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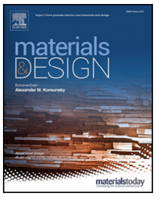

Experiential characterization of materials in product design: A literature review

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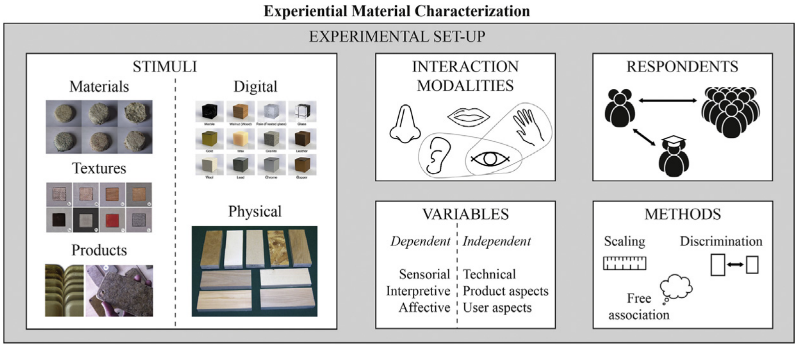
HIGHLIGHTS

- Abstract physical material representations are defined as crucial aspect of multimodal material characterization experiments.
- The integration of extensive user aspects is needed to facilitate consumer segmentation within materials experience context.
- A gap is defined in longitudinal studies to understand the temporality of materials experience.

GRAPHICAL ABSTRACT



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ABSTRACT

Driven by the competitive market that product designers face today, a growing interest emerges in exploring experiential material qualities to enhance product experience. The maturing of the research area calls for standardization to evolve to more streamlined and systematic approaches to conduct characterization experiments. To this aim, we conducted a literature review on 64 cases of experiential characterization studies in the materials and design domain. In this paper, we summarize the current state of the art, formulate an overview to facilitate systematic studies to explore experiential qualities of materials, and identify gaps or opportunities for further research. The presented learnings shed light on the following aspects used in materials experience studies: (i) variables, (ii) stimuli, (iii) interaction modalities, (iv) experimental set-up, (v) methods employed in the conducted studies, and (vi) respondents. Two important gaps were identified with regard to *the physical material representations in an abstract form* as a critical element for *multimodal* material characterization experiments, and to an integration of *extensive user aspects beyond demographic variables to facilitate consumer segmentation*. Additional future research suggestions were formulated, concerning within-material-class comparisons, complementary methods and experimental set-up, and the temporality of materials experience.

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1. Introduction

In product design, materials are considered as the building blocks of physical products and contribute to the product's functionality and meaning. Technical material properties which relate to a materials' physical function can be objectively measured by means of standardized tests [1,2]. This has led to an extensive amount of material data in datasheets and text books. However, over the last decade an increased interest established in materials experience, which brings to the attention the role of materials in affecting our ways of thinking, feeling and doing [3–5]. In a relatively recent study, Giaccardi and Karana [3] defined four experiential levels which constitute our material experiences, namely *sensorial* (e.g., it is soft or rough), *interpretive* (e.g., it is modern or nostalgic), *affective* (e.g., it is surprising, disgusting), and *performative* (e.g., invites me to touch). These four levels interrelate with each other and collectively constitute our ultimate experiences. For example, a material with a high gloss quality (sensorial) can be associated with professionalism or office environment (interpretive); or a material can look hard but feel soft to touch (sensorial), which can elicit surprise (affective) and calls to be caressed (performative).

From the perspective of a product designer, materials should be incorporated early in the design process and should involve both experiential and technical aspects [1,6]. However, no equivalent data support is available for the former characteristics, as the approaches are not correlated with standard, established procedures [7]. This is partly because materials experience is a complex phenomenon with many influential contextual and temporal factors related to the product which embodies materials, context of use and socio-cultural aspects. By contrast, experiential studies in other domains, for example within the food industry, have been well developed since the 1950s, involving very defined tests and well-founded procedures to statistically discriminate or describe food product experiences [8–10]. Recently, these insights have been applied to materials science to measure visual and tactile material properties [7,11,12]. In addition, within architecture, warmth and roughness perception of interior and building materials has been studied as well in relation to technical properties [13,14].

When it comes to a holistic experiential characterization of materials in product design, which takes all four experiential levels into consideration, the tools and methods are limited. There is still a large gap in the domain “to translate subjective experiences of materials into data” [15]. We particularly identified a gap in a straightforward set-up of such materials experience experiments that study the different experiential qualities. Accordingly, this research aims to review previously conducted experiential characterization studies to date, in order to map the critical elements with particular attention to the variables, stimuli, interaction modalities, experimental set-up, employed methods, and respondents. Based on an analysis of their advantages and disadvantages, our aim is to support a better understanding of the phenomenon to facilitate the transition to more streamlined and standardized approaches to conduct experiential material characterization studies in product design. We end with a discussion section addressing gaps and opportunities for further studies within this field.

2. Method

First, a general literature search was conducted in three steps: (i) initial keyword search, (ii) backward and forward search [16], and (iii) additional keyword search. We used four online libraries: ScienceDirect, Scopus, ACM Digital Library, and Web of Knowledge, containing publications of various scientific domains. The native search engines of these databases were used to proceed with initial keyword search. Finally, the full text articles were analysed to extract information about different aspects of the experiments.

2.1. Constructing a list of keywords for initial search

In order to construct a list of search keywords, we have built upon existing frameworks to encompass the foundations of Materials Experience. This subject can be traced back to the work of Manzini [17], The Material of Invention, in which he reported on the **aesthetics of materials** and their role in creating **user experience**. Only later, Ashby and Johnson [1] referred to the **aesthetic experience** and aesthetic **attributes** of materials as well. They assigned a dual role to materials, that is to provide both technical functionality and **product personality**. In this context, they mentioned **sensorial properties** and other **personal** dimensions of materials.

Doordan [18] suggested a triad framework involving the fabrication, application, and **appreciation** of materials, whereas the latter referred to the **consumer's** or **user's reception** of a material embodied in an **artefact**. Zuo et al. [19] deepened this understanding in their **material representation** framework with a focus on **texture perception** in design, and described **perceived characteristics** of materials such as **sensory** properties, **emotional/affective** and **associative/interpretive** dimensions (**meanings, values**). Rognoli and Levi [20] introduced the expressive-sensorial qualities of materials. Finally, we build upon the work within the Materials Experience Lab [21] who extended the **product experience** frameworks or models [22–26] – that include reflective dimensions such as product personality, self-concept and expression [25] – to the context of **Materials Experience**, defined by Karana et al. [27] as “the experiences that people have with, and through, the materials of a product”, with the physical reality of an artefact as one of its prominent sources [28]. In their work, Karana et al. [28] concluded that:

> …designing **meaning**ful materials experiences requires competence in materials that is tied not only to three **experiential** components (i.e., **aesthetics, meanings**, and **emotions**), but also to understanding the possible effects of various design aspects (e.g., **form**, process, finishing), **user** characteristics (e.g., gender, culture, age), and context of use on the resulting materials **experience**. (p. 27).

Overall, experiential **characterization** is a cross-disciplinary subject, including design domains such as material-oriented textile or fashion design, product design, interaction design (both material and immaterial), and architecture, as well as social sciences, psychology, materials science and engineering. For example, Faucheu et al. [12] reported on the **tactile evaluation** of materials and products, while Masson et al. [29] studied **sensory** and **subjective** characteristics of coffee cups. Although many studies could also be found on sensory **analysis** and related methods from the perspective of Food [9,30], ‘food’ was excluded in this particular review as we focussed on the context of product design. Thus, based on the above-mentioned frameworks and a first backward and forward search, additional synonymic keywords (*) were found to complete the list of subtopics and combinable keywords for the literature search, such as multi-modal, haptic, semantics, sample, stimuli, etc.:

- Materials experience, product experience
- Perception, perceived, perceptive*
- Experiential, expression, expressive
- Aesthetic(s), appearance, visual
- Sensorial, sensory, multi-sensory*, multi-modal*, touch, haptic*, tactile
- Meaning(s), associative, associations, interpretive, subjective, semantic(s)*
- Consumer, (end)* user
- Personality, personal, self-expression
- Artefact, form, sample*, stimuli*
- Properties, attributes, characteristics, values, variables*, qualities
- Analysis, evaluation, characterization

For clarity, in this paper we use ‘qualities’ to refer to the distinct nature of materials as received, described and acted-upon by people, and we use the ‘characterization’ to refer to the process by which we reveal these qualities [31]. Thus, besides ‘technical properties’ of materials, we refer to ‘experiential qualities’ such as ‘sensorial attributes’ and ‘interpretive characteristics’.

2.2. Publication pool

We used the above-mentioned keywords and combinations thereof (e.g. “design” and “materials” and “sensory*” and not “food”) to search the libraries of ScienceDirect, Scopus, ACM Digital Library, and Web of Knowledge for relevant publications. For our analysis, we selected only those papers in the initial results, that described or defined user-centred characterizations in any form, if they did address: experiential or (multi)sensory evaluation of material samples or products (see list of Keywords). In addition, the results of the keyword search were limited by publication time between January 2000 and March 2019, based on the dates of the frameworks in the previous Section. Initial inclusion resulted in 68 articles, from which 42 were selected as relevant based upon abstract that involved characterization experiments. A backward and forward search of these articles led to 24 new articles. Finally, all articles were screened based on their full texts with a focus on method and results, leading to the discarding of 16 papers. In total, 80 articles were screened whereof 50 of them were included for this review.

The following descriptive data were collected: title of the article, authors' names, year of publication, type of publication (e.g. journal), publication name (e.g. Materials and Design), five-year impact factor of journal articles or CORE rank of conference proceedings, author's affiliation, number of citations, and finally the article's keywords that facilitated the refinement of the described search. Impact factor or conference rank, and number of citations expressed the scientific relevance, indicating the validity and scientific interest in the topic. Year of publication and authors' affiliation showed how the interest was distributed timewise and geographically.

The herein presented literature review builds on 50 articles that were found in both journals (40) and conference proceedings (10). Based on an initial screening of the articles, three different focusses within the conducted experiments could be detected, depending on their main focus. First of all, 11 articles focused on the evaluation of Products as a whole (e.g. hairdryers [32] and hammers [33]), while 30 articles were directed to Materials in particular (e.g. isolated material samples [34] or materialized in existing products [35]), and 9 articles even investigated Textures specifically (regardless the material on which it is applied [36]). Table 1 sums up the titles, number of individual findings, and impact or rank of the journals and conferences respectively, including the references of the 50 articles, subdivided over the three focusses, and chronologically ordered within each category.

Next, the 50 full text articles were analysed in-depth to extract information about different aspects of the described methods in the context of Experiential Material Characterization. However, as several articles discuss multiple studies, we could actually include 64 conducted studies in total. After coding, the following subjects were found in the literature and selected as relevant encryption categories for organizing and providing a framework for the literature review: (i) experiential and independent variables, (ii) stimuli used in experiential characterization studies, (iii) interaction modalities with stimuli, (iv) experimental set-up, (v) methods employed in the conducted studies, and (vi) respondents, complemented with Experiment duration, Data analysis, Study limitations, and Conclusions. All information was collected in an Excel spreadsheet. In the following sections, the results are discussed according to the six main themes above, as building blocks of the total experimental set-up.

Table 1
Distribution of articles (and studies) over the three focusses, with Thomson Reuters 5-Year impact factor/CORE rank.

Sources

Journals (N = 40)	#	IF	Conferences (N = 10)	#	Rank
Materials & Design	9	4.75	ICED: International Conference on Engineering Design	3	B
International Journal of Design	6	1.94	IDETC/CIE ASME: International Design Engineering Technical Conferences & Computers and Information in Engineering	2	N/A
International Journal of Industrial Ergonomics	6	1.61	International Academic MindTrek Conference	1	N/A
Acta Psychologica	3	2.22	ACM SIGGRAPH: Symposium on Applied Perception	1	C
Applied Ergonomics	2	2.66	IEA: Congress of the International Ergonomics Association	1	B
Food Quality and Preference	2	4.19	D&E: International Conference on Design & Emotion	1	A
Journal of Cleaner Production	1	6.35	NordDesign Conference	1	B
Design Journal	1	N/A			
International Journal of Designed Objects	1	N/A			
Vision Research	1	2.0			
Building and Environment	1	5.22			
Color Research & Application	1	1.03			
Intern. Journal on Interactive Design and Manufacturing	1	N/A			
Sustainability	1	2.18			
Wear	1	3.27			
Journal of Wood Science	1	1.30			
Consciousness and Cognition	1	2.52			
Design Studies	1	2.64			

Articles

Within material focus	Within texture focus	Within product focus
[37] Giboreau et al., 2001 (2 studies)	[36] Picard et al., 2003 (2 studies)	[66] Hsu, Chuang, & Chang, 2000
[38] Karana, Weelderen, & Woerden, 2007 (3 studies)	[61] Chen et al., 2009	[67] Petiot & Yannou, 2004
[39] Bergmann Tiest & Kappers, 2007	[62] Hope, Jones, & Zuo, 2013	[68] Chang & Wu, 2007
[40] Chen et al., 2009 (2 studies)	[11] D'Olivo et al., 2013	[69] Artacho-Ramírez, Diego-Mas, & Alcaide-Marzal, 2008
[35] Karana, Hekkert, & Kandachar, 2009	[63] Chen & Chuang, 2014	[70] Mugge, Govers, & Schoormans, 2009
[41] Karana & Hekkert, 2010	[64] Etzi, Spence, & Gallace, 2014 (2 studies)	[71] Chang & Wu, 2009
[42] Høibø & Nyrud, 2010 (2 studies)	[12] Faucheu et al., 2015	[33] Vergara et al., 2011
[43] Fenko, Schifferstein, & Hekkert, 2010	[65] Yanagisawa & Takatsuji, 2015	[72] Mugge, 2011 (2 studies)
[44] Georgiev & Nagai, 2011	[32] Zuo et al., 2016	[73] Agost & Vergara, 2014
[34] Overvliet & Soto-Faraco, 2011		[29] Masson et al., 2016
[13] Wastiels et al., 2012b		[74] Kapkın & Joines, 2018
[45] Crippa, Rognoli, & Levi, 2012		
[14] Wastiels et al., 2012a (2 studies)		
[46] Lindberg et al., 2013		
[47] Wastiels et al., 2013		
[48] Karana & Nijkamp, 2014		
[49] Martín et al., 2015 (2 studies)		
[50] Fujisaki, Tokita, & Kariya, 2015		
[51] Silvennoinen et al., 2015		
[15] Wilkes et al., 2016 (4 studies)		
[52] Overvliet, Karana, & Soto-Faraco, 2016		
[53] Lilley et al., 2016		
[54] Sauerwein, Karana, & Rognoli, 2017 (2 studies)		
[55] Piselli et al., 2017		
[56] Ndengue, Juganaru-Mathieu, & Faucheu, 2017		
[57] Ulusoy & Nilgün, 2017		
[58] Choi, 2017		
[7] Piselli et al., 2018		
[59] Bahrudin & Aurisicchio, 2018		
[60] Veelaert et al., 2018		
30 articles — 41 studies	9 articles — 11 studies	11 articles — 12 studies

3. Results

3.1. Variables

3.1.1. Dependent experiential variables

As discussed in the introduction on materials experience, experiential characterization of materials can manifest on different levels, and both from a holistic and a detailed perspective. We build upon the Materials Experience framework [4] for analysing the dependent variables, as this is considered the most relevant framework in literature that provides an extensive understanding of material-people relationships in design. Other works in literature either elaborates on understanding one experiential level, or focusses on only sensory perception of materials. Furthermore, substantiated by many other papers and used as a reference within the field, Camere and Karana [75] recently incorporated this framework and four experiential levels in their Ma2E4 toolkit: (i) *sensorial* level, (ii) *interpretive* level (i.e. associations or meanings), (iii) *affective* level (i.e. emotions), and (iv) performative level (i.e. actions) [3]. However, the latter has not yet been studied in found articles and was therefore discarded from cross Table 2 below. Moreover, within the affective level, seven studies specifically mention material preference (like-dislike) that incorporates emotional justification and cognitive reasoning, e.g. [7,42,50,53,61,62,66].

Table 2
Frequencies of experiential levels within Material, Texture and Product focus.

	Sensorial	Interpretive	Affective	Total
Material	27	19	11	57
Texture	11	5	5	21
Product	2	11	4	17
Total	40	35	20	95

Overall, Table 2 shows that sensorial attributes (42%) and interpretive characteristics (37%) were most often involved as dependent variables in the studied experiments. However, sensorial attributes (47%) were most common within a material (and texture) focus, while within a product focus mostly interpretive characteristics (65%) were adopted. When looking at combinations of multiple experiential levels in one assessment, within a material focus, 68% of the studies stayed within one level, while 16% involved two levels and 16% three levels. Within a texture focus, 36% involved merely one level, 45% two levels and 18% three levels. Finally, within a product focus, 45% focused on one level and 55% on two levels.

Next to the twelve sensorial attributes that are incorporated in the Ma2E4 toolkit (Hard-Soft, Smooth-Rough, Matte-Glossy, Not Reflective-Reflective, Cold-Warm, Not Elastic-Elastic, Opaque-Transparent, Tough-Ductile, Strong-Weak, Light-Heavy, Regular Texture-Irregular Texture, Fibred-Not fibred), various other properties were mentioned in the articles, such as Scratchability, Acoustics, Stiffness, etc. All in all, Smooth-Rough was mentioned most (28×), followed by Hard-Soft (24×) and Cold-Warm (22×). Also, Matte-Glossy (9×), Sticky-Non-Sticky (9×), Moist-Dry (7×) were common.

Furthermore, the list of interpretive characteristics is even longer, as compared to the eleven meanings in the vocabulary of the Ma2E4 toolkit (Aggressive-Calm, Cosy-Aloof, Elegant-Vulgar, Frivolous-Sober, Futuristic-Nostalgic, Masculine-Feminine, Ordinary-Strange, Sexy-Not Sexy, Toylike-Professional, Natural-Unnatural, Handcrafted-Manufactured). Luxurious/Cheap-Expensive and Playful/Cheerful-Dull were each counted seven times, while Masculine-Feminine, Natural-Unnatural, Modern-Traditional were all counted six times. Other common meanings are Beautiful-Ugly (5×), Ordinary-Strange (5×), Elegant-Vulgar (4×), Futuristic-Nostalgic (4×), High Quality-Low Quality (4×), Old-New (4×), Aggressive-Calm (3×), Cosy-Aloof (3×), Sexy-Not sexy (3×), Toy like-Professional (3×), Lasting-Disposal (3×), and Safe-Unsafe (3×).

Finally, Pleasant-Unpleasant (8×) is mostly mentioned within the emotional attributes, compared to the other emotions used within the PrEmo tool of Desmet [24]. Crippa et al. [45] state that in general, emotions evoked by materials are rather weak, however, Ludden, Schifferstein and Hekkert [76] showed that materials are one of the most effective tools for eliciting ‘surprise’, and Karana and Van Kesteren [77] reported that also for ‘love’ and ‘hate’ materials play a substantial role.

3.1.2. Independent experiential variables

In addition to the previously mentioned dependent variables that are frequently studied, different independent variables were involved as well, mainly within material focus (63%), as shown in Table 3. Although this review focused on experiential qualities of materials, twelve studies also included *technical* material properties – that can be objectively measured – and searched for a correlation with subjective perceptions of these properties, as was first attempted by Rognoli [78] in the Expressive-Sensorial Atlas. In this regard, material roughness was often incorporated [7,39,46,55], as well as warmth [13] or even both [14,40,61]. Moreover, Wilkes et al. [15] used different developed tools and physical property data to predict acoustics, taste and touch perception.

Since Karana's Meanings of Materials Model presents “the meaning of a material as a relational concept in which material, product and user are jointly effective” [78], independent variables can be included from both a *product* or *user* perspective. Within the former, product's function and shape or form can affect the materials experience, while within the latter, a user's age, gender, culture or personal values can be included. Overall, the effect of form was considered eight times, mainly focusing on form curvature that influences the material's expression.

Although recognized as an important factor in literature, and repeatedly mentioned in the discussion or future research [48,57,62,63,66,80], few studies actually investigated in depth the effect of user aspects as moderating aspects of the materials experience, but remained rather limited to the demographic variables. Ulusoy and Nilgün [57] stated that meanings are related to society and cultural background, making them more sensitive than sensorial attributes for that matter. Currently, only two studies were found that involved personal or expressive values of consumers, i.e. in the form of Schwartz personal values [60] and reference personality values [72]. The former concluded that relationships can be found between someone's self-expression, their material preference and the expressive values that are seen in a material. The latter stated that “not only target customers' demographic data but specifically their values and criteria must be taken into account from the beginning of the development process”. In addition, in her work on product personality, Mugge [72] reported that specific personality of the respondents was not considered. However, building on the self-congruity theory [81], she adduced that a person's personality is a potential moderator and should thus be investigated in future studies.

3.2. Stimuli used in product and materials experience studies

3.2.1. Materials (type and class)

The studied stimuli concerned different materials in different material classes, such as textile (natural or synthetic fabrics), metal, plastic, composite (compositions of plastics with other materials), elastomer, wood, ceramic, glass, and other (e.g. natural materials). Within one study, the number of material classes went up to eight different classes, however with a median of only two classes for both material and texture focus.

Table 4 summarizes the material stimuli used in experiments within each material class. Overall, metals were used 24 times, followed by both plastics and wood with 21 times, and textile 18 times. Within texture focus, 28% of the stimuli were textiles, representing the great interest in texture and touch within textile research [37]. Within material focus, metals, woods and plastics appeared the most, representing the most common materials in industrial design. However, when looking at the studies focusing on comparing one specific material to another one of the same class, clearly textiles (n = 6), wood (n = 5) and other materials (n = 6) are most often examined. Studies concerning only plastics, glass or rubber materials have not been found.

Two main reasons could be detected for the studies' material choice. Firstly, materials were often selected as being familiar, most typical or commonly used in everyday products [39,41,44,53,65], in construction/architecture or interior design [13,46,47,57], in other specific sectors [61,64] such as automotive fabrics [36,37], or distributed along several material classes [49,60]. Secondly, materials were often selected

Table 3

Frequencies of various technical, product and user aspects within the three focusses.

	Technical	Function	Shape/form	Culture	Gender	Age	Personal values	Total
		Product aspects		User aspects				
Material	12	1	4	2	1	0	1	22
Texture	1	0	0	1	0	0	0	2
Product	0	1	4	0	1	1	1	11
Total	13	2	8	3	2	1	2	35

Table 4
Frequencies of different material classes studied in articles within Material and Texture focus.

	Textile/leather	Metal	Plastic	Composite	Elastomer/rubber	Wood	Ceramic/stone	Glass	Other	Total
Material	11	21	17	2	6	19	10	10	16	112
Texture	7	3	4	2	2	2	0	1	4	25
Total	18	24	21	4	8	21	10	11	20	137

to cover relative heterogeneity, assuring observable differences, and providing a wide and diverse range of tactile/physical properties, such as roughness, and aesthetic properties, such as colour and appearance [11,13,15,39,40,47,49,50,53,61]. When investigating free impressions, Georgiev and Nagai [44] made a distinction based on frequently touched and sometimes touched materials.

Moreover, five studies conducted a pre-study to reduce and select the final material stimuli set. Hereby, duplication could be reduced while maintaining a range of variable values [40], or the strongest ratings on particular attributes were selected [49], such as the ugliest and most beautiful samples [54] or the most pleasant and unpleasant ratings [64].

3.2.2. Material representations

Several material representations were used in the studies (frequencies shown in Table 5), going from abstract words (e.g. “plastic”, “metal” and “wood), to digital renders or photographs of the stimuli, and finally to physical samples. Martín et al. [49] state that “physical samples are still the standard”. Whether digital or physical, materials could also be used in different forms. Among the various studies, often multiple samples are evaluated and compared, going from a flat material sample (decontextualized), to an abstract form, or to an actual product (contextualized). Fig. 1 shows several examples of used material representations such as text-digital models, flat samples, blocked samples, and products.

Representing materials by means of words was only done twice, reflecting only on general material classes [58], and rather pre-studying the effect of material form on meaning [38]. The use of *photographs* or *rendered images* was mostly used in the context of a multimodal comparison [33,49,64,69], in the case of materials applied in products [59], or when adapting curvature of specific products in an online survey [72]. Practical advantages are time-saving surveys online and a wider range of materials while obtaining a controlled and equal presentation or context [60,73]. The disadvantage is the limitation to one modality, in contrast to a multimodal materials experience. Nevertheless, it could show resemblance with a realistic (pre) purchase situation [69], such as a catalogue or web shop, where products can be compared with each other as well [72].

By contrast, the vast majority of the reviewed studies utilized tangible *physical samples*, either decontextualized material samples or contextualized product samples. Within the material and texture focus, 75% of the cases used small and *flat material samples* devoid of context, differing in terms of shape, size, and preparation. 50% was found rectangular, 46% square and 4% round, with a surface area between 15 cm2 [56] and 1600 cm2 (Md = 98 cm2) so that the surface could be touched by the whole hand [13,47]. Samples were usually provided as free-standing pieces or cut-outs, but could also be mounted on foam [37] or MDF board for an equal background [39,62], or even mounted in standard sample holders with a specific window to display the top surface, isolated from the background [7,11,12,34,50,52,54]. In one case, the holders were weighted to overwrite the material's weight perception [15]. In their discussion, Piselli et al. [7] recommended to conduct sensory tests with *abstract shaped specimens*.

Following the MOM model [82], the appraisal of materials also depends on the application context [59]. Crippa et al. [45] stated that “materials are experienced mainly through the product they are embodied in”. Consequently, besides product related studies, also within material or texture related studies, *products were used as material representations* (22%), going from imaginary products to isomorphic material-object sets and product applications. Referring to [83], Wilkes et al. [15] in particular investigated sound and taste perception by means of isomorphic tuning forks and spoons. In other studies, products were used for various reasons, including (i) product type or value, (ii) shape/appearance, (iii) function/context, (iv) familiarity, and (v) practical considerations.

First, products were chosen from different categories (kitchen products, hi-tech products, household appliances, personal or fashion products, and interior products) that are mentioned most frequently as cherished household possessions, and most involved in creating the owner's identity [68]. For example, both car and vacuum cleaner [70] and ceramic flooring tiles [73] were chosen to represent products with high or low symbolic value, while waste basket and lighter [41] and breakfast tray and smartphone case [48] were selected for high or low personal value.

Second, most studies aimed at a great variety of appearances both in colour [29,56], size and shape going from very angular or sharp-edged to very curved or rounded [41,72], as sufficient variation was stated to be essential for a reliable scale [70]. In contrast, some studies consciously kept the shape constant, as was the case with smartphone cases [56] and bowls with both concave and convex surfaces [45]. In the latter study, nine bowls were used, however, with no uniformity or equal wall thicknesses, and their perception could be associated with food because of the product's function. In addition, several studies mentioned an appropriate level of complexity, choosing simple forms with a minimum of production details or additional elements such as buttons and screens [35,41,69,74]. Only one study deliberately varied CD players with both low and high complexity by means of shape and buttons [72].

Third, products were chosen as stimuli for being objects with an identified function [56], e.g. smartphone covers, that provide contextual information [74], e.g. soap dispensers, leading to studies with the same products having the same function [29,45], e.g. bowls or coffee cups, as opposed to studies with a set of products that was chosen to vary the functionalities in different contexts [48,72], e.g. smartphone cases and trays.

Fourth, products such as a bowl [45], razor, wallet, backpack, sunglasses, toothbrush, cool box, plate [59], hammer [33], CD player [72], hard disk drive, soap dispenser [74] were selected because they

Table 5
Frequencies of material representations within Material, Texture, and Product focus.

	Words	Render	Photo	Physical	Total	Flat sample	Abstract form	Product	Total
Material	2	2	4	35	43	28	2	10	40
Texture	0	0	0	11	11	10	0	1	11
Product	0	2	6	7	15	0	0	12	12
Total	2	4	10	53	70	38	2	23	64

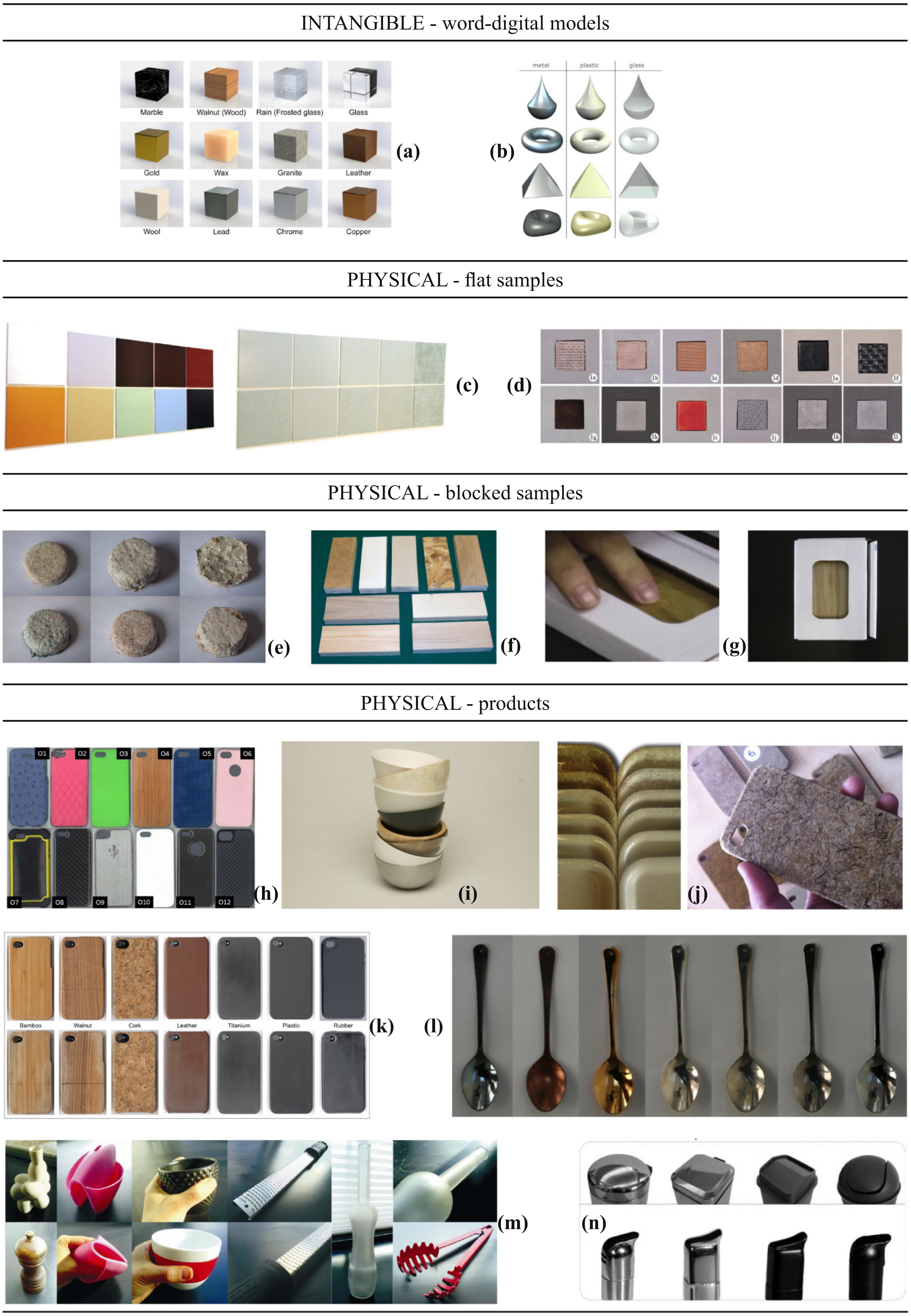

Fig. 1. Overview of selection of used material stimuli in reviewed papers: word-digital models (a) [60], (b) [38], flat samples (c) [14], (d) [11]; blocked samples (e) [54], (f) [46], (g) [50]; and products (h) [56], (i) [45], (j) [48], (k) [53], (l) [15], (m) [35] (n) [41]. Reprinted from [60], Copyright (2019), with permission from Springer Nature. Reprinted from [38], Karana ©. Reprinted from [14], Copyright (2012), with permission from Elsevier. Reprinted from [11], D'Olivo ©, with permission from Design Society. Reprinted from [54], in accordance with Creative Commons regulations. Reprinted from [46], Copyright (2013), with permission from Elsevier. Reprinted from [50], Copyright (2015), with permission from Elsevier. Reprinted from [56], Juganaru-Mathieu ©, with permission from Design Society. Reprinted from [45], in accordance with Creative Commons regulations. Reprinted from [48], Copyright (2014), with permission from Elsevier. Reprinted from [53], in accordance with Creative Commons regulations. Reprinted from [15], Copyright (2016), with permission from Elsevier. Reprinted from [35], Copyright (2009), with permission from ASME. Reprinted from [41], in accordance with Creative Commons regulations.`

represent concrete and familiar, daily consumer products that are commercially available and mature with a high market penetration degree.

Fifth, products had to be able to be purchased in a great variety [70], be simple enough to reproduce without difficulties, or be easily manipulated experimentally in a lab [43,69]. Karana and Nijkamp [48] and Lilley et al. [53] chose to employ mobile phone cases (both) and trays (only Karana and Nijkamp) as a rapid and cost-effective method to interact with different materials in the same object.

Finally, when examining the number of stimuli – whether they are material samples or product stimuli – the number of stimuli in one study varied between 3 and 96 (Md = 10) within the material focus, 5 and 51 (Md = 13) within texture focus, and 4 and 120 (Md = 16) within product focus.

3.3. Interaction modalities with stimuli (material representations)

Based on the studied articles, seven different levels of modalities were detected referring to the senses that were involved in the interaction and manipulation of material (or product) stimuli. Within a material focus, a few specific cases investigated (i) *auditory*, (ii) *audio-visual*, or (iii) *oral* (taste) perception of materials. However, Sauerwein et al. [54] state that “in material appraisals, touch and vision are the most dominant sensorial modalities [5,84]”.

The unimodal (iv) *visual* condition implies that participants are merely allowed to look at stimuli, whether it is presented in a photo, render, or physically present. Despite such static evaluation, our mental process could create an integrated representation of both visual and tactile content. Indeed, “in apperception process, information from different sensory modalities as well as already existing mental information contents are integrated into a meaningful mental representation. Apperception can be described as ‘seeing something as something’” [51].

By contrast, a solely tactile condition or (v) *blind touch* only involves haptic sense avoids focus towards sight as the primary sense, and “reduces potential bias attributable to preconceptions about certain materials” [53], which could explain its frequent occurrence within texture-focused research. Moreover, a distinction could be made between passive and active stimulation, wherein the latter implies that “the stimulus is stationary and the subject actively explores [the] object or surface” [85], and the former means that the experimenter applies and moves the stimuli on the participant's cheek, hand, or arm. Lindberg et al. [46] were able to control unimodal tactility by blocking vision and hearing with black painted goggles, noise-cancelling headphones, and soft pads between samples and table. Next, (vi) *visual touch* integrates a tactile sensation that could either complement or contradict the visual perception, which is defined as visual-tactile (in)congruity [11]. Yet, this dual modality entails a rather static touch, e.g. index finger touches sample surface. Finally, when vision is again included as well, we reach ultimate multimodality by means of (vii) *free exploration* or dynamic touch [62] in which the sample is grabbed, picked up, rubbed and fully assessed by rubbing it between thumb and index finger, manipulated, and “played with” [63]. Chen and Chuang [63] suggested that further researches should investigate the opportunities of such extensive contact when exploring material expressions. Giboreau et al. [37] observed four most common one-hand gestures that were performed to describe tactile properties of fabrics, as shown in Fig. 2.

Table 6 summarizes the frequencies of these modalities within material, texture and product focused studies. Overall, the singular modalities of visual and blind touch perception were the most common in past research, and 27% of the studies mentioned to compare results of multiple modalities. Within a product focus, either visual (57%) or free exploration (36%) were preferred, while within texture focus, blind touch (50%), visual touch (22%) and visual perception (17%) were found. Finally, within a material focus, sample interaction was more evenly distributed over visual (27%), blind touch (23%), visual touch (19%), and free exploration (19%), apart from a few specific cases that included other senses.

Conclusively, visual stimulation is most prominent in existing research, which makes sense as visual appearance is a “critical determinant of consumer response and product success [68,86,87]. Indeed, Artacho-Ramírez et al. [67] state that:

> …in the actual marketplace there is a wide range of similar products in terms of functionality, price and quality. In this kinds of markets, attention is increasingly focused on the visual characteristics of products, as their functionality and performance are often taken for granted [86].

However, while the visual sense clearly has a key influence only in the consumer's (pre) purchase decision process (or in web shop situations), the majority of product uses are operated through physical contact with products, increasing the importance of the tactile sense in product design nowadays [63]. Moreover, human perception is inherently multisensory [88], thus the senses cannot be isolated when human behaviour is analysed, but a holistic, multimodal approach is needed in sensory material evaluation [11]. Ndengue et al. [56] argue that integration across senses can lead to several advantages:

Combining complementary sources of information is advantageous because it extends the range and variety of what can be perceived from one sense in isolation and can reduced perceptual ambiguity. Furthermore, integrating multiple sensory sources usually leads to improved perceptual performance, more precise judgements and enhances detection of stimuli. (p. 431).

Additionally, different sensorial attributes require different or even multiple modalities for perception, e.g. a material's colour is perceived by vision and its hardness by touch, while the roughness of a material can be assessed by both looking at it and touching it [65].

3.4. Experimental set-up

Most papers reported the conditions of their experimental set-ups, only some of which include full laboratory environment. First of all, in the context of (visual) material characterization, twenty studies indicated to control the light conditions, and eight studies also mentioned constant room temperature (between 20 and 27 °C). Concerning the former, Høibø and Nyrud [42] specifically mentioned the ISO 1988 standard, while Overvliet et al. [34,52] used a photographic daylight tent, illuminated by 6 × 50 W white daylight 5000 K light bulbs that provided constant lighting conditions with scattered light, and others blind windows and doors to control diffuse, artificial lighting [12,14,39,49,65] or maintain natural lighting. In addition, other senses can be controlled or restricted as well, for example using noise cancelling headphones [34,46,50], blocking vision by means of black painted goggles [46,63] or blindfolds, and using ear plugs to dampen any sounds [64]. By contrast, Wastiels et al. [47] stated that auditory, smell and taste stimuli were constant for all test conditions and could thus be ignored.

Clearly, most studies took place in isolated test rooms, where tables were set-up that displayed the various samples, representing a physical scale or ranking, and participants were seated in front [37,66,71]. Hope et al. [62] used a benchmark material as a reference for assessing texture by positioning it in the middle of the scale. This way, equal interpretation of attributes in between participants was increased. Furthermore, in the case of Napping procedures [11,12], a table cloth or area of 75 × 75 cm was delimited, representing a physical, two-dimensional scale. Piselli et al. [55] displayed their samples on a stand at 45° to guarantee the same incident lighting angle on a material's surface, while Wastiels et al. [47] positioned them vertically at eye-height.

Overall, several studies involved a custom-made experiment box with one open side — with or without curtain to hide the sample in blind conditions [36,40,43,51,61]. For example, Ulusoy and Nilgün [57] employed a box of 40 × 50 × 50 cm and a floor-fixed chair to maintain a 50 cm viewing distance. Furthermore, three studies described a very precise and practical experimental set-up (see Fig. 3).

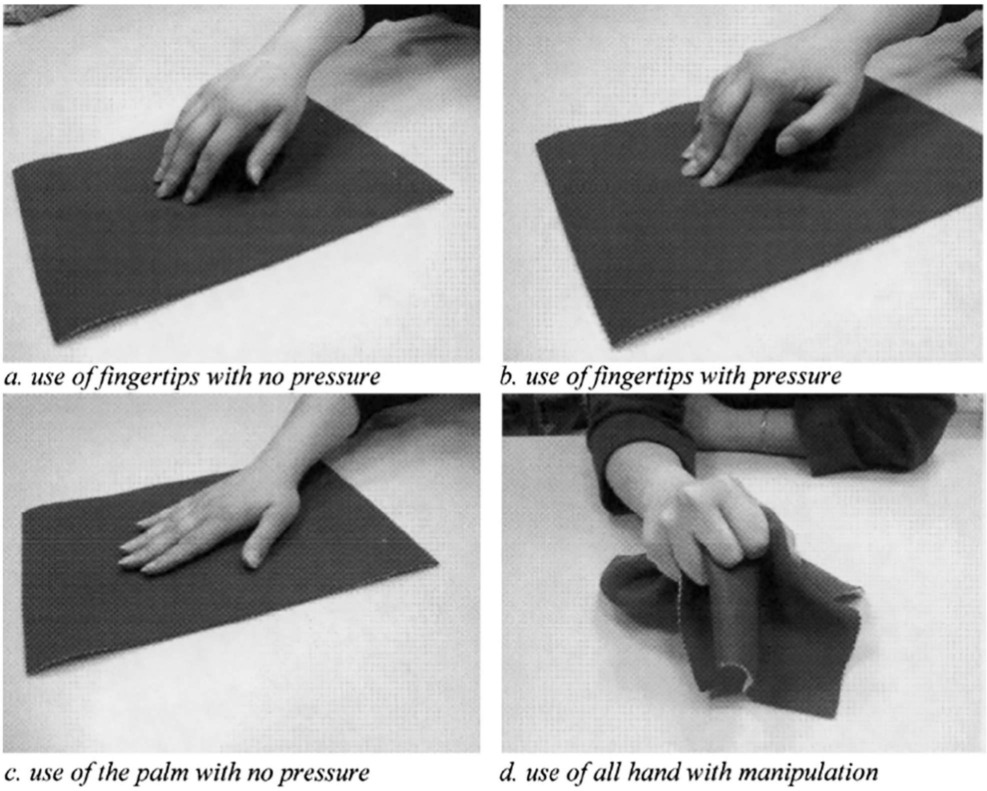
a. use of fingertips with no pressure
b. use of fingertips with pressure
c. use of the palm with no pressure
d. use of all hand with manipulation

Fig. 2. Photos of [37] showing most common gestures with fabrics. Reprtined from [37], Copyright (2001), with permission from Elsevier.

First, Overvliet et al. [34,52] repeatedly used a 80 × 80 × 80 cm photographic tent, covered with white cloth for tactile exploration, and with an opening in the middle of the back so the experimenter can change the sample. The samples were placed on a 50 cm viewing distance with an angle of 45°. Participants needed to maintain a stable head posture while exploring each sample for exactly 3 s in each modality, making circular movements with the index finger's pad of their dominant hand. Second, Faucheu et al. [12] employed a translucent table top as a napping area, with (UV) light and a camera underneath that recognizes QR codes on the bottom of the material samples in order to automatically log the napping results of a participant. Third, Yanagisawa and Takatsuji [65] operated a half-mirror apparatus that allowed them to virtually synthesize differing combinations of visual and tactile stimuli. At 45° in the box, a half-mirror plate was placed to separate it in two spaces, one for the visual sample and one for the tactile sample, each placed horizontally. Both halves had a window, either to look or to touch the sample, and a modulated light allowed to adjust luminance accordingly. The participant was seated on a chair in front of the table with the box and could touch the sample using his/her right index finger.

Finally, 58% of the studies mention a random order in which the material stimuli are presented, and 14% mention a random order in which the variables or scale items are assessed.

3.4.1. Duration of test

Forty-four percent of the studies specifically mentioned the average duration of their experiments, leading to an average time of 37.1 min per participant. However, if we excluded the three cases that involve notable time-consuming interview techniques, the average would drop to 30.3 min. Nevertheless, in general experiments in the context of experiential characterization could be considered not time efficient, and near a typical concentration limit of 40 min [40]. Duration measurements of Faucheu [12] et al. and Wastiels et al. [13] showed contradictory results between different modalities. The former reported that the tactile condition took twice the time of the visual or visuo-tactile condition, while the latter noted a clearly shorter time for the tactile condition compared to visual or visuo-tactile. Also, in the study concerning roughness perception of Bergmann Tiest and Kappers [39], the visual condition (38 min) was significantly faster that the tactile condition (69.5 min).

All in all, some researchers countered the time disadvantage by distributing respondents over specific conditions. For example, Wastiels et al. [13] used a between-subjects design where participants were randomly assigned to a condition (visual, tactile or visuo-tactile), as did [51]. Karana and Nijkamp [48] eased the judgment process and reduced a single session time by dividing their sample set of twelve versions of two products to two respondent groups, with each group evaluating the different material versions of the same product, as did [57,69,72]

Table 6
Frequencies of included modalities within Material, Texture, and Product focus.

	Auditory	Audio-visual	Oral	Visual	Blind touch	Visual touch	Free exploration	Total
Material	4	1	2	17	14	12	12	62
Texture	0	0	0	3	9	4	2	18
Product	0	0	0	8	0	1	5	14
Total	4	1	2	28	23	17	19	94

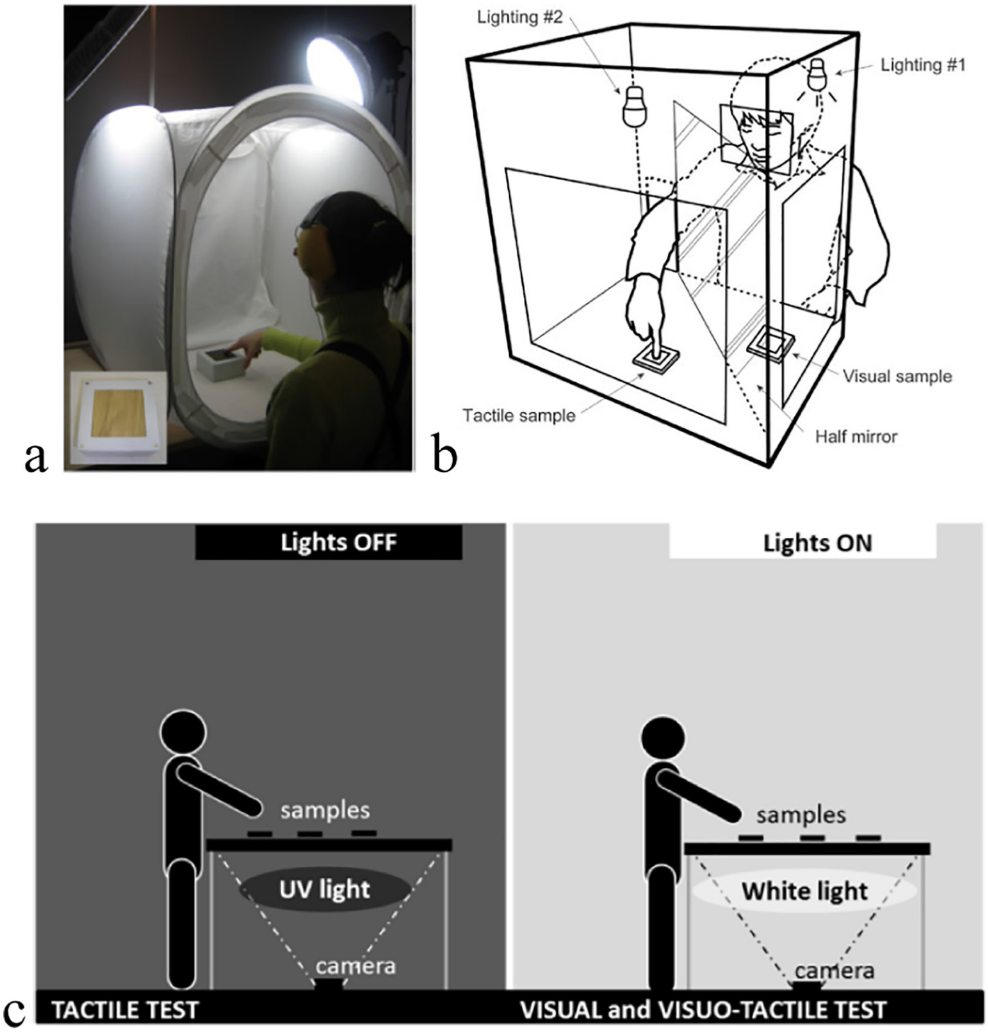

Fig. 3. Three experimental set-ups used in studies by (a) [52]; (b) [65]; (c) [12]. Reprinted from [52], Copyright (2016), with permission from Elsevier. Reprinted from [65], in accordance with Creative Commons regulations. Reprinted from [12], Faucheu ©, with permission from Design Society.

with one model per participant, and [55] who provided fifteen out of thirty combinations for each participant.

3.5. Methods employed in the conducted studies

In the context of marketing research and sensory evaluations, various methods can be proposed to study the perception of consumers and create perceptual maps [67,89]. Although this has been primarily developed for the food industry, explorations into the application on non-food products or even materials can be found as well [7,90]. Overall, such sensory tests are subdivided in three categories: (i) *descriptive* analysis to characterize sensory attributes, (ii) *discrimination* tests to examine similarities or differences, and (iii) more subjective *hedonic* tests to assess consumers' preferences [7], albeit the latter can be considered as a specific descriptive method. In addition, (iv) open interviews or *free impressions* can also be recorded to evaluate a stimulus. Table 7 shows the usage of different tests within the three main categories, that will be further described below, and within a material, texture or product focus.

3.5.1. Descriptive testing

Descriptive testing is usually done by means of scaling methods, elaborating on perceived experiential qualities, their intensity and direction. In this regard, the *semantic differential method* (SDM) developed by Osgood et al. [91] was probably the most frequently used [66,67], as is shown in Table 7 with 40% of the observations. It consists of *unstructured* scales with verbal anchors at beginning and end by various semantic attributes, that are defined by pairs of antonymous or *bipolar* adjectives. Fig. 4 shows an example of a semantic differential scale used in [53]. Often, factor analysis or principal component analysis

Table 7
Frequencies of measure methods within Material, Texture, and Product focus.

	SDM	Unipolar	Binary decision	Ranking	MDS (sorted napping)	Pairwise comparison	Hierarchical grouping	Free associations	Total
	Scaling			Discrimination				Free	
Material	17	13	3	4	2	1	1	5	46
Texture	6	1	0	0	3	0	0	2	12
Product	8	4	0	0	2	1	1	3	19
Total	31	18	3	4	7	2	2	10	77

was applied to reduce the number of items and to find underlying correlations [67]. In the context of materials experience, the SDM method was applied in the sensorial scales of Karana et al. [79], and also used by [35,54], where the items were reinforced and clarified by the use of pictograms. They stated that in this way, even untrained respondents can reliably assess sensorial attributes, leading to a higher agreement and lower ambiguity of personal interpretations.

However, Kapkın and Joines [74] argued that such bipolar scales presume that two experiential qualities are antonyms, whereas contradictory meanings can co-exist and thus be independent. Consequently, also *structured, unipolar scales* can be applied to evaluate to what extent a certain characteristic is present or absent. This scale is labelled with numbers and/or descriptive terms going for example from 'not at all …' to 'completely …'.

Choi [58] stated that untrained respondents "are not always able to clearly specify their perceptions of materials and it is very difficult for participants to differentiate material perceptions semantically through a seven point scale". Consequently, a simple *binary decision* or digital-logic approach can be employed as well, which allows to indicate whether a characteristic is present or not, but not to what extent.

When looking at the 49 experiments with scales in the reviewed papers, the scales consisted of at least five points and maximum hundred points, with an average of ten points (Md = 7). Lilley et al. [53] preferred an odd number of scale points, as this provides a midpoint for neutrality. Similarly, 85% of the scaling experiments employed an odd number as well. Moreover, each experiment evaluated one to thirty-four different items, with an average of ten items.

3.5.2. Discrimination testing

While scaling methods usually involve a single stimulus to evaluate in an absolute manner and without the presence of a reference framework or reference stimuli, discrimination tests are used to determine relative differences among two or more samples. Indeed, Cleaver [92] pointed out that human beings "perform better when assessing products in relation to another rather than in absolute terms", as perception is inherently more comparative. Hence, holistic approaches or multi-attribute issues are becoming increasingly popular, especially in sensory analysis [93].

First, a *ranking test* is an easy and fast method where the participant has order a set of samples according to a specific attribute from least to most, however combining the limited data from multiple rankings is rather difficult [7,92].

Second, *multidimensional scaling* (MDS) is used for visualizing the distances between stimuli, and thus the degree of similarity as well, within a perceptual space that is not limited to two dimensions [67]. A specific method within sensorial analysis, derived from a food focus, is the *napping* test that has also been applied to sensory evaluation of materials, and is easy and fast to set up, taking about 15 min and ten assessors to evaluate a large sample set of minimum ten stimuli [7,12,56,93]. Pagès et al. [92] define this procedure as follows:

> …The set of *I* products is presented to the panellists who are asked to position the products on a large sheet of paper (tablecloth) according to their similarity, i.e., two products are all the more close (on the tablecloth) as they look alike and all the more distant as they differ. For a given panellist, the data can be assimilated to the two coordinates of the products on the tablecloth. For each of these procedures, panellists are informed of the overall character of the evaluation (hence, the term "holistic approach") and of the fact that they must use their own criteria, i.e., those which are the most important to them.

This process can also be enhanced by asking assessors to characterize the groups or the samples with associated descriptions and attributes. In addition, two variants of Napping exist: Sorted Napping and Mapping. *Sorted napping* is a combination of Napping and a categorization task where samples are grouped according to their resemblances [93], while *Mapping* is a combination of Napping and a ranking task where two descriptors are used as dimensions of a sensory space or map, and their correlation can be studied [7], as shown in Fig. 5.

Third, a *paired comparison* (PC) test is a fast way to examine whether relative differences can be detected with regard to a specific attribute between two samples out of a set of many, however, it does not indicate the extent of the difference, making it rather hard to interpret the outcome of the test [7,55]. Nevertheless, it can be used to provide a measure of judgment inconsistency [67].

Fourth, in a *hierarchical grouping* task, participants are asked to divide a group of stimuli in two or more (unequal) subgroups based on similarities, and to substantiate their categorization choice [37,71]. Depending on the number of stimuli, this can be done in intermediate steps, facilitating the articulation of the freely selectable attributes that define the similarity.

Fig. 4. Materials samples physically placed on semantic scale [53]. Reprinted from [53], in accordance with Creative Commons regulations.

3.5.3. Free impressions

Finally, 13% of the studies use an open interview technique to discover *free associations or impressions* of the subjects, whether or not in combination with additional methods that can reinforce each other (8%). By means of in-depth interviews (often semi-structured) not only the stimuli's characteristics can be collected, but also the underlying reasons why a sample is perceived in that way can be explored and elaborated on. However, this qualitative method is rather time-consuming, both to conduct and to process, as it requires software for coding and qualitative data analysis (content analysis) [57,59].

3.6. Respondents

3.6.1. Number of respondents

Considering the time-consuming experiments within experiential characterization of materials or products, along with the practical feasibility of conducting such test, the number of respondents was in general quite low for statistical operations. Indeed, Kapkıin and Joines [74] indicated insufficient or unbalanced number of participants in certain groups to reliably investigate possible effects, and in the discussion section of reviewed articles, eleven studies specifically mentioned that future work should cover a larger sample size in order to generalize findings [29,33,44,46,53,58–60,62,63,66]. The overall average was 51 respondents, with a median of 30 respondents, and going from 10 to 474 respondents.

However, when these results were viewed from the three focuses, clear differences could be detected. Within the texture focus, 10 to 25

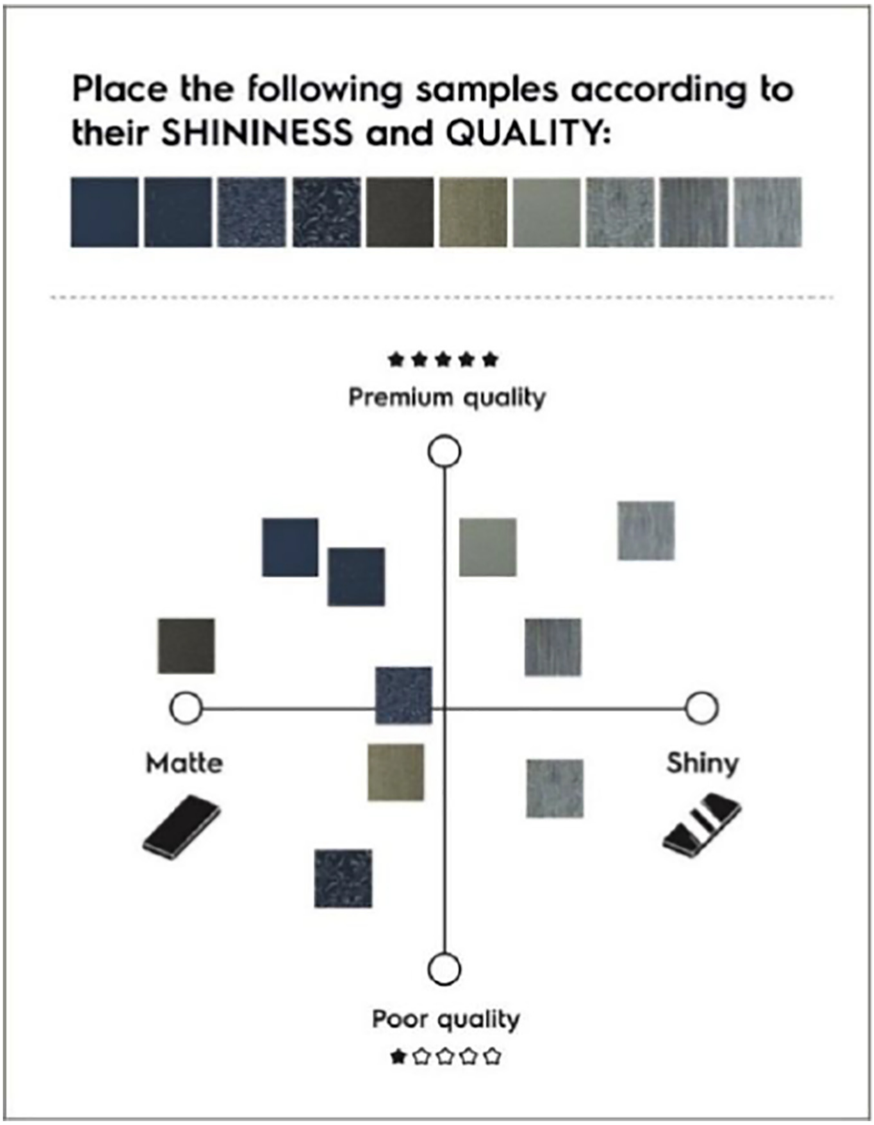

Fig. 5. Test example of Mapping by [7]. Reprinted from [7], Copyright (2018), with permission from Elsevier.

people participated in the experiments, which gave an average of 16 respondents (Md = 17). Within the material focus, 10 to 221 people took part, leading to an average of 42 participants (Md = 30). Yet, it must be noted that in the case of the largest sample group, the 221 respondents only scored one semantic scale on preference, while a sensory panel of eleven expert assessors ranked the material samples on additional attributes [42], as did 10 untrained subjects in a Napping procedure [12]. Within the product focus, 11 to 474 people responded, leading to the highest average with 119 respondents (Md = 73). The high numbers such as 474 [72] or 283 [73] occurred in the case of large scale online surveys using digital renders or photographs as stimuli.

3.6.2. Experience and discipline

Apart from the number of respondents, also the experience background and discipline of the respondents distinguished between the different studies (see Table 8). In 43% of the studies, *students or academics* were involved (with $\mu = 37$ respondents), whereas *consumers* participated in 30% ($\mu = 85$), and *professionals* ($\mu = 20$) or others ($\mu = 21$) in 13 or 14% of the experiments. However, Chang and Wu [68] noted that college students may not represent a broader consumer population.

Building on the cases in which the respondents' discipline was specified, 56% of the cases involved *non-design* background, whereas 29% of the respondents had a *design* background, 9% an *architecture* background, and 7% an *engineering* background.

Table 8
Frequencies of experience and discipline levels within Material, Texture, and Product focus.

	Students/academics	Professionals	Unspecified	Consumers	Total	Design	Non-design	Architecture	Engineering	Total
	Experience					Discipline				
Material	20	5	5	14	44	8	20	4	1	33
Texture	5	1	4	2	12	1	2	0	1	4
Product	5	3	1	5	14	4	3	0	1	8
Total	30	9	10	21	70	13	25	4	3	45

Nine papers included respondents within different experience levels and/or disciplines [7,32,33,37,42,45,66,71,80]. On the one hand, this was done to have broad distribution of respondent types [32,45,71]. On the other hand, comparisons could be made mostly between professionals and consumers (4 times), or between all three disciplines (1 time), and between designers versus non-designers (2 times).

For example, Vergara et al. [33] compared three user groups in their study on hammers; professionals, DIY enthusiasts, and trainees. They reported several factors that were affected by the users' level of experience, wherein trainees specifically led to significant differences as they seemed more negative and critical. Moreover, they stated that experts described more usability problems and provided stronger considerations for future usage scenarios. Similarly, Høibø and Nyrud [42] reported that consumers without experience in wood evaluation, had greater difficulties to detect small differences in wood quality than professionals. Hsu et al. [66] showed some significant differences between professional designers and users in the context of product form perception. Also in the study of Kapkin and Joines [74], occupation (designers versus non-designer) appeared to have a main effect on several meanings such as seriousness, and had an interaction effect with gender. Piselli et al. [7] used a two-by-two design, including respondents with (no) experience in an industrial product context, and (no) experience in materials, and concluded that all participants recognized certain sensory differences and similarities. All in all, their results supported the claim that sensory analysis could allow the consumer's involvement early in the design process, however a specific training of the panel members – whether they consist of designer and/or consumers – could lead to a higher level of consensus, as this would align their perception or interpretation of the sensorial attributes. Finally, Giboreau et al. [37] suggested that a complementary approach, involving different levels of expertise, could be a powerful methodology for sensory profiling and categorization. This perspective might offer interesting opportunities concerning time and feasibility aspects.

Based upon the reviewed studies we could conclude that the advantage of including designers or professionals is that they might have more feeling with materials and the application thereof, and that they might be more capable of abstract thinking, increasing feasibility of experiments with merely flat material samples. By contrast, addressing end-users or consumers in experiential characterization might be more challenging, as their interest and empathy need to be captured. In that regard, for example, Choi [58] employed a digital-logic approach (yes/no) to ensure an easier users' evaluation of attributes. A closer look on the studies involving consumers, revealed that physical but flat samples were used eleven times, a material rendered on an abstract form two times, a picture of a flat material sample once, and both a physical product and a photo/render of product each three times. Using a physical, yet abstract material form to trigger consumers, did not occur.

4. Discussion

In this section, we aim to reveal learnings to systematically address experiential material characterization, with increased attention to the physicality of stimuli and to user aspects. The reviewed articles showed different attempts to respond to the methodological challenges within the field of experiential material characterization. For example, several studies tried to cope with the influence or interaction of different senses when assessing materials by experimenting with blind conditions, such as [40,43,46,53,55]. Notwithstanding, an additional challenge can be seen on the choice of material stimuli or representation as this experimental aspect has a great influence on the overall perception of a material. The interaction between product (or form) meaning and materials meaning proved rather difficult to bridge, and researchers are challenge to find abstract forms or products that do not carry too much meanings in itself so that material meaning can be projected more independently.

4.1. Need for within-material-class comparisons

Most of the reviewed experiments involved familiar material classes such as metal, wood and plastic that are commonly used in mass produced everyday products. However, little experiments were done on comparisons within material classes instead of between classes. In the context of texture focus (e.g. textiles) and building materials (e.g. woods), efforts have been made already, yet a lack can be detected within-class concerning other materials and contexts. For example, plastics [94] were first introduced as “identity-less” imitation materials, were later boosted by Tupperware, but are now facing issues concerning sustainable perception in relation to bioplastics, recycled plastics and many more. Consequently, this material class could serve as an interesting and valuable path to pursuit in further research, and a valuable contribution for designers. One of the consequences of studying materials within the same class, is that they are more difficult to compare than metal to wood for example, and that materials such as plastics are nearly impossible to experience by means of photos or renders [60]. Therefore, physical tests with material samples must be the standard [49].

4.2. Need for physical material representations

When physical material stimuli are intended, several considerations and challenges arise. In the reviewed studies, mostly decontextualized samples (flat cut-outs) or contextualized materials applied in products were employed. Piselli et al. [7] suggested shaped specimens in further research, however, since Karana et al. [38] showed the effect of form on material meaning, we propose an abstract “in-between”; a form that allows an equal and thus constant presentation of various materials, but is varied in itself, similar to the bowls of Crippa et al. [45] that were both convex and concave, but not associated with food or other specific product functions. The shaped specimen means should evoke interaction and allow or facilitate free exploration. Moreover, it does require an appropriate level of complexity of the form to trigger the respondent to empathize with a material sample multimodally.

In addition, we suggest that a digital layer could be explored as well, as we see potential in Virtual Reality techniques to complement the experiential understanding of materials [95]. All in all, by means of a physical in-between sample form, controlled experimental conditions would be possible and additional product or contextual factors can be included by asking participants to envision the studied material in particular situations (envisioning factors), in order to create more flexibility despite standardization, as done by [50,57], which can increase the time-efficiency and can overcome practical issues in the production of samples (i.e. form must be simple enough to reproduce without difficulties).

4.3. Need for multimodal interaction with stimuli

In the case of physical material samples and within-class comparisons, the interaction context is an important aspect to be considered. In material appraisals, the most dominant sensory modality is that of vision. In addition, blind touch and visual touch are also often studied. However, human perception is inherently a multisensory experience [56], thus the senses cannot be isolated when human behaviour is analysed, but a holistic, multimodal approach is needed in sensory material evaluation [11], reducing perceptual ambiguity. This could decrease the difficulty of comparing e.g. various plastics (such as ABS versus PP) when using only touch or only vision, as occurred in [60].

Therefore, we argue that free exploration (or dynamic touch) deserves more attention in experiential characterizations as this is most consistent with the use phase of a material/product. In this way, participants can “play with” a sample and fully explore all experiential quality levels. Hence, future research can also anticipate to the performative level that is currently understudied. Camere and Karana [75] emphasized the need for understanding of the ‘performative’ level of experience. Grounding on the study presented in "The Tuning of Materials: A Designer's Journey" [96], they attempted to create an initial vocabulary of actions which can be used in experiential characterization. Yet, the vocabulary is suggested to be further developed and tested in future studies. All in all, we see opportunities in involving multiple experiential levels (for full materials experience), and in exploring the links between these levels as well.

4.4. Need for complementary experimental set-up and methods

The experimental set-up should be adjusted to the context of physical material representations and multimodal exploration. As we suggested free exploration, higher flexibility instead of control is needed in order to lower the threshold. A table setup might be convenient to display the physical material sample(s). We suggest a custom-made experiment table, in line with the sample box holders as often found in the reviewed articles. This table could include a benchmark with a reference material so that equal interpretation between participants is increased as well, and should facilitate the chosen measure method such as scaling, ranking, etc. Finally, both scale items and samples should be supplied in a random order, and their number should balance between exhaustion and time efficiency.

In order to measure experiential qualities, various methods were analysed. Although in-depth interviews (also 'elicitation interviews) are time-consuming to conduct and process, they can be employed as a complementary approach to empirical studies, as less people are required; e.g. depending on the context, minimal three up to ten people in case of elicitation [97]. Within descriptive measures, scaling (e.g. the semantic differential method, SDM) was most frequently used, with five or seven scale points, an average of ten items per test, and without or with pictograms to increase reliability and agreement and decrease ambiguity among untrained subjects. However, as perception is inherently more comparative, we acclaim the increasing popularity of holistic approaches or multi-attribute issues in sensory analysis, that allow to asses relative distances between samples (creating a reference framework). Thus, we see potential in MDS methods such as structured Napping (Mapping) that employs a pre-defined couple of descriptor items to accommodate untrained consumers and to overcome the limitations of SDM that lacks a comparative reference framework and is more analytical instead of spontaneous. Moreover, multiple experiential levels can be combined, and a rather large group of stimuli can be assessed (minimum ten to fifteen).

4.5. Need for studying temporality of materials experience

In addition, we detect a gap in longitudinal studies to understand materials experience over time. In the context of user's product experience and product adoption, Karapanos et al. [98] concluded that "while early experiences seemed to relate mostly to hedonic aspects of product use, prolonged experiences became increasingly more tied to aspects reflecting how the product becomes meaningful in one's life", which can be related to the expression of the self through materialized objects that we own. In order to study the temporality of materials experience as well, ethnographic studies are required which can be complemented again with empirical in-lab experiments.

4.6. Need for integration of extensive user aspects for consumer segmentation

The effect of user aspects has been already demonstrated, albeit insufficiently studied in depth beyond demographic aspects despite the fact that in the end it is the consumer's opinion that is important for market success. Specially meanings of materials are sensitive to such user aspects that can act as important moderators in the creation of material expression. Firstly, several authors [62,63,74] mentioned insufficient or unbalanced number of participants in certain groups to reliably investigate possible user effects, which made them reluctant to generalize findings. As large-scaled studies might be required for marketing database purposes [66], we argue that this can also offer segmentation opportunities to thoroughly include extensive user aspects beyond demography – such as personal values, personality traits, or the self-identity of consumers – that will offer more valuable insights to designers in their materials selection, as well as to marketeers.

Secondly, in contrast to designers or professionals that might have more feeling with materials, the application thereof, and abstract thinking (increasing the feasibility using merely flat samples), we argue that consumers must be addressed in experiential characterization to properly include user aspects, which might be more challenging as their interest and empathy need to be captured. Although this combination did not occur in the reviewed studies, we propose that the use of a physical, yet abstract material sample form can trigger consumers in a dynamic, multimodal characterization, while minimizing the interference with product context associations, and should be the first step in future research.

5. Conclusion

In this paper, we presented a literature review study on experiential characterization in product design, in which we described the current state of the art and identified gaps or opportunities for further research. As a directive for optimal future research, we suggest to respond to the specific scope of the intended study, and make use of the proposed needs as learnings or points of attention that can be translated into an appropriate experimental set-up. For example, a scope can start from a specific material and its material characteristics, that can be conducted with abstracted stimuli, or rather from a material application and the underlying dynamics of materials experience. Moreover, the scope can focus on one specific experiential level, or on the interaction between multiple levels, or can also manifest within a material, texture or product focus. In addition, a future scope can include more quantitative studies to include experiential preferences of users and to segment people (self-experience and material experience can be congruent with each other) extensive inclusion of user aspects, compared to other combinations of more experimental studies. Although the scope of an intended study will have a major influence, the main conclusions can be made with regard to [i] Material representations; we suggest that a physical representation of a material in an abstract form (next to more defined forms, such as flat samples) can be a critical element for multimodal material characterization experiments that allow a certain flexibility (by means of envisioning factors) despite standardization of experimental conditions, as well as they can show form possibilities of materials in a broader sense; and [ii] attention to User aspects; we suggest that the user aspects included in experiential characterization studies should go beyond demographic aspects (e.g. values, personality, etc.) so that more detailed segmentation profiles can be included when assessing the expression of materials by consumers, not only designers. Additionally, future research is suggested on within-material-class comparisons (e.g. virgin versus recycled polypropylene), complementary methods and experimental set-up that facilitates free exploration of materials and multi-attribute comparison of different samples, and the temporality of materials experience (e.g. longitudinal ethnographic studies that complements empirical in-lab experiments).

CRediT authorship contribution statement

Lore Veelaert: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Els Du Bois:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Ingrid Moons:** Conceptualization, Methodology, Writing - review & editing, Supervision. **Elvin Karana:** Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability statement

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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