briefly explained the steps of the experiment and provided a guideline worksheet form and a questionnaire guided the Mapping test. The test has been divided into different steps, according to the number of the maps to be evaluated: Map 1 ("matte–shiny", "premium quality–poor quality") and Map 2 ("cold–warm", "elegant–shabby"). The participants were first asked to read the test guidelines that reported the definition of each sensory descriptor evaluated in the test. Each participant was seated on a chair in front of a white table and simultaneously presented with ten differently coded material samples. The assessors were asked to place the samples on the map according to the descriptors selected in a multimodal way (vision and touch). The samples, which were perceived as more similar, were placed close together, otherwise, they were positioned in the opposite side of the map's axes.

4.2.4. Data analysis

The statistical elaboration of the Mapping test was made with Minitab ver. 17 (Minitab, State College, PA), and SensoMineR package of RStudio ver. 1.0.153. The data analysis consisted of multi-dimensional analysis (Multiple Factor Analysis (MFA)) and correlation (Pearson). To determine influences of the experience in the industrial context object of the analysis or in materials on sensorial and intangible properties' evaluation, one-way analysis of variance (ANOVA) was performed. If a significant difference of means ($p < 0.05$) was indicated by the ANOVA, post-hoc comparisons were performed using Tukey's (HDS) test.

5. Results

The average duration for each Mapping test ($n = 37$) is in line with literature experiences [60]. The mean time for the evaluation of Map 1 (Glossiness/Perceived Quality) was 5.49 min (SD = 2.48), while for Map 2 (Warmth/Elegance) was 4.32 min (SD = 1.56). No statistically significant difference between the four groups (EP/NEP and EM/NEM) has been registered concerning the timing to perform the test.

5.1. Physical characterisation of samples

Prior to the analysis of the sensory responses of assessors, physical measurements on visual and tactile characteristics of the samples have been collected, namely colour, gloss and surface roughness. Comprehensive data are reported in the Annex II.

The CIELAB parameters (L^*, a^*, b^*) were used to determine the ΔE – the distance between the input colour (stainless steel) and the colour of the alternative finishes evaluated [28,79]. In Table A1, ΔE values lower than 2 indicate that the difference between the colour of two samples is barely perceivable by the average human eye [80,81]. The most similar polymer to stainless steel in terms of colour is the one already used in the aesthetical components for professional kitchen (C) ($\Delta E = 3.304$), followed by G ($\Delta E = 5.413$) and H ($\Delta E = 5.733$).

Determined by the surface roughness, the refractive index of a material and the angle of incident light, gloss is generally used to describe the visual appearance of a material, as it has an impact also on colour perception [82,83]. "The ratio between the reflected and incident light for the specimen […] compared with the ratio for the gloss standard […] is recorded as gloss units (GU)" [84]. Looking at Fig. 5, the finishing that is more similar to stainless steel (I) in terms of gloss is the metal-look painted ABS (G). Even though, it has to be considered that assessors could perceive the two types of gloss as very different. Stainless steel surface, indeed, exhibits metallic glossiness that is distinguished by the one of the polymer because a larger portion of the incident light is polarised in specular reflection. A positive correlation is observed between the estimations of glossiness (visuo-tactile modality) and the physical characteristics measured in the paragraph above [P = 0.716; p-value = 0.02]. In the same way, a strong correlation of results is evident in evaluation of D, E, G, H, I, L samples compared to their gloss measure [P = 0.952; p-value = 0.003] (Fig. 5). This evidence a good consistency of the panel as "instrument" of evaluation of visual properties of materials.

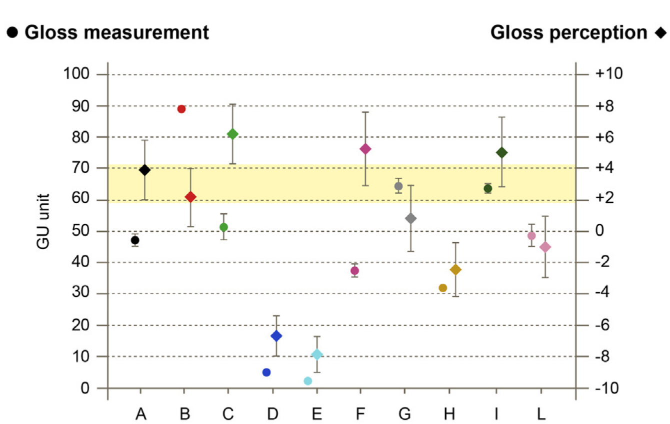

Fig. 5. Correlation between gloss measurement and perception (single-column).

Roughness represents one of the most important characteristics in the haptic perception of surfaces. It is correlated to some physical parameters of the material surface, typically height differences (peak-valley), or deviations, in the direction of a normal vector that represents the ideal form of the surface [85]. Moreover, roughness perception strongly depends on the skin friction and on the vibrations produced while touching the materials surface [77]. The most common standardized roughness parameter (Ra) [25,63,76,86,87] has been taken into consideration in this analysis. The smoothness of the samples was between the range of 4.048 and 0.176, with the values on these ends representing the aluminium sample (F) and the stainless steel sample (I), respectively. Thus, the samples characterised by a more similar Ra to stainless steel are G (Ra = 0.529), A (Ra = 0.827) and L (Ra = 0.844). Based on the previous considerations, the candidate finishes that show more similar visual and tactile characteristics to stainless steel are metal-look painting (G), In-Mould Labeling (IML) finishing (H), and stainless steel Physical Vapor Deposition (PVD) (L). Even if physical measurements represent an objective method for evaluating aesthetical properties of materials, they present some limits. For example, physical measurements only allow for an analysis of separate surface parameters without easily taking into account the overall sensory perception.

5.2. Mapping test – confidence ellipses

A graphical representation of the Mapping test results (Figs. 6–7) is useful to detect the qualitative macro effects of user-material interaction. In this experiment, the evaluation could be strongly influenced by the subjectivity of the assessors. Multiple Factor Analysis (MFA) was used to treat projective mapping data [88,89]. These data consist of a set of coordinates per material sample from each assessor. The size of the confidence ellipse is determined by the variance of the data: in this case study, the length of the ellipse's axes is defined by the data standard deviations (σ_x, σ_y). Confidence ellipses around each material and finishing sample's mean position have been built with the total bootstrap method [59,60,90], in which virtual panels are simulated.

Map 1 results from the different groups (Fig. 6) shows that many confidence ellipses are well separated, suggesting that the panel, independently from their experience in products or materials, recognised the differences among the samples concerning Glossiness and Perceived quality. On the contrary, the ellipses in Map 2 (Fig. 7) overlap, evidencing that the panel categories judge the samples as similar in Warmth and Elegance. With the only exception of EP, the size of the ellipses in Map 1 indicate a narrow distribution of the data. The opposite situation could be observed almost for all the groups in Map 2, where the magnitudes of numerous ellipses (e.g., A, B, D, E, G) could be correlated with a higher dispersion of the data.

With the exception of NEM category, stainless steel (I) is evaluated as the material characterised by the highest perceived quality and glossiness. Moreover, the material is perceived by EP and EM as the most cold and elegant between the samples. On the contrary, aluminium (F) and the metal-look polymer (C), currently used in the aesthetical components of professional appliances, are evaluated by all the assessors as characterised by high gloss and low perceived quality (Map 1). The same samples are judged differently among the four groups. EP and NEP agree that C sample is a shabby and warm finish, while NEM considers that the material is one of the most elegant samples. Concerning aluminium (F), all categories

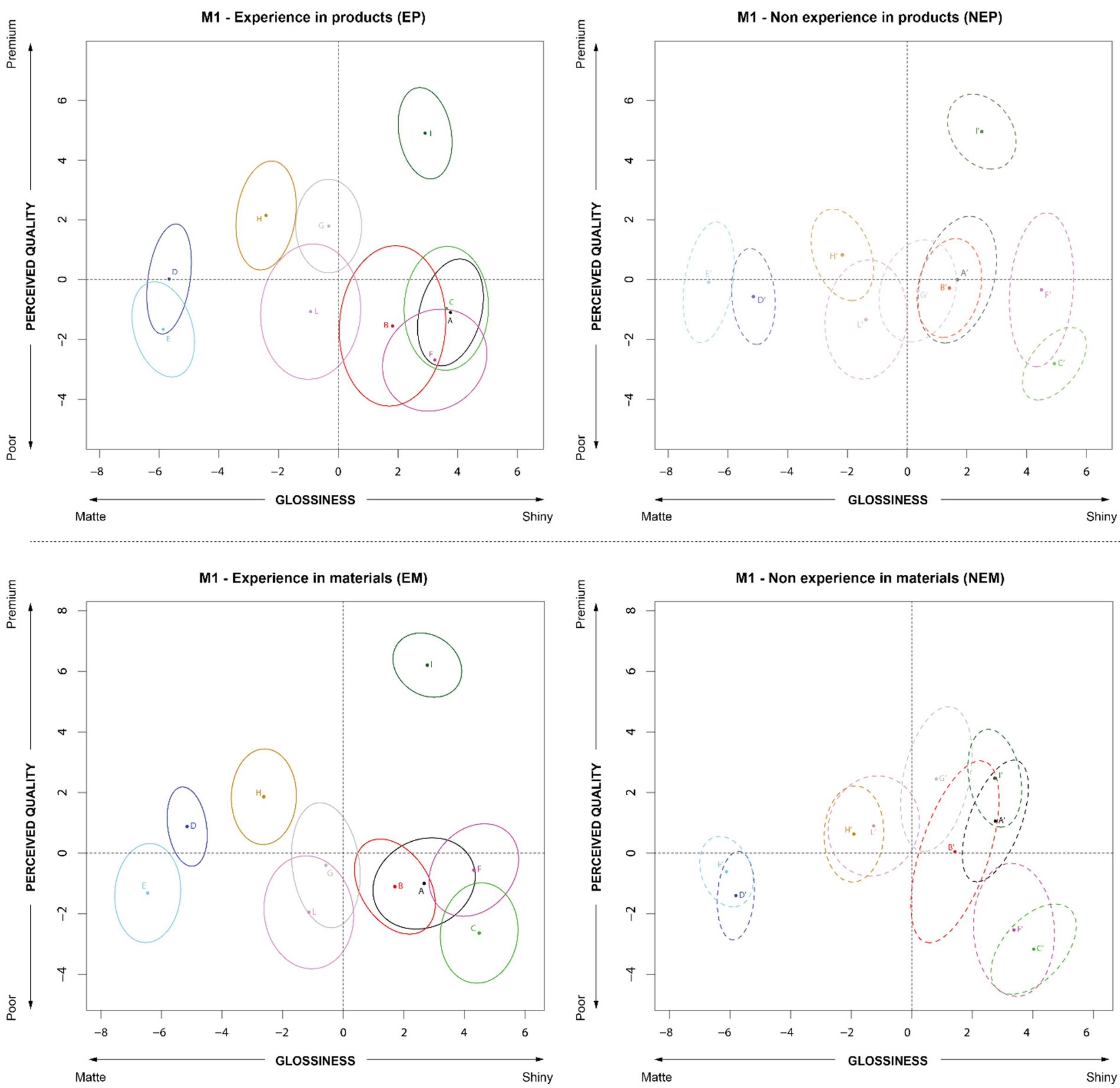

Fig. 6. MFA result plots with confidence ellipses from Map 1. Colours and letters are referred to different material samples (2-column).

recognise it as cold-metal, but only EP and EM assessors judge it as characterised by low elegance. The results from experienced assessors (EP and EM) confirm the company's industrial designers' opinion about stainless steel (I). Observing the two graphical representations (Figs. 6–7), there are no close ellipses to I sample, evidencing the peculiarity of the material compared to the other finishes. Due to this, an analysis of the singular descriptors evaluated in the test is required.

5.3. Mapping test – radar plot

The four descriptors were analysed in singular rankings by one-way analysis of variance (ANOVA). Graphical representations and details are available in Supporting information. From a general observation, the results are characterised by high standard deviations, meaning a high variability and dispersion of data in the answers given by the panel, probably due to the use of untrained assessors.

Radar plot, built on normalized data (mean values and standard deviations), permit to clearly visualize the sensory profiles of each sample studied [65,70,91]. The Fig. 8 shows the sensory profiles of the solutions identified as more suitable for metal replacement, based on their physical characteristics (G, H, L). Results evidence that G sample represents an ameliorative solution to the already employed metal-look polymer finishing (C) in terms of perceived quality and elegance. Moreover, L finishing is depicted as a comparable solution to C, despite its lower perceived gloss.

5.4. Assessors categories

Analysing the results from the four categories of assessors by one-way ANOVA, no statistically significant difference between the four groups emerges at the 0.05 level concerning the evaluation of the samples. A very strong correlation is observed in the evaluation of Glossiness ($P = 0.965$, p-value < 0.001), Warmth ($P = 0.883$, p-value $= 0.001$), Perceived quality ($P = 0.847$, p-value $= 0.002$)

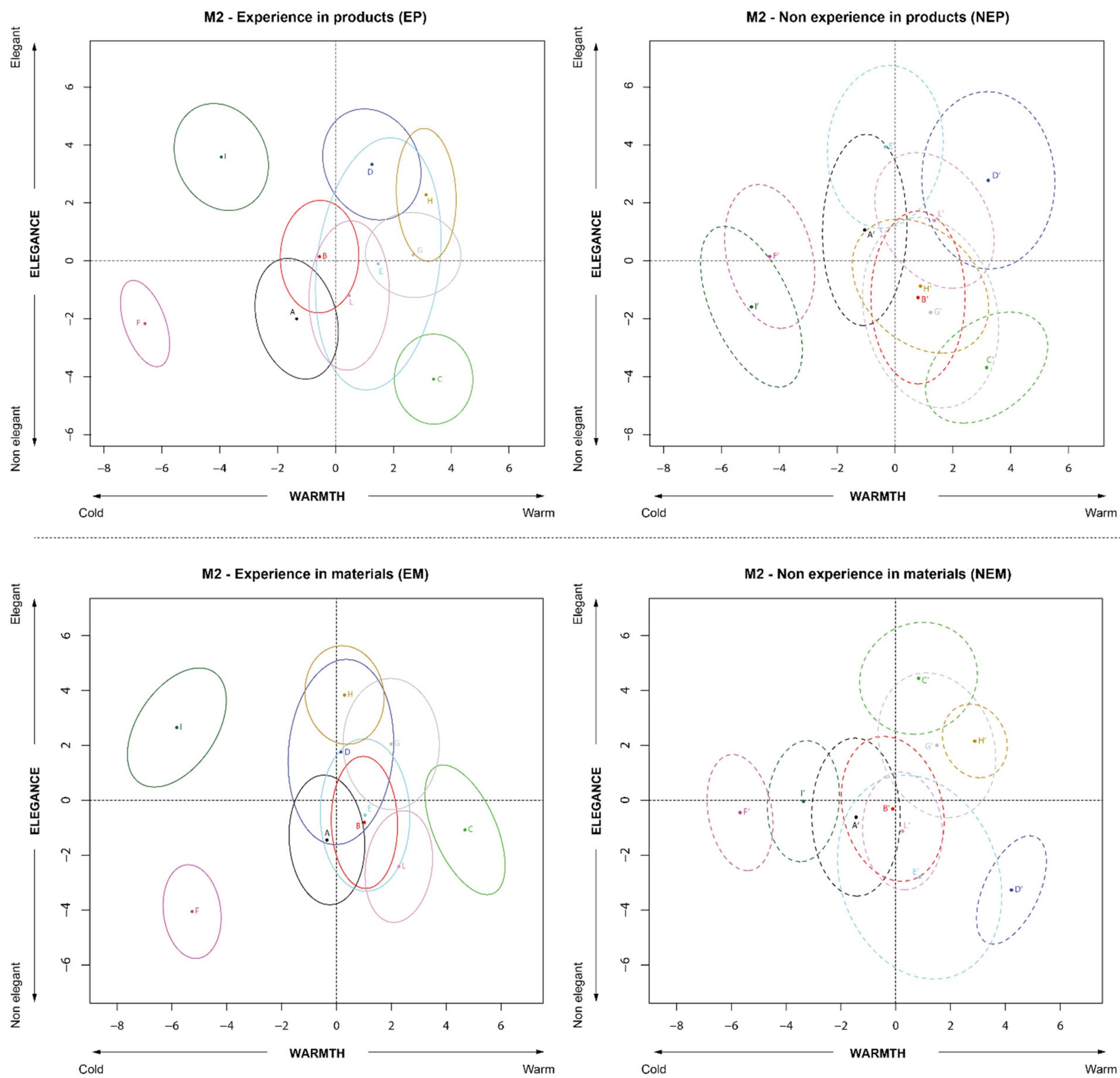

Fig. 7. MFA result plots with confidence ellipses from Map 2. Colours and letters are referred to different material samples (2-column).

and Elegance (P = 0.932, p-value < 0.001) between EP and NEP assessors. This affirms that the experience in product context does not influence the perception on materials and finishes. In the same way, assessor expertise in materials seems not affect the perception of materials' sensory criteria. A very strong correlation is observed between EM and NEM panellists concerning Glossiness (P = 0.994, p-value < 0.001), Warmth (P = 0.779, p-value = 0.006), Perceived quality (P = 0.749, p-value = 0.013) and Elegance (P = 0.778, p-value = 0.008).

6. Discussion

The main aim of this work is to define an integrated method for materials selection that allows to choose raw materials and finishes. In order to provide industrial designers with measurable data to support and explain materials aesthetic decisions [59,60,92], a sensory analysis test was selected and adapted for the evaluation of sensorial and intangible properties. A motivating example focusing on the metal-to-polymer replacement of aesthetic components of professional kitchen appliances is used to describe the proposed method. The proposed method was tested to understand its ability to identify metal replacement materials with mechanical, durability and aesthetic properties similar to those of stainless steel.

The method developed by Ashby [10] and the CES Selector software [17] were initially used to select bulk polymeric alternatives (PA and ABS) to metals. The Mapping test, an adaptation of Napping® [67,68], was then used to select the most suitable finishes to be applied on the bulk materials identified, based on the evaluation of specific sensorial and intangible properties.

The results show that sensory analysis tests are easily adaptable to the evaluation of material properties in an industrial context. The Mapping test represents a rapid and low cost technique: it requires only a limited number of assessors [90], which are involved in testing sessions that last less than half an hour per person, and it does not need ad hoc prototyping tools. Consequently, the involvement of professionals from the company in the tests does not affect their daily workloads. In particular, the Mapping test allows the evaluation of two properties at a time, analysing also possible associations among them.

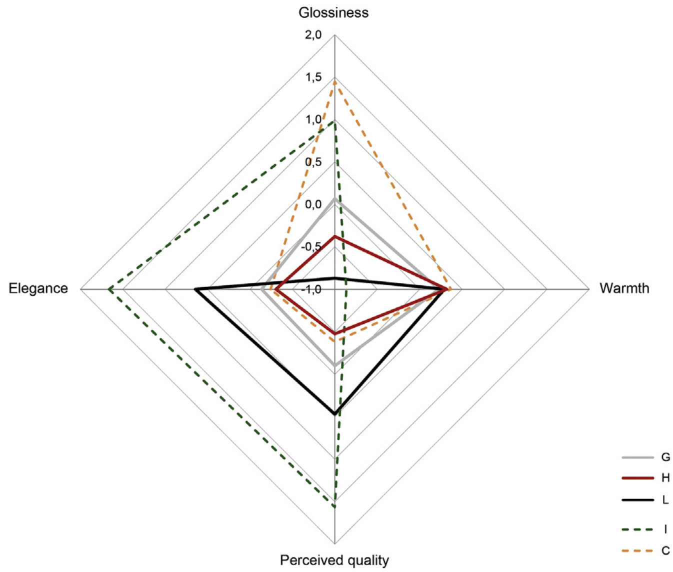

Fig. 8. Radar plot: comparison of the sensory profiles of reference samples (I, C) and finishing alternatives evaluated for the replacement (1.5-column).

Sensory analysis techniques allow the development of deep understanding of the relationship between the physical properties of materials and finishes, and human sensory perception [76,93]. In particular, the positive correlation between the estimation of glossiness and the physical characteristics measured confirmed the consistency of the panel as an "instrument" for the evaluation of visual properties of materials [94]. Furthermore, the results of this work support the argument that sensory analysis enables to integrate the voice and preferences of the consumer in the early phases of the product development process [16,31,32,58,95].

The study has also shown that physical measurements are useful to provide visual references and tactile information on material surfaces, even though they are not sufficient to depict the aesthetic dimension of the finishes [96]. For this reason, qualitative assessment by sensory analysis is proposed to complement existing systematic quantitative methods [93]. With reference to the motivating example presented, this contributes to depict the physical parameters that characterise most "quality perception" of metal-look surfaces.

On the other hand, the representation of the Mapping test results, through the confidence ellipses, has shown the macro effects of the user-material interaction. However, it did not permit to depict unequivocally a material alternative that is perceived as the most similar to the reference material. For instance, in the case study analysed, the quantitative analysis of the confidence ellipses is not sufficient to define a specific metal-look finishing characterised by perceived quality and elegance ratings similar to stainless steel. This is probably due to the peculiar aesthetical properties of the reference material (i.e., stainless steel), which resulted in a very distinguished evaluation compared to all the other samples. In the case of more homogeneous samples evaluation (e.g., only polymeric metal-look alternatives), it is expected that the selection of the alternative material candidates could probably be extrapolated from the graphical analysis. To overcome this issues, the radar plot has been identified as an instrument [70] to represent the sensory profiles of materials based on the analysis of the singular descriptors evaluated in the test.

Attributes pairing's choice could influence sensory analysis results. In this manuscript, attributes choice is strictly linked to the test aims [89] and to the motivating example analysed [91,97]. The study's sensory descriptors were selected and paired in order to identify possible associations among sensorial and intangible properties, and qualitative and "quantitative" properties (e.g. perceived gloss and measured gloss). A pilot Mapping test has been conducted by 16 assessors (8 M, 8 F) to optimize the selection of the attributes pairings: one sensory and one intangible property on each map were evaluated. The proposed method can be used with any possible combination of the descriptors selected together with the company's designers (Table 1). Despite this, as the assessment was limited to only four attributes, was not possible to include a generalization of the pairing's choice in the method. Further studies are needed to better evaluate the sensitivity of the results based on differences in pairings.

From the data analysis, the assessment of the warmth perception was used to understand if the panel was able to distinguish a metal from a polymer material by touch. The results confirm the consistency of the panel assessment, but this type of evaluation did not give any information about possible differences among the polymer-based finishes. In future experiments, the warmth property would be substituted on the map by another one (e.g., smoothness), in order to allow a direct comparison and to get more insights on the tactile properties of surfaces. As an alternative, after the Mapping test the assessors would be asked to identify the metal based materials.

The test results evidence a high dispersion of data among the assessors: a specific training of the panel is suggested to reach a higher level of consensus [98]. Additionally, the shape of the specimens used as stimuli may have had an influence on the perception of materials and finishes [99–101]. In order to scale up the qualitative evaluation in a more real context of application, sensory tests should be practiced not only on flat samples, but also on shaped specimens and prototypes.

Even if there was not a clear material alternative identified through the case study, the method has provided a measured comparison upon which design rationale can be based. This is relevant not only to the material selection topic: since designers are faced with trade-offs at different steps of the product development process, the approach presented allows those trade-offs to be compared in a more systematic way.

Looking at the two-step framework some considerations must be done. If the aim of the selection is new product development, or alternative bulk material selection in structural components, the AMS should prior require TMS phase. On the other hand, if the objective of the selection is to pursuit a certain sensorial/expressive effect, maintaining the bulk material previously selected, the AMS step should not necessarily require a previous TMS phase. Whereas the advantages in applying the proposed method in the professional appliances field were investigated in detail, research can further improve such insights and assess their transferability and relevance to other industrial contexts, especially the ones where sensory criteria have the highest priority compared to technical properties.

Moreover, future works could focus on the application of sensory analysis techniques at stages of the product development process such as quality control (e.g., quality assurance, raw materials specification, storage stability) [102–104], and concept generation (e.g., competitor analysis, product sensory specification) [105,106]. At last, further studies are needed to explore whether the framework could be employed as a guidance for design education, and the tools developed could help stimulate user-experience design by integrating sensorial and intangible properties' evaluation.

7. Conclusion

The main aim of this study was to develop an integrated method of materials selection to lower the gap in the interpretation of materials


Materials Selection - **Datasheet request**

Required by .... Date ....

1. Object of selection

Category: Hot ○ Wet ○ Cold/Dynamic ○

Appliance

Component

Item

Dimension: L .... W .... H .... thickness ....

Current material

Images, technical drawings

2. Selection aim

☐ Material substitution

☐ New material implementation

☐ Material development

☐ Material pre-study

Description

3. Service conditions

☐ Mechanical conditions — Description

☐ Chemical conditions (Chemicals, food) — Description

☐ Thermal conditions

Food contact compliance: Yes ○ No ○

NSF/ANSI 51: Yes ○ No ○

☐ Sensorial properties

☐ Electrical properties

☐ UV resistance: Yes ○ No ○

☐ Other conditions

4. Internal inputs

Inputs from supplier, ...

5. Degree of detail

☐ Low (at least 2 material alternatives, NO durability, NO sensorial)

☐ Medium (at least 2 material alternatives, durability OR sensorial)

☐ High (at least 3 material alternatives, durability AND/OR sensorial)

Annex I. "Context analysis datasheet".

properties between engineers and industrial designers. As a result of this research, the following points illustrate the main findings:

1) A two-step framework for materials selection has been proposed consisting of tools for Technical Materials Selection (TMS) and Aesthetical Materials Selection (AMS).
2) Traditional methods of materials selection are used to guide the choice of raw materials, taking into consideration technical properties.
3) Sensory analysis tests are used to support the selection of materials and finishes based on sensorial and intangible properties.
4) Sensory analysis integrates user perception in the materials selection process. Moreover, it provides industrial designers with tools to justify Colour Materials and Finish (CMF) choices with quantifiable information.
5) The Mapping test represents a low cost and rapid technique, easily adaptable to the analysis of materials and finishes for different industrial contexts.

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Appendix A

Annex II Physical measurement results

Table A1
Visual properties.

Sample[a]	Colour						Gloss		
	L*	a*	b*	C*	h	ΔE	20°	60°	85°
							Gloss unit (GU)	Gloss unit (GU)	Gloss unit (GU)
A	81,933	−0.420	1223	1300	108,913	13,371	47,2	95,9	81,4
B	66,510	0,063	2713	2713	88,677	5958	89,0	99,3	99,7
C	68,267	−0.447	5023	5047	95,067	3304	51,4	95,1	90,4
D	59,410	0,333	2600	2620	82,687	11,748	2,6	7,1	5,6
E	40,557	0,060	1577	1577	87,800	30,150	0,3	1,9	2,3
F	78,690	0,110	1433	1437	85,670	10,442	37,6	106,8	27,4
G	68,883	−0.760	2380	2500	107,713	5413	21,7	64,3	65,9
H	71,897	−0.153	2017	2020	94,313	5733	55,5	32,2	56,7
I	70,133	0,963	7357	7423	82,567	–	63,6	113,8	98,3
L	54,437	−0.193	2043	2053	95,467	16,612	48,5	86,1	87,4

[a] Colour/gloss: average on 3 measurements.

Table A2
Tactile properties.

Sample[b]	Roughness					
	Ra	Rq	R3z	RzISO	Rmax	Sk
	μm	μm	μm	μm	μm	
A	0,827	1037	3848	5655	6624	0,412
B	1756	2304	7626	12,438	13,847	1175
C	1719	2211	7403	11,956	13,487	0,879
D	5172	6612	20,602	33,801	37,328	0,045
E	0,943	1207	3976	6509	7553	−0.062
F	4048	5053	16,904	23,992	26,050	−0.664
G	0,529	0,674	2819	3916	4339	0,146
H	1404	1736	6184	8333	8819	0,260
I	0,176	0,227	0,871	1277	1525	−0.599
L	0,844	1052	4101	5648	6356	0,216

[b] Roughness: average on 2 measurements.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.matdes.2018.04.081.

References

[1] I. Van Kesteren, S. De Bruijn, P.J. Stappers, Evaluation of materials selection activities in user-centred design projects, J. Eng. Des. 19 (2008) 417–429.
[2] H. Ernst, Success factors of new product development: a review of the empirical literature, Int. J. Manag. Rev. 4 (2002) 1–40, https://doi.org/10.1111/1468-2370.00075.
[3] N. Bhuiyan, A framework for successful new product development, J. Ind. Eng. Manag. 4 (2011) 746–770, https://doi.org/10.3926/jiem.334.
[4] V. Krishnan, K.T. Ulrich, Product development decisions: a review of the literature, Manag. Sci. 47 (2001) 1–21, https://doi.org/10.1287/mnsc.47.1.1.10668.
[5] F. Giannini, M. Monti, G. Podehl, Aesthetic-driven tools for industrial design, J. Eng. Des. 17 (2006) 193–215, https://doi.org/10.1080/09544820500275396.
[6] L. Rampino, The innovation pyramid: a categorization of the innovation phenomenon in the product-design field, Int. J. Des. 5 (2010) (Online).
[7] G. Parsons, The Philosophy of Design, John Wiley & Sons, Ltd., New York, 2015.
[8] C. Townsend, S. Sood, Self-affirmation through the choice of highly aesthetic products, J. Consum. Res. 39 (2012) 415–428, https://doi.org/10.1086/663775.
[9] B. Pham, Design for aesthetics: interactions of design variables and aesthetic properties, Proceeding SPIE IS&T/SPIE 11th Annu. Symp. - Electron. Imaging '99 1999, pp. 364–371 (San Jose, USA).
[10] M. Ashby, Material Selection in Mechanical Design(Cambridge) 1992.
[11] M. Ashby, H. Shercliff, D. Cebon, Materials: Engineering, Science, Processing and Design, 2007 (London).
[12] M.M. Farag, Quantitative methods of materials selection, in: M. Kutz (Ed.), Handb. Mater. Sel., 2002.
[13] E.H. Cornish, Materials and the Designer, 1987 (New York).
[14] E. Manzini, The Material of Invention: Materials and Design, Arcadia Ed, Milano, 1986.
[15] R. Cooper, The stage-gate idea-to-launch process - update, whats new and nex-gen systems, J. Prod. Innov. Manag. 25 (2013) 213–232.
[16] A. Piselli, M. Simonato, B. Del Curto, Holistic approach to materials selection in professional appliances industry, Proc. 14th Int. Des. Conf. Des. The Design Society, Cavtat, Dubrovnik 2016, pp. 865–874.
[17] Granta Design Ltd., Cambridge Engineering Selector Software (CES), 2017.
[18] W.J. Patton, Materials in Industry, Prentice-H, Englewood Cliffs, N.J, 1968.
[19] K.G. Budinski, Engineering Materials: Properties and Selection, Prentice-H, New Jersey, 1996.
[20] J.R. Lindbeck, Product Design and Manufacture, Simon & Sc, New Jersey, 1995.
[21] M. Grujicic, V. Sellappan, T. He, N. Seyr, A. Obieglo, M. Erdmann, J. Holzleitner, Total life cycle-based materials selection for polymer metal hybrid body-in-white automotive components, J. Mater. Eng. Perform. 18 (2009) 111–128.
[22] P. Chatterjee, V.M. Athawale, S. Chakraborty, Selection of industrial robots using compromise ranking and outranking methods, Mater. Des. 30 (2009) 4043–4053.
[23] C. Javierre, D. Elduque, V. Camanes, J. Cuartero, A systematic material selection process applied to a luminaire diffuser, Light. Res. Technol. 48 (2015) 1–14.
[24] V.T. Srikar, S.M. Spearing, Materials selection in micromechanical design: an application of the Ashby approach, J. Microelectromech. Syst. 12 (2003) 3–10.
[25] S. Wongsriruksa, P. Howes, M. Conreen, M. Miodownik, The use of physical property data to predict the touch perception of materials, Mater. Des. 42 (2012) 238–244, https://doi.org/10.1016/j.matdes.2012.05.054.
[26] H. Zuo, M. Jones, T. Hope, R. Jones, Sensory perception of material texture in consumer products, Des. J. 19 (2016) 405–427.
[27] H. Zuo, M. Jones, Exploration into formal aesthetics in design: (material) texture, 8th Gener. Art Conf. 2005 2015, pp. 1–11.
[28] N. Na, H.J. Su, The emotional characteristics of white for applications of product color design, Int. J. Des. 8 (2014) 61–70.

[29] H. Isoaho, Color, Material and Finish Design, Kyamk University of Applied Sciences, 2016.
[30] E. Karana, P. Hekkert, P. Kandachar, Meanings of materials through sensorial properties and manufacturing processes, Mater. Des. 30 (2009) 2778–2784, https://doi.org/10.1016/j.matdes.2008.09.028.
[31] M. Ashby, K. Johnson, Materials and Design: the Art and Science of Material Selection in Product Design, 2002 (Oxford).
[32] A.A. VV, Materials experience, Fundamentals of Materials and Design, Butterworth-Heinemann, Boston, 2014https://doi.org/10.1016/B978-0-08-099359-1.18001-4.
[33] L. Veelaert, E. Du Bois, K. Ragaert, S. Hubo, K. Van Kets, Bridging design and engineering in terms of materials selection, Proc. 7th Int. Polym. Mould. Innov. Conf. 2016, pp. 319–326 (doi:978-90-813136-0-5).
[34] C. Asbjorn Sorensen, A. Warell, S. Jagtap, Material selection - a qualitative case study of five design consultancies, Proc. Int. Conf. Eng. Des. ICED 2017, pp. 439–448.
[35] E. Karana, Meanings of Materials, Delft University of Technology, 2009.
[36] M. Figuerola, Q. Lai, M. Ashby, The CES EduPack products, Materials and Processes Database - A White Paper 2016, pp. 1–23.
[37] I.E.H. Van Kesteren, P.J. Stappers, J.C.M. de Bruijn, Materials in products selection: tools for including user-interaction in materials selection, Int. J. Des. 1 (2007) 41–55.
[38] S. Camere, H.N. Schifferstein, M. Bordegoni, The experience map. A tool to support experience- driven multisensory design, Proc. 9th Int. Conf. Des. Semant. Form Mov., Milano (Italy) 2015, pp. 147–155.
[39] J. Cagan, C.M. Vogel, Creating Breakthrough Products, FT Press, Upper Saddle River, NJ, 2002.
[40] L. Wastiels, I. Wouters, Material considerations in architectural design: a study of the aspects identified by architects for selecting materials, Undisciplined! Des. Res. Soc. Conf., 2009, Sheffield Hallam University, Sheffield, UK 2008, pp. 379/1–13.
[41] H. Zuo, M. Jones, T. Hope, A matrix of material representation, Proceeding Int. Conf, "Futureground", Melbourne, Australia, 2004.
[42] E. Karana, B. Barati, V. Rognoli, A.Z. Van Der Laan, Material driven design (MDD): a method to design for material experiences, Int. J. Des. 9 (2015) 35–54.
[43] V. Rognoli, A broad survey on expressive-sensorial characterization of materials for design education, METU J. Fac. Archit. 27 (2010) 287–300.
[44] E. Karana, P. Hekkert, P. Kandachar, A tool for meaning driven materials selection, Mater. Des. 31 (2009).
[45] K.W. Johnson, T. Lenau, M.F. Ashby, The aesthetic and perceived attributes of products, Iced 2003, 2003.
[46] H. Zuo, T. Hope, P. Castle, M. Jones, An investigation into the sensory properties of materials, Proceedings 2nd Int. Conf. Affect. Hum. Factors Des. Ascan Academic Press, London 2001, pp. 500–507.
[47] A. Piselli, M. Simonato, B. Del Curto, Improving the learning process in materials selection: the role of context in choosing material solutions, Proc. 10th Int. Technol. Educ. Dev. Conf., IATED, Valencia 2016, pp. 6713–6722, https://doi.org/10.21125/inted.2016.0582.
[48] J.E. Burge, D.C. Brown, Design Rationale Types and Tools, http://web.cs.wpi.edu/Research/aidg/DR-Rpt98.html 1998.
[49] R.W. Fleming, Visual perception of materials and their properties, Vis. Res. 94 (2014) 62–75, https://doi.org/10.1016/j.visres.2013.11.004.
[50] M. Vergara, S. Mondragon, J.L. Sancho-Bru, P. Company, M.J. Agost, Perception of products by progressive multisensory integration. A study on hammers, Appl. Ergon. 42 (2011) 652–664, https://doi.org/10.1016/j.apergo.2010.09.014.
[51] V. Mohan, Hygenic importance of stainless steel in developing countries, ISSF Int. Stainl. Steel Forum (2009) 1–4.
[52] L. Gardner, The use of stainless steel in structures, Prog. Struct. Eng. Mater. 7 (2005) 45–55, https://doi.org/10.1002/pse.190.
[53] J. Rauschenberger, A. Cenigaonaindia, J. Keseberg, D. Vogler, U. Gubler, F. Liébana, Laser hybrid joining of plastic and metal components for lightweight components, Proc. SPIE vol. 9356 (2015) 1–8, https://doi.org/10.1117/12.2080226.
[54] A. Davitti, Plastic to Metal Transition an Intake Manifold Airflaps Actuator, http://www.eriseventi.com/conference-proceedings-smart-plastics-forum 2015.
[55] A. Piselli, Material selection in the professional appliances industry, POLIMI Des. PHD_018, Vol. 9, PhD Theses Des. as We Do POLIMI, Franco Angeli DESIGN INTERNATIONAL, Milano 2018, pp. 19–41.
[56] A. Piselli, Material Selection in the Professional Appliances Industry. Methods and Tools for Evaluating Sensory Criteria and Aesthetic Obsolescence of Materials, 2018 (Politecnico di Milano Unpublished Doctoral Thesis).
[57] H. Zuo, The selection of materials to match human sensory adaptation and aesthetic expectation in industrial design, METU JFA. 2 (2010) 301–319.
[58] I. Van Kesteren, P. Stappers, S. De Bruijn, Defining user-interaction aspects for materials selection: three tools, Des. Inq., The Nordic Design Research Conference 2007, pp. 1–10.
[59] P. D'Olivo, B. Del Curto, J. Faucheu, D. Lafon, J.-F. Bassereau, S. Lê, D. Delafosse, Sensory metrology: when emotions and experiences contribute to design, 19th Int. Conf. Eng. Des. The Design Society, Seoul, South Korea 2013, pp. 75–77.
[60] J. Faucheu, A. Caroli, B. Del Curto, D. Delafosse, Experimental Setup for Visual and Tactile Evaluation of Materials and Products Through Napping ® Procedure, Proc. 20th Int. Conf. Eng. Des. (ICED 15), Vol. 1, 2015 1–10 (Des. Life.).
[61] F. Philippe, L. Schacher, D.C. Adolphe, C. Dacremont, Tactile feeling: sensory analysis applied to textile goods sensory analysis: state of the art, Text. Res. J. 74 (2004) 1066–1072.
[62] D. Schacher, Laurence; Bensaid, Sourour; Jeguirim, Selsabil El-Ghezal; Adolphe, Sensory and Physiological Issue, in: S. Vassiliadis (Ed.), Adv. Mod. Woven Fabr. Technol., InTech Europe, Rijeka, Croatia 2011, p. 240, https://doi.org/10.5772/25244.
[63] A. Piselli, M. Basso, M. Simonato, R. Furlanetto, A. Cigada, L. De Nardo, B. Del Curto, Effect of wear from cleaning operations on sintered ceramic surfaces: correlation of surface properties data with touch perception and digital image processing, Wear 390–391 (2017) 355–366, https://doi.org/10.1016/j.wear.2017.09.003.
[64] International Organization for Standardization, ISO 5495, Sensory Analysis — Methodology — Paired Comparison Test, 2005, 2005.
[65] K.W. Chapman, H.T. Lawless, K.J. Boor, Quantitative descriptive analysis and principal component analysis for sensory characterization of ultrapasteurized milk, J. Dairy Sci. 84 (2001) 12–20, https://doi.org/10.3168/jds.S0022-0302(01)74446-3.
[66] J. Pagès, F. Husson, Inter-laboratory comparison of sensory profiles: methodology and results, Food Qual. Prefer. 12 (2001) 297–309.
[67] L. Perrin, R. Symoneaux, I. Maître, C. Asselin, F. Jourjon, J. Pagès, Comparison of three sensory methods for use with the napping® procedure: case of ten wines from Loire valley, Food Qual. Prefer. 19 (2008) 1–11.
[68] S. Lê, T.M. Lê, M. Cadoret, Napping and sorted napping as a sensory profiling technique, Rapid Sens. Profiling Tech, Elsevier 2015, pp. 197–213.
[69] British Standards Institution, BS ISO 8587:2006+A1:2013, Sensory Analysis - Methodology - Ranking, 2013.
[70] M.C. Gacula Jr., Descriptvie Sensory Analysis in Practice, Trumbull, Connecticut, 2008.
[71] L. Wastiels, H.N.J. Schifferstein, A. Heylighen, I. Wouters, Red or rough, what makes materials warmer? Mater. Des. 42 (2012) 441–449, https://doi.org/10.1016/j.matdes.2012.06.028.
[72] B. Piqueras-Fiszman, J. Alcaide, E. Roura, C. Spence, Is it the plate or is it the food? Assessing the influence of the color (black or white) and shape of the plate on the perception of the food placed on it, Food Qual. Prefer. 24 (2012) 205–208, https://doi.org/10.1016/j.foodqual.2011.08.011.
[73] M.V. Diamanti, P. Pozzi, F. Randone, B. Del Curto, M.P. Pedeferri, Robust anodic colouring of titanium: effect of electrolyte and colour durability, Mater. Des. 90 (2016) 1085–1091, https://doi.org/10.1016/j.matdes.2015.11.063.
[74] W.L. Baxter, M. Aurisicchio, P.R.N. Childs, Materials, use and contaminated interaction, Mater. Des. 90 (2016) 1218–1227, https://doi.org/10.1016/j.matdes.2015.04.019.
[75] A. García, Measuring perceptions: meeting the challenge of perceived quality, User Exp. Mag. (2016) 1–7.
[76] H. Yanagisawa, K. Takatsuji, Effects of visual expectation on perceived tactile perception: an evaluation method of surface texture with expectation effect, Int. J. Des. 9 (2015) 39–51.
[77] W.M. Bergmann Tiest, Tactual perception of material properties, Vis. Res. 50 (2010) 2775–2782.
[78] A. Haug, A framework for the experience of product aesthetics, Des. J. 19 (2016) 809–826, https://doi.org/10.1080/14606925.2016.1200342.
[79] E. Ertaş, A.U. Güler, A.C. Yücel, H. Köprülü, E. Güler, Color stability of resin composites after immersion in different drinks, Dent. Mater. J. 25 (2006) 371–376, https://doi.org/10.4012/dmj.25.371.
[80] F.D. Jarad, M.D. Russell, B.W. Moss, The use of digital imaging for colour matching and communication in restorative dentistry, Br. Dent. J. J. 199 (2005) 43–49, https://doi.org/10.1038/sj.bdj.4812559.
[81] View Sonic Europe, Delta E ≦ 2 Colour Accuracy - Technical Introduction, (n.d.). http://www.viewsoniceurope.com/uk/products/lcd/pdf/ti_delta_E.pdf.
[82] B. Xiao, D.H. Brainard, Surface gloss and color perception of 3D objects, Vis. Neurosci. 25 (2008) 371–385, https://doi.org/10.1017/S0952523808080267.
[83] S. Rebeggiani, B.-G. Rosén, Factors influencing the surface quality of polished tool steels, Surf. Topogr. Metrol. Prop. 2 (2014), 35004. .
[84] B.-J. Wen, Gloss Meter, in: M.R. Luo (Ed.), Encycl. Color Sci. Technol, Springer New York, New York, NY 2016, pp. 694–697, https://doi.org/10.1007/978-1-4419-8071-7_355.
[85] C.J. Barnes, T.H.C. Childs, B. Henson, C.H. Southee, Surface finish and touch—a case study in a new human factors tribology, Wear 257 (2004) 740–750, https://doi.org/10.1016/j.wear.2004.03.018.
[86] K.E. Overvliet, E. Karana, S. Soto-Faraco, Perception of naturalness in textiles, Mater. Des. 90 (2016) 1192–1199, https://doi.org/10.1016/j.matdes.2015.05.039.
[87] W.M. Bergmann Tiest, A.M.L. Kappers, Haptic and visual perception of roughness, Acta Psychol. 124 (2007) 177–189, https://doi.org/10.1016/j.actpsy.2006.03.002.
[88] C. Dehlholm, P.B. Brockhoff, W.L.P. Bredie, Confidence ellipses: a variation based on parametric bootstrapping applicable on multiple factor analysis results for rapid graphical evaluation, Food Qual. Prefer. 26 (2012) 278–280, https://doi.org/10.1016/j.foodqual.2012.04.010.
[89] M. Cadoret, F. Husson, Construction and evaluation of confidence ellipses applied at sensory data, Food Qual. Prefer. 28 (2013) 106–115, https://doi.org/10.1016/j.foodqual.2012.09.005.
[90] J. Dacleu Ndengue, M. Juganaru-Mathieu, J. Faucheu, Computing ideal number of test subjects - sensorial map parametrization, Proc. 8th Int. Jt. Conf. Knowl. Discov. Knowl. Eng. Knowl. Manag., 1, 2016, pp. 437–442.
[91] C. Dehlholm, Descriptive sensory evaluations, Comparison and Applicability of Novel Rapid Methodologies, University of Copenhagen, 2012.
[92] J.D. Ndengue, I. Cesini, J. Faucheu, E. Chatelet, H. Zahouani, D. Delafosse, F. Massi, Tactile Perception and Friction-induced Vibrations: Discrimination of Similarly Patterned Wood-like Surfaces, 9, 2016.
[93] S. Wilkes, S. Wongsriruksa, P. Howes, R. Gamester, H. Witchel, M. Conreen, Z. Laughlin, M. Miodownik, Design tools for interdisciplinary translation of material experiences, Mater. Des. 90 (2014) 1228–1237, https://doi.org/10.1016/j.matdes.2015.04.013.
[94] K.E. Overvliet, S. Soto-Faraco, I can't believe this isn't wood! An investigation in the perception of naturalness, Acta Psychol. 136 (2011) 95–111, https://doi.org/10.1016/j.actpsy.2010.10.007.

[95] E. Karana, O. Pedgley, V. Rognoli, A. Korsunsky, Emerging material experiences, Mater. Des. 90 (2016) 1248–1250, https://doi.org/10.1016/j.matdes.2015.07.042.
[96] Y. Liu, Engineering aesthetics and aesthetic ergonomics: theoretical foundations and a dual-process research methodology, Ergonomics 46 (2003) 1273–1292.
[97] I.A. Kim, D. Van Hout, H.S. Lee, Development of a consumer-relevant lexicon for testing kitchen cleansers considering different product usage stages, J. Sens. Stud. 30 (2015) 448–460, https://doi.org/10.1111/joss.12179.
[98] M.C. Zamora, M. Guirao, Performance comparison between trained assessors and wine experts using specific sensory attributes, J. Sens. Stud. 19 (2004) 530–545.
[99] C. Spence, X. Wan, Beverage perception and consumption: the influence of the container on the perception of the contents, Food Qual. Prefer. 39 (2015) 131–140, https://doi.org/10.1016/j.foodqual.2014.07.007.
[100] G. Van Doorn, A. Woods, C.A. Levitan, X. Wan, C. Velasco, C. Bernal-Torres, C. Spence, Does the shape of a cup influence coffee taste expectations? A cross-cultural, online study, Food Qual. Prefer. 56 (2017)https://doi.org/10.1016/j.foodqual.2016.10.013.
[101] E. Karana, P. Hekkert, User-material-product interrelationships in attributing meanings, Int. J. Des. 4 (2010) 43–52.
[102] E. Costell, A comparison of sensory methods in quality control, Food Qual. Prefer. 13 (2002) 341–353, https://doi.org/10.1016/S0950-3293(02)00020-4.
[103] T. Debrosse, M. Pillet, J.L. Maire, N. Baudet, T. Debrosse, M. Pillet, J.L. Maire, N. Baudet, Sensory perception of surfaces quality - industrial practices and prospects, KEER 2010 - Int. Conference Kansei Eng. Emot. Res., Paris 2010, pp. 252–262.
[104] L. Magnier, J. Schoormans, R. Mugge, Judging a product by its cover: packaging sustainability and perceptions of quality in food products, Food Qual. Prefer. 53 (2016) 132–142, https://doi.org/10.1016/j.foodqual.2016.06.006.
[105] C. Spence, M. Zampini, Auditory contributions to multisensory product perception, Acta Acust. United Acust. 92 (2006) 1009–1025.
[106] C. Llinares, A. Page, Application of product differential semantics to quantify purchaser perceptions in housing assessment, Build. Environ. 42 (2007) 2488–2497, https://doi.org/10.1016/j.buildenv.2006.06.012.