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Design tools for interdisciplinary translation of material experiences

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Abstract
Designers increasingly have the opportunity to influence the development of materials as they emerge from the laboratory. In order for this to be successful, designers need to be able to communicate effectively with materials scientists so that materials can be developed with desired functionalities and properties. This paper reviews evidence in favour of using isomorphic sets of material stimuli as tools to bridge the disciplinary gap between designers and materials scientists. We show how these isomorphic sets and their accompanying experiments can be used to translate between the two communities, and to systematically explore the relationship between the technical attributes of materials and subjective experiences of their sound, taste and feel. This paper also explores the limitations of psychophysical approaches and other quantitative techniques for elucidating material experience, and suggests new possibilities for interdisciplinary collaborations that draw on ethnographic approaches.

1. Introduction

In their journey from laboratory to marketplace, materials pass through numerous different disciplinary communities. The materials that define our clothes, homes and cities are made by materials scientists and chemists in laboratories and manufacturing facilities, and chosen by fashion designers, product designers and architects from the vast array of materials in production, before being selected by users. As Ashby and Johnson note, a product's "market share is won (or lost) through its visual and tactile appeal, and the associations it carries, the way it is perceived and the emotions it generates" [1]. However, the sensory and aesthetic properties (henceforth sensoaesthetic properties) of materials are not traditionally the focus of materials researchers, nor are their cultural and historical associations. Physical parameters such as hardness, elastic modulus and shear strength are typically used to predict how a material will perform in technical applications, but the ways in which materials are perceived by the people that use them are less well studied by the materials science community. As a result, sensoaesthetic properties and cultural associations are largely ignored in the development of new materials, leading to a great many failing to find a niche in a competitive marketplace [2].

Designers therefore play a very important role in identifying the materials that "please users" and "touch them emotionally in some way", with implications for economic and environmental sustainability, as well as users' quality of life [3]. The work of researchers like Karana et al. [4][5] and Rognoli [6] helps designers to better understand the relationship between material, form and context of use in order to more effectively "manipulate meaning creation" through their choice of materials, thereby influencing users' experiences of their products [4]. The space constraints of this paper do not allow a complete overview of this varied body of work on material experiences, but in general these approaches tend to focus on the interface between designers and users of products. This paper, by contrast, explores the ways in which designers influence the materials development process. The work presented here therefore sits further upstream in the lifecycle of the material at the interface between materials research and design.

Since designers are often the bridge between the lab and society, their ability to communicate with materials researchers is important. However, the language of materials science is not often taught to designers, and as such they struggle to relay their materials requirements back to materials researchers in a language that they can understand. There is therefore a need for tools to translate subjective experiences of materials into data that can be used by materials researchers, and vice versa, to allow for the development of new, more sensoaesthetically appealing materials [7][8][9].

This becomes particularly crucial in light of research projects like Light.Touch.Matters ([10] henceforth LTM), in which the development of new materials is designer-led. Designers increasingly have the opportunity to influence the development of materials as they emerge from the laboratory. As Ball [11], Bensaude-Vincent and Hessenbruch [12] have noted, with the advent of performance specification, computational modelling of materials and the development of sophisticated nanotechnological techniques for visualising and manipulating atoms and molecules, materials production increasingly resembles a "systems approach" rather than a "linear model" [12]. We can increasingly specify behavior in a material rather than just selecting it from a range [11], which requires increasing cooperation between materials scientists, designers and other users of materials [12]. The LTM project aims to bring materials researchers and designers together to develop a new generation of affordable products that use flexible organic light-emitting diode (OLED) and piezoelectric polymer technologies in such a way that the whole product responds to touch by lighting up. In this context, designers are not just using a new material with a set of predetermined physical parameters; they have the opportunity to influence the development of a material's functionality and sustainability as well as its sensory and aesthetic properties.

In order for this sort of endeavour to be effective, there is a need for specialist tools for interdisciplinary translation between materials researchers and designers. Materials libraries have emerged as one solution to this problem. Their aim is to ensure that specialist knowledge about materials is not split along the divide between the arts and the sciences. Like a traditional library, they are repositories of knowledge, but instead of containing books they contain samples of materials. These collections enable designers, engineers and materials scientists to physically encounter materials, gain an understanding of them and develop a sensitivity to their physical properties and sensoaesthetic qualities. The spaces, and the collections they contain, also aim to facilitate the creation of personal and professional networks between artists, designers, architects, artisans, materials scientists and manufacturers [13]. In general, materials libraries have been very effective in enabling the arts community to access a wealth of materials samples, allowing them to literally 'get a feel for' a much wider range of materials than ever before, through hands-on experience. However, materials libraries are only a partial solution to the problems hindering the materials and creative industries. A materials library does not *de facto* translate subjective experiences of materials into data that can be used by materials researchers to direct the development of new materials, and a collection of manufacturers swatches does not, on its own, demonstrate thermal emissivity or stiffness in materials.

This article describes some of the work that has been done to convey the science of materials to the design community, to systematically explore sensoaesthetic experiences associated with particular materials, and to translate these subjective experiences into a technical language materials researchers are more familiar with. A growing collection of isomorphic material-object sets lie at the heart of our research [14]. These isomorphic sets employ the principle of keeping the form and dimensions of each sample constant whilst changing the material, allowing for an exploration of materiality independently of form. These specially made objects and their accompanying psychophysical experiments seek to systematically explore the relationship between the physical material properties of the objects and the subjective sensations and perceptions they elicit [15].

The structure of this paper is as follows. Section 2 reviews the different experiments we have conducted, describing the different isomorphic materials stimuli we have used over the last six years to investigate the link between physical properties and subjective experiences of materials, including their tactile, gustatory, somatosensory and acoustic qualities. The Institute of Making is composed of an interdisciplinary team of researchers, who draw on a wide variety of perspectives and expertise in their work. This section therefore teases out the different approaches that these studies draw on, the different audiences they speak to, and their suitability to the ends that they wish to achieve. In bringing together the sound, taste and touch experiments in one paper, differences in aim and method become evident. This section therefore also provides commentary on the ways in which these different experiments feed into each other, leading to evolution of the methodology. Section 3 assesses the utility of the isomorphic materials stimuli in relation to commercially focused materials development projects such as LTM. It explores the ways in which systematic psychophysical experiments can inform interdisciplinary dialogue but also examines their limitations. Finally, this article considers psychophysical approaches in relation to other, complementary approaches to material experience, and suggests new possibilities for interdisciplinary collaborations that draw on ethnographic techniques.

2. Materials Sets: Methods & Results

Materials selection is a mature discipline where physical parameters such as hardness, elastic modulus and shear strength are used to predict how a material will perform in technical applications [16]. The systematic exploration and theoretical prediction of the sensoaesthetic properties of materials, however, has been less well studied [17]. We have been using isomorphic material sets in our research group as a way of systematically exploring the relationship between perceived experiences of materials and those measured material properties explored by materials science. They also serve as a physical manifestation or demonstrator of particular principles in materials science; as stimuli that can be used to communicate with designers and other non-scientists.

Section 2.1 examines the acoustic properties of materials, exploring the relationship between perceived acoustic pitch and quantitative acoustic properties like acoustic brightness, density and elastic modulus. Section 2.2 examines the feel of materials and the relationship between perceived roughness, hardness and coldness of materials and measured physical properties like surface roughness, elastic modulus and thermal

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effusivity. Section 2.3 explores the taste of materials and the correlation with perceived hardness, roughness, coldness, sweetness and bitterness with measured physical properties like surface roughness, elastic modulus, thermal effusivity and standard electrode potential.

2.1 Sound of Materials

In 2008 we first reported a study that explored the relationship between quantified acoustic properties like acoustic brightness, density and elastic modulus and the perceived acoustic properties of materials [18]. We chose the tuning fork as the isomorphic form to explore the acoustic properties of different materials, commissioning a specially made set of isomorphic tuning forks from the following materials: blue steel, mild steel, stainless steel, solder, lead, zinc, brass, copper, glass, spruce, ironwood, walnut, balsa, nylon, plywood, tufnol, obeche and acrylic (see Fig. 1) [15].

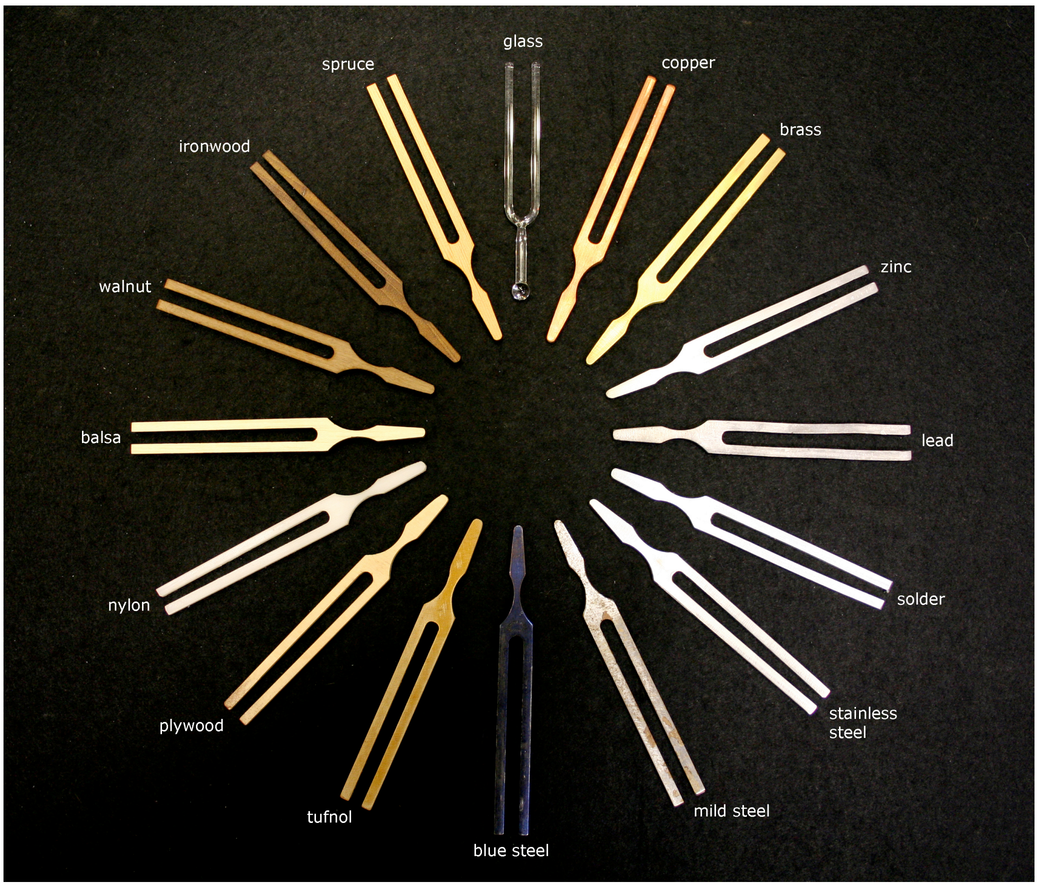

Fig. 1. A picture of the set of tuning forks, made from the following materials: blue steel, mild steel, stainless steel, solder, lead, zinc, brass, copper, glass, spruce, ironwood, walnut, balsa, nylon, plywood, tufnol, obeche (not pictured) and acrylic (not pictured).

The three principle factors that influence the sound emitted by a tuning fork are the shape, the density and the elastic modulus of the material. By keeping the shape of the tuning forks constant we were able to create a set of material stimuli that explore how the density and elastic modulus of different materials influence their pitch and acoustic brightness, and ultimately the sound that we experience when we strike them. Our experiment aimed to compare the perceived acoustic properties of these different materials against their theoretical acoustic properties as predicted by Ashby and Johnson's multidimensional scaling (MDS) map. According to the MDS map, materials like steel and balsa wood should behave alike acoustically on the basis of their density and elastic modulus, even though they are from different material families [1].

Ten participants were invited to handle, play and assess the actualised multi-material tuning forks through haptic encounter, and in gathering their qualitative descriptions of perceived pitch and brightness we were able to compare perceived acoustic properties against those predicted ones. The sound of materials encounters largely relied on qualitative data: in using a recognisable object like the tuning fork as the material set for this experiment, participants' experiences were situated in a specific context of use. The data gathered from the experiments was based on participants' subjective and freeform descriptions of their experiences and was analysed qualitatively for patterns in behaviour and response. We also experimentally measured both the pitch and the coefficient of damping in our set of tuning forks, to compare actual measured acoustic properties against the predicted MDS properties and perceived experiences of pitch and brightness.

In general there was broad agreement between the predicted acoustic properties of materials and the measured and perceived properties [18]. This experiment therefore established that in principle it is possible to identify correlations between subjective perceived experiences and measurable physical properties. This study also identified anomalies where participants' experiences of the quality and pitch of the sound for the tuning forks differed from the measured and predicted acoustic property data. The copper tuning fork, for example, sounded duller to the human ear than measurements and predictions suggested. It became apparent that in the course of their "encounter" with the tuning forks, familiarity with or previous experience of some materials affected the predictions that participants made when assessing the possible sounds of playing a particular tuning fork, and their behaviour in using each tuning fork [15]. Prior knowledge of the behaviour of glass for example, led many participants to shy away from playing the glass fork. They understood that it should make a high 'ping' sound when played, in the same way as a wine glass would when tapped, but feared the tuning fork would shatter. For the woods and plastics, there was less expectation of what they should or might hear. The acoustic behaviour of the metals surprised many as a result of the huge variation in coefficient of damping, with some being very bright and resonant, such as brass, and others being completely inaudible, such as lead and zinc. This first set of experiments therefore established that participants' familiarity with or preconceptions of materials can affect their experience of them.

In the course of this encounter, participants were able to acquire a relative appreciation of the materials on the basis of differences and similarities as experienced through their performance, without a detailed knowledge of how these acoustic effects resulted from elastic modulus and density. Through the act of encounter, the set of tuning forks became a physical manifestation of density and elastic modulus, which could be experienced in the playing of the tuning forks. These experiments showed the pedagogical potential of the tuning forks, which can be effectively used as a learning experience for non-scientists.

2.2 Feel of Materials

Having established that it was possible to identify correlations between subjective experience and physical properties with the sound experiments, we designed a second study aimed at developing a framework for the prediction of psychophysical material properties from well-characterised material properties. This study aimed to systematically explore what became apparent through

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participant observation in the first set of experiments: that peoples' preconceptions or familiarity with materials affected their experience of them. In 2012 we reported this study into the relationship between the quantified physical properties of a materials set and their psychophysical counterparts during a pair of tactile perception experiments [17].

The experiment compared the perceived roughness, hardness and coldness of these stimuli with analogous standard physical properties, defined by materials science and independent of object geometry: surface roughness R_a, elastic modulus and thermal effusivity, respectively. The surface roughness R_a of the samples was measured using a surface roughness tester, and the materials property data**,** including elastic modulus, thermal conductivity, heat capacity, and density of all the material samples, was obtained using the CES database [19]. A mixed set of materials were studied to establish whether simple psychophysical tests could provide an accurate correlation between perception and physical characteristics. The sample set consisted of materials (woods, polymers and metals) commonly found in the design of haptic interfaces.

The isomorphic form chosen for this experiment was a non-specific object form; a rectangular sheet with dimensions of 100 × 20 × 1.5 mm. Twenty three identically-shaped stimuli were produced from metals (brass, copper, sterling silver, stainless steel, monel, nickel silver, aluminium and mild steel), polymers (acrylic, ABS and polystyrene) and woods (balsa, plywood, walnut, obeche, spruce, basswood and mahogany) (see Fig. 2).

Fig. 2. A picture of the 23 materials samples used in this study, made from metals, woods and polymers.

All the samples used in this experiment were prepared using an identical procedure, which involved sequential grinding using SiC papers with grit numbers of P180, P320, P600, P800, P1000 and P1200. This yielded a sample set with a range of roughness values. Forty volunteers took part in this study, and a sighted and unsighted condition were used to ascertain the effect of vision upon touch perception, following a standardised method detailed in the paper [17]. The experiential data were analysed using standard statistical techniques, and the physical property data was plotted against the corresponding perceptual data for the roughness, softness and coldness on logarithmic scales. The touch experiment employed a more recognisably scientific approach than the sound experiment, with a standardised and controlled laboratory-style method to gather quantitative data from a non-specific object form that could then be analysed using standard statistical methods.

Across the three properties tested (roughness, coldness and hardness), there was a strong positive correlation between the measured physical property and the tactile perception, which showed that participants were consistently able to perceive differences in the physical properties of the materials. The results showed that the psychophysical property of hardness broadly correlated with elastic modulus for the materials tested (see Fig. 3). This was quite surprising at first; although the materials tested covered a large range of elasticities, they were relatively stiff by comparison with the range of materials found in a domestic environment [1]. Soft and pliable materials like silicone rubbers on tool handles and on kitchen utensils are soft, as are clothing and fabrics. By contrast woods, plastics and metals are stiff and hard to the touch. Nevertheless, this experiment showed that participants were able to distinguish between the materials quite easily. Thermal effusivity also showed a strong correlation with perceived coldness (see Fig. 4).

In performing the experiment with two conditions (unsighted and sighted), it was possible to evaluate whether participants seeing the materials had any influence on their tactile perception of them. Our results showed that there were significant differences between participants' judgments of coldness and roughness in sighted and unsighted conditions. In the unsighted condition, polymers were consistently rated as colder than woods with similar thermal effusivity values (see Fig. 4). This may have been due to a multi-modal effect: if coolness and hardness are associated with each other then it may be that the unsighted evaluation of the hardness of the plastic samples was influenced by their coolness. In addition, the woods, metals and polymers used in the experiment were rated differently in sighted and unsighted conditions. When sighted, the woods were rated as smoother, metals as colder and polymers as softer than when unsighted, which suggested that preconceived ideas of these materials were influencing participants' responses. Other studies have shown that visual perception plays a significant role in judgments of softness and compliance [20] and colour has an influence on perceived warmth [21]. However, as Wongsriruska et al. discuss in the original paper [17], biases are less likely to originate from visual perception in situations where the materials used do not significantly deform under pressure, as was the case in this experiment. The touch experiments therefore concluded that anomalies in texture perception were the result of participants' prior knowledge or preconceptions of a material. Even in the face of these strong cultural associations with some materials however, we found that in general the physical properties studied were good predictors of perceived qualities.

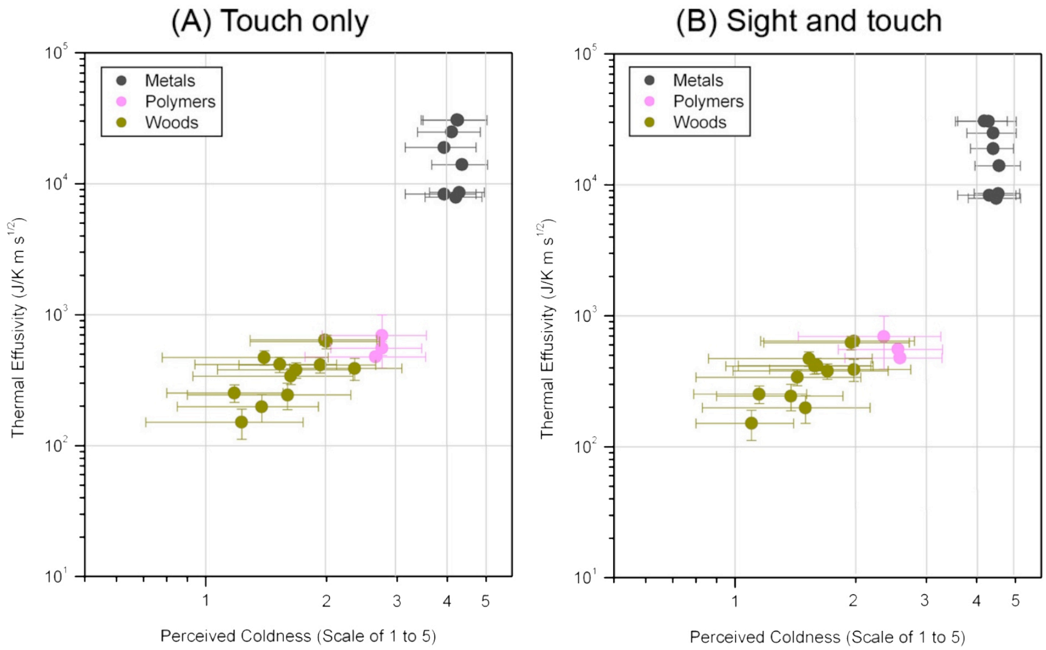

Fig. 3. A plot of the elastic modulus versus perceived hardness for the 23 materials: (a) data collected under the **unsighted condition** (participants were blindfolded); (b) data was collected under the **sighted condition.** The data is categorised by material class, each data point represents the response averaged for all participants.

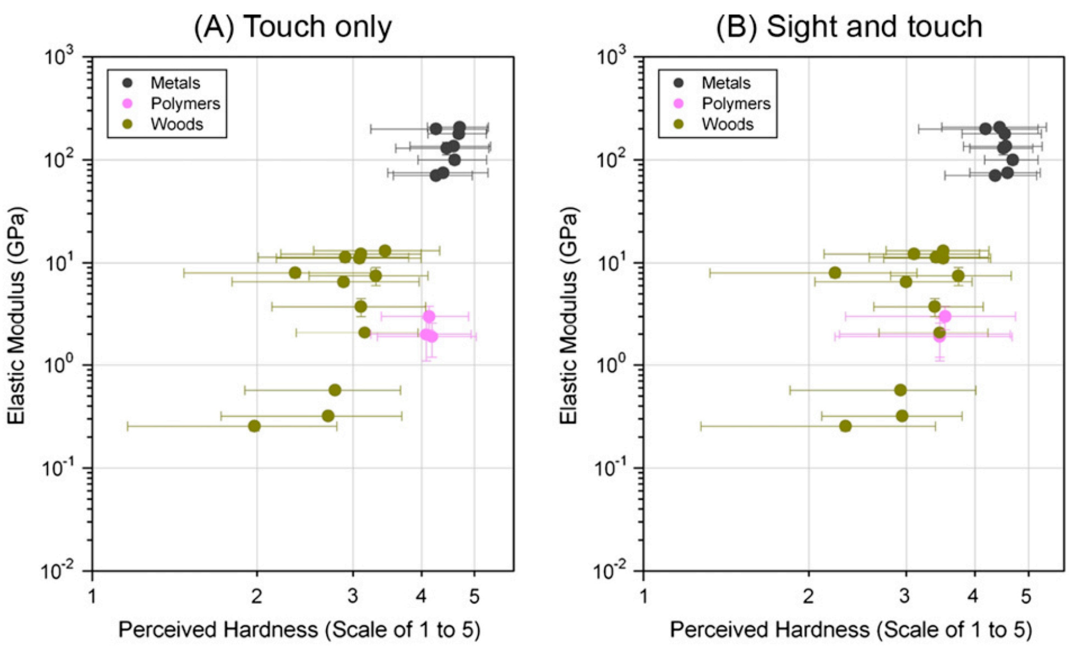

Fig. 4. A plot of the thermal effusivity versus perceived coldness for the 23 materials: (a) data collected under the **unsighted condition** (participants were blindfolded); (b) data was collected under the **sighted condition.** The data is categorised by material class, each data point represents the response averaged for all participants.

2.3 Taste of Materials

In 2011 [22] and 2014 [23] we reported two experiments that explored the taste of materials and the correlation of perceived hardness, roughness, coldness, sweetness and bitterness with measured physical properties like surface roughness, elastic modulus, thermal effusivity and standard electrode potential. We chose spoons as the isomorphic forms for our first set of taste experiments, in which we explored how the perception of metallic taste relates to the physical properties of various metals. A set of eight stainless steel teaspoons of identical shape were electroplated with zinc, copper, gold, silver, tin and chrome (see Fig. 5).

Fig. 5. The spoons material set. From left to right: zinc, copper, gold, silver, tin, stainless steel and chrome.

Two of the spoons were not plated and remained as stainless steel ‘control spoons’. Thirty-two participants tasted the seven spoons of identical dimensions in a set of controlled conditions described in the paper [22]. They were asked to rate the spoons on a rating scale from 1 to 7, in accordance with the following adjectives: cool, hard, salty, bitter, metallic, strong, sweet and unpleasant. This subjective experiential data was analysed using standard statistical techniques, and plots investigating the correlation between the perceptions and the relevant physical or chemical property of the pure metals were obtained from standard physical [19] and chemical data sources [24][25].

The zinc and copper spoons stood out as the strongest tasting spoons, rating highest with the adjectives bitter, metallic and strong. Silver was the next strongest taste, rating highest in saltiness, bitterness and strength of flavour. Gold, closely followed by chrome, was determined to be the least strong-tasting spoon. The results of this experiment showed that standard electrode potential, a measure of how easily atoms are oxidized, was a good predictor of metallic taste sensation [14][15].

The first taste experiment sat somewhere in between the sound and feel experiments on the spectrum from quantitative to qualitative and experiment to encounter, employing a repeatable, scientific method to gather quantitative data, but using a selection of materials in a recognisable object form; the spoon. For our second set of taste experiments we chose to use a non-specific object form; a rectangular sheet with dimensions of 150 × 17 × 2mm [23]. The material stimuli used for this experiment were birch wood, glass, balsa wood, stainless steel, silicone rubber, smooth copper, rough copper, smooth polystyrene plastic and rough polystyrene plastic. The study aimed to examine the correspondence between perceptions of warmth, hardness and roughness and the physical properties of thermal effusivity, elastic modulus and surface roughness, respectively. Numerous psychophysical studies explore the fundamental perceptual factors affecting our experience of solid materials through the fingers [17, 26–29], but techniques of this kind had not been used to study oral sensation and perception before.

The stimuli were presented to thirty participants in holders (handles) to stop them touching the surface and receiving tactile cues from their fingers, and the holders were weighted to make them heavy so that weight differences between the sticks were masked by the weight of the handle. These measures were designed to ensure that the participants were judging the objects from oral sensation alone. Following a highly controlled and standardised method described in the original paper [23], participants were then asked to place the material stimuli in their mouths and focus on the sensations they experienced.

In studies concerning touch only, which typically look at sensation through the fingertips, the dominant factors in tactile perception have been identified as roughness, hardness, coldness and slipperiness [30], with roughness being the most significant factor. However, in our study roughness was less important than hardness and coldness as a factor contributing to tactile experience. This is because the wet environment of the mouth lowers friction between the object and the skin [31], severely decreasing the vibrational component, which is vital for roughness perception. This seems to have had the effect of ‘promoting’ the relative perceptual importance of hardness and coldness in oral perception, when compared with tactile perception through the fingers and skin.

This study also explored how sensory integration influenced the oral perception of solid materials, such as those used for eating and drinking. Existing research on taste experience showed that oral perception was the function of complex interactions between the senses. For example, somatosensory sensations are known to contribute to taste experience, with interactions taking place between gustatory and somatosensory stimuli at every level of the taste system, and chemical, thermal, and mechanical stimuli merging into coherent perceptions of foods and beverages [32]. These complex interactions were not taken into account in our original spoon study, so we wanted to address them in this multimodal study, which allowed us to explore the relative dominance of the senses in the perception of materials in the mouth.

From our data it became evident that when participants distinguished between materials in the mouth, somatosensory perceptual factors dominated over taste perceptual factors. Within those somatosensory perceptual factors, the main sensations used by the participants to distinguish between the stimuli in this materials set were the warmth, hardness, roughness and to a lesser extent, bitterness. The somatosensory perceptual factors all showed a strong correlation with their corresponding physical properties, suggesting that the use of materials data to predict tactile perception of materials may be extended to oral perception. The linear correlation was particularly striking for thermal effusivity versus perceived warmth (see Fig. 6).

These results supported our first taste study [22] in its conclusions that there is a rich body of quantitative data available from materials science databases that could be used to predict the perception of some psychophysical properties. Such an approach would provide an inexpensive analytical tool for manufacturers of oral equipment, such as dental and medical apparati, for identifying promising materials, as well as artists, designers, chefs, and other makers and manufacturers of objects designed to go into the mouth, such as cups and cutlery.

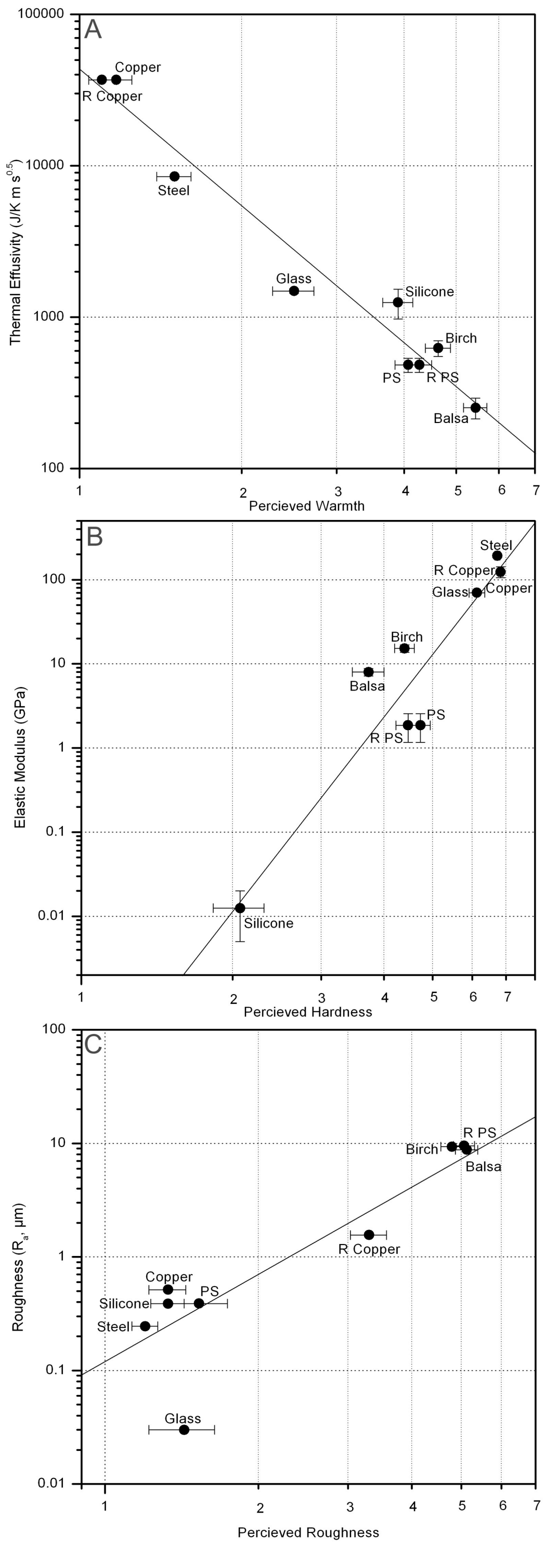

Fig. 6. The three-dimensional MDS solutions plotted in paired dimensions, with the subjective taste ratings regressed over the MDS coordinates and plotted as vectors.

3. Discussion

The purpose of these materials stimuli sets and their associated experiments has always been three-fold. Firstly, they aim to allow for two-way interdisciplinary translation: of materials science principles into the language of design and of designers' intuitive experiences of materials into the language of materials science. Secondly, they aim to generate new data to increase our understanding of the relationship between physical properties of materials and perceived aesthetic and sensory properties. Finally, they aim to change the course of materials research and of the design process as a result. Studies that increase our understanding the relationship between physical properties and human sensory perception can lead to the development of materials and products that more effectively meet peoples' sensory and aesthetic expectations, with both economic and environmental implications [7][8][9]. The implications of the sensoaesthetics work therefore reach beyond simply improving the understanding of tactile, oral and auditory perception. As discussed in the introduction, designers increasingly have the opportunity to influence the development of materials as they emerge from the laboratory. Understanding how subjective experiences of materials relate to physical properties therefore becomes particularly important in the face of research projects that attempt to forge stronger links between materials science and design, with a view to collaboratively developing new materials. This discussion considers the efficacy of our material sets in light of observations from the application of this approach to a specific materials research and design crossover project: Light.Touch.Matters (LTM).

3.1 Using Materials Sets for Interdisciplinary Communication of Properties

The LTM project is a pan-European research project, involving seventeen partners in nine EU countries, which aims to bring these different communities together. The project aims to develop a new generation of affordable materials and products that use flexible OLED and piezoelectric polymer technologies to respond to touch with light. In order to do this effectively, the materials research partners need to communicate the unique properties and functionalities of their flexible OLED and piezoelectric materials to the designers so that they can develop a series of products that showcase the state of the art in materials research. At the same time, the design partners need to direct the materials research process by specifying what kinds of properties they would like for their designs. The project explicitly sets out to create designer-led materials. As a result, the consortium has to develop techniques to help its members to communicate effectively across disciplinary divides. The project also aims to create products that will contribute positively to the health and wellbeing of users of those products. The specific requirements of this consortium have led us to consider how the approaches, methods and findings of the sound, touch and taste experiments might be useful to this project, and how they might be further developed to better fit those requirements.

In the context of the LTM project, materials researchers talked about the measurable material properties of 'stiffness', 'elastic modulus' and 'shear modulus' as well as the 'topology' of the material, whilst designers talked about their experience of 'flexibility of the material', 'flexibility of the surface', 'bendiness', 'twistiness' and 'stretchiness'. Throughout the course of group discussions, these terms were identified as broadly analogous and related to the same kinds of observed behaviour in LTM materials, but some translation and quantification issues hindered communication between the two groups as observed by both Rognoli [6] and Pedgley [33] in the context of design education. Firstly, the translation between experiential terms and physical properties was not accurate or one-to-one; the term 'flexible', for example, could be used to refer to the stiffness, elastic modulus or shear modulus of a material, as well as the mechanical flexibility of an object or surface that results from object geometry or topology. There was also some tension between quantitative and qualitative approaches to materials; whilst designers talked qualitatively about the different kinds of flexibility afforded by different materials, materials research partners wanted a numerical value for desired elastic modulus or shear modulus so that they could begin to incorporate this into the materials specifications that guide their research.

In response to these communication issues, and drawing on tools developed to encourage designers to consider the expressive-sensorial dimensions of materials [4,6], a set of material stimuli were developed to aid accurate translation between designers and materials researchers. The purpose of these material sets was to allow materials researchers and designers to refine and compare their terms for the same observed behaviour, and to discuss the kinds of material properties or experiences they wanted from LTM materials. These materials sets were also developed to enable translation without designers having to specify numerical values for material properties, but in a way that would allow materials researchers to extract numerical values that could inform their research.

This LTM material set took the form of stimuli containing a variety of materials in the form of rectangular bars. We produced six tool sets in total, divided into three pairs, with each pair exploring a material quality that LTM partners were struggling to communicate: luminosity, flexibility and tactility. One of each pair was made in silicone rubber and the other was made using a selection of materials commonly found in domestic products, including various different types of polymer, wood, glass and metal. Silicone rubber was chosen because it had been specified by the LTM materials researchers as the most likely candidate to encapsulate the OLED and flexible piezoelectric materials. The multi-material sets were intended to give a sense of what might be possible in materials other than silicone and to be the basis for analogy, so that participants could request a similar stiffness and density to balsa wood for example. These materials sets were labelled with one term used by materials researchers and one analogous term used by designers: stiffness / flexibility, opacity / luminosity and tactility / feel.

The LTM material sets were developed to establish a consistent connection between material property data and experiential terms during the project. In keeping with the other isomorphic materials sets [14], we also explored their role as "boundary objects" [34] that would encourage consortium partners to share different ways of looking at the same materials in a workshop environment and allow for two-way interdisciplinary translation. Star and Griesemer's observations of scientific objects that "inhabit several intersecting social worlds…*and* satisfy the informational requirements of each of them" led them to define these boundary objects as those which have "different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation" [34]. Even though the LTM consortium partners may experience different kinds of material qualities in the same material-objects, or read the same material qualities in different ways as a result of their disciplinary biases, they still have a common anchoring point, which is much more concrete and unbending than a verbal dictionary or glossary of terms.

These tool rolls enabled a different kind of conversation than would have been possible simply through verbal description or by browsing a materials library. For example, one group discussed the "difference between flexibility in a surface and flexibility in a material; the texture or geometry of a printed structure can make it fluid" [35]. Another explored how "twisting is influenced by the thinness of the sample", and third discussed the ways in which "spring-back could be deadened to make the silicone feel more flesh-like" [35]. They did not need a refined technical materials science vocabulary to talk about the differences between stiffness, elastic modulus, shear modulus and the topology of the material with the materials researcher as they could demonstrate accurately and be understood using the materials to hand. Various material culture scholars have commented on the limitations of describing a material whose expressive potential is largely tacit since "materiality always exceeds language" [36]. Anthropologist Tilley, for example, asserts that "similarity and difference can often be much more subtly conveyed through the colours, textures, shapes and smells of things than through words", as the material "does the talking in a much more profound, succinct and vivid manner" [37].

These materials sets also have the potential to act as small, curated and standardised mobile materials libraries that can circulate between LTM partners and help with translation and communication across geographic as well as borders. Historians of science Latour [38], Roberts [39] and Daston [40] have all commented on the key role played in the development of modern science by immutable, standardised, readable and mobile objects or technologies like maps, the printed book and the weight and measure system, for example, which could be transported across qualitative and spatial boundaries and still maintain their consistency. In the context of this project, if all partners have the same sets of samples they can function as "immutable mobiles" [38] that allow for long-distance communication about material properties over email or the phone.

In the light of the LTM project, the materials sets can be seen immutable, mobile, boundary objects that allow for interdisciplinary translation. The same set of samples can allow designers to have an experiential encounter with materials, exploring the kinds of qualitative experiences that they want in their products, and allows materials researchers to approach the same objects with a systematic, quantitative approach, producing data can be used to inform and change the course of materials research and manufacturing. Where possible, the set aims to help translate experiential properties of materials like flexibility and warmth into physical property measures like stiffness and thermal effusivity, and vice versa. Where a direct translation is not possible, these material-objects allow researchers and designers to communicate using the shared language of the physical object, and to work on developing a 'materials dictionary' for this specific project. Star and Griesemer describe the task of translating between disciplines and reconciling different understandings of the same phenomenon as one that "requires substantial labour on everyone's part" [34]. This two-way translation of physical properties and human experience of materials can be labour-intensive, but the ultimate goal is to influence both design and materials research processes to produce products that actively contribute to the wellbeing of users. The materials set enabled LTM consortium members to begin refining their materials vocabulary in a new way, supporting the idea that discursive material-objects can be central to interdisciplinary dialogues.

3.2 The Limits of Quantitative Approaches: Explaining Anomalies in Material Experience

As discussed above, some sensory experiences of materials, like roughness, warmth and bitterness, can be translated readily into analogous, measurable physical properties. Other qualities, like healthiness, naturalness or sustainability, are no less constitutive of our experiences of materials but are much harder to correlate with a set of physical properties. This lack of correlation between material properties and material meanings or experiences has been discussed by Karana et al. [4] and Overvliet and Soto-Faraco [41]. In the context of the LTM project, design partners might explore the enchanting, relaxing, tactile or sustainable qualities of a material. These material qualities do not directly correspond with a single, measurable physical property like surface roughness, lumen output, or thermal effusivity, so communicating qualitative experiences in terms familiar to materials researchers becomes much less straightforward. Studies of perceived naturalness by Bialek et al. [8] and Overvliet and Soto-Faraco [41] provide sophisticated analyses of the relationship between multiple physical material properties and perceived material properties. However, their work still does not explain the reasons *why* people distinguish between different woods, textiles and stones in this way. Similarly, our sensoaesthetic experiments showed that there were some instances when the experience of the sound, taste or touch of a material differed from the predictions of MDS maps and the properties as measured using traditional materials science techniques. As discussed above, the touch experiments concluded that anomalies in texture perception were the result of prior knowledge about the material. The limitations of the psychophysical approach becomes evident at this juncture, as it does not allow for an understanding of *how* the cultural associations of materials or participants' preconceptions about them contribute to this dissonance between measured and perceived properties.

The work of Karana, Hekkert and Kandachar [4] and Karana and Nijkamp [5] is complementary to the psychophysical approach. The Meaning of Materials tool, for example, helps designers to identify patterns in how materials obtain their meanings [4]. This approach provides a systematic method for exploring and capturing the perceived, aesthetic and emotional aspects of materials. The resulting data is a combination of quantitative ratings of materials against either a sensorial scale (soft, warm, glossy) or an affective scale (sexy or elegant) and some qualitative details of participants' motivations for their responses. However, as Karana et al. themselves note these 'intangible', sensory, emotional and associative characteristics of materials are "highly intertwined, subjective, time and context dependant" in our daily engagements [5]. Equally, Ashby and Johnson recognise the limitations inherent in quantifying the immense complexity of our experiences of materials as this "rolls many attributes into a single number, and in doing so…throws away a great deal of information" [1]. In a similar vein, anthropologist Keane has argued that the social effects of one sensuous quality or icon, like softness, redness, or lightness, cannot be abstracted from the "cultural totality" of the whole material in its context of use [42]. Keane notes that individual qualities are always bound in a material form, and as such "they are…bound up with other qualities". He gives the example of redness in an apple, which is bound up with its "spherical shape, light weight, sweet flavour, a tendency to rot, and so forth" [42]. In practice, materials are 'bundles' of qualities, and although these qualities will shift in their "salience, value, utility and relevance across contexts", they all have the potential to be socially significant and to make a material attractive [42].

This suggests that there is a need for in-depth, qualitative investigation into the cultural associations of materials to complement existing systematic quantitative methods offered by psychophysics and design research. Ethnographic approaches to materials can contribute to an understanding of how particular preconceptions or anxieties about materials arise in culturally and historically specific contexts. Over the last twenty years, numerous anthropologists, geographers and historians have highlighted the dynamic historical and cross-cultural trajectories of materials. Anthropologist Schneider documents polyester's journey from a democratic, affordable and multi-purpose 'wonder material' to being seen as artificial, deceptive and cheap [43] and historians of science Klein and Lefèvre demonstrate that even a material as basic and ubiquitous as water can have a dynamic history [44]. Historian Mintz showed that the uses and meanings of sugar have changed over time and between cultures. Although sugar's most recognisable characteristic could now be considered its sweetness, historically it had numerous different uses including as a "medicine, spice, condiment, decorative material, sweetener, and preservative" [45]. These approaches demonstrate that a material's meaning, value and uses do not inhere naturally or inevitably in materials, but arise as people use materials in specific contexts of use, sometimes over long periods of time.

Whilst historical and anthropological approaches can contribute another facet to the study of material experiences, they can also learn something from materials science and design research. Until recently, social science approaches tended to focus on the ways in which the actions and perceptions of people influence the cultural associations of materials, and they have only recently begun to pay attention to the ways in which their physical and sensoaesthetic properties influence their popularity and uses. Geographer Hawkins, for example, demonstrates that the "material affordances" of PET bottles, like their "lightness, strength and physical lustre…translucency and clarity" play an important role in their uses and identities [46]. As scholars like Gregson et al. [47], Bensaude-Vincent et al. [48] and Hawkins [46] have shown in their studies of asbestos and DDT, materials can be obstinate, resistant and surprising, generating effects independently of the intentions of their designers.

In the last few years, social scientists have demonstrated that our experiences of materials are not defined by a material's physical properties, sensory and aesthetic properties, or cultural associations in isolation, but result from the interplay between all these different factors. Wilkes [49] shows that the perceived sustainability of a material cannot be reduced to a set of measurable physical properties, nor can it simply be attributed to cultural preconceptions. The perceived sustainability of a material depends on our criteria for the category of sustainable, which vary from community to community. Understandings of sustainability are not fixed or separable from cultural practices and world-views: the kinds of issues that we prioritise and the materials that we classify as sustainable or unsustainable vary over time, across different societies and even between different professional groups [50]. At the same time, a material's perceived sustainability also depends on its specific biography, including the constituent substances it contains, the conditions of its production, use and disposal, and how far it accords with or resists peoples' attempts to govern it by making it recyclable, biodegradable, innocuous or durable. Materials have an immense social significance that cannot be reduced to their functional or aesthetic qualities, but equally the cultural and historical associations of materials cannot be completely isolated from their physical properties. A holistic approach to material experience therefore needs to explore this relationship between the physical properties of materials, their "expressive-sensorial properties" [6] and their historical and cultural associations in particular contexts of use (see Fig. 7).

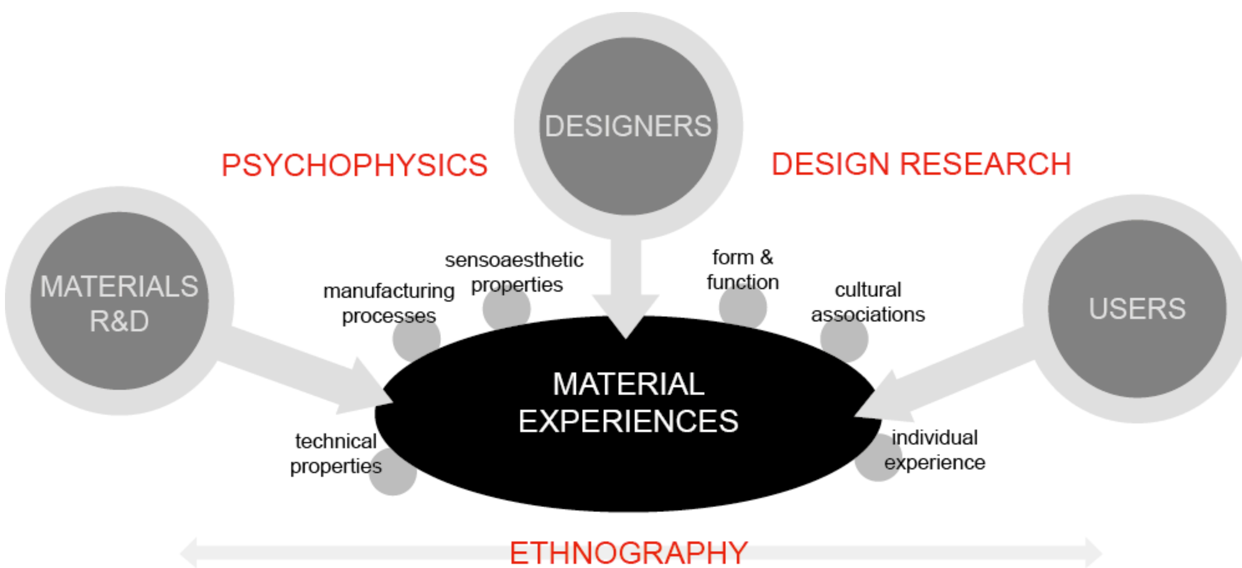

Fig. 7. Diagram illustrating how materials science, psychophysics, design research and anthropology all inform materials experiences.

4. Conclusions

When viewed all together in this paper, the sensoaesthetics experiments can be seen to straddle ethnographic and scientific approaches. These subtle differences in approach make them suitable for different purposes. The sound and taste encounters are the most effective in communicating the principles of materials science to a non-scientific audience in a way that is immediately perceptible through haptic engagement with the material set. In gathering standardised and reliable quantitative data about the relationship between human experience and physical properties, the touch and taste experiments provide data that can be used to inform and change the course of materials research and manufacturing. Regardless of whether the aim is to communicate the science of materials to designers, to find links between physical properties and perceived experiences, or to encourage two-way interdisciplinary communication between materials science and design, the physical object or 'materials set' plays a crucial role.

The discussion highlights insights we have gained on the benefits and limitations of this experimental work in light of the LTM project, and the possibilities opened up by interdisciplinary engagement between materials scientists, design researchers and anthropologists. This paper argues that in order to fully understand how materials move from laboratory to society we need a holistic, interdisciplinary approach that combines systematic, scientific studies of sensoaesthetics properties, quantitative design research approaches to sensorial and intangible characteristics and ethnographic approaches that explore how particular preconceptions or anxieties about materials arise in specific contexts of use. We suggest that the study of materials experience benefits from a tripartite, interdisciplinary approach characterised by experiment, encounter and ethnography.

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