Material perception for philosophers

(*Penultimate draft*)

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Acknowledgements:

Thank you to Kevin Lande and an anonymous referee for providing helpful feedback on the manuscript. This research received funding from the FWO (Fonds Wetenschappelijk Onderzoek) and European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 665501, via an FWO [PEGASUS][2] Marie Skłodowska-Curie fellowship (12T9217N). This work was supported by the Deutsche Forschungsgemeinschaft (SFB-TRR-135: "Cardinal Mechanisms of Perception," Project 222641018; also, Project PA 3723/1-1), a European Research Council Consolidator Award (ERC-2015-CoG-682859: "SHAPE"), and the Alexander von Humboldt foundation.

Abstract:

Common everyday materials such as textiles, foodstuffs, soil or skin can have complex, mutable and varied appearances. Under typical viewing conditions, most observers can visually recognize materials effortlessly, and determine many of their properties without touching them. Visual material perception raises many fascinating questions for vision researchers, neuroscientists and philosophers, yet has received little attention compared to the perception of colour or shape. Here we discuss some of the challenges that material perception raises and argue that further philosophical thought should be directed to how we see materials.

Keywords: Vision, materials, representation, secondary qualities, touch

1. Introduction

Philosophers have long been preoccupied with the puzzles that vision presents. Sometimes these puzzles reflect familiar aspects of what we see, such as color or shape. Some aspects – such as motion or depth – while not as puzzling, are certainly in the philosopher's purview. Other aspects are not. We also see what material things are made of (e.g., wood, glass, or velvet) and from sight alone have a vivid sense of their material properties (e.g., rough, soft, glossy or fragile). In the last two decades the scientific study of how we visually perceive materials has rapidly expanded (Fleming, 2017). Yet, philosophy has paid scant attention to this growing field. The present paper aims to remedy this oversight. In Section 2, we further introduce the phenomenon of material perception. In Section 3, we review main themes in empirical research on the topic. In Section 4, we highlight the apparent absence of material perception in the history of philosophy, but not art. Finally, in Section 5, we make preliminary connections between materials and philosophical issues of perception.

2. The phenomenon of material perception

To begin, we hope to impress upon the reader a subjective appreciation for material perception as a salient and pervasive aspect of how we see the world. Broadly speaking, the phenomenon has two main aspects.

Figure 1. *A mundane still-life of synthetic materials (i.e., plastic or polyester).*

First, when we look at our surrounding world, we see not only objects, but also what things are made of. In other words, one essential component of perceiving materials is our capacity to *recognize* things in our environment as being constituted by materials of different types. In Figure 1, we can readily pick out what types of objects are present in the scene: a sponge, watering can, to-go container, hand towel, and resealable bag. We also perceive what they are made of – all of the items depicted are composed of different synthetic materials (plastics or polyesters) even while sharing few obvious visual features in common, such as shape or color. Materials are not just the things from which objects are made however. Many parts of our surroundings cannot be described as objects with distinctive shapes and numbers (i.e. by applying count nouns), but are instead "stuff", described by mass nouns: sand, yoghurt, water, soil, wallpaper (Adelson, 2001).

The second essential component of perceiving materials is perception of their *properties*. In Figure 1 we see that the container is transparent, the bag is glossy, the sponge and towel are matte, and the watering can is translucent. We also have a visual impression of many properties we normally associate with touch: the towel looks soft, the sponge rough, the lid of the container smooth, and the bag slick. Furthermore, we can predict how these objects would interact with one another or our hands: the sponge would feel squishy, the can rigid, the container springy, the towel limp, and the bag crinkly.

Since our first impression of our surroundings is usually by sight, this ability to see what things are made of, and what material properties they likely have, provides crucial information to help guide our actions. Because we are able to predict how things will feel when touched or behave when manipulated, we are better able to interact successfully without breaking, crushing, or slipping on them. Thus, seeing materials is both a salient and pervasive part of our visual experience, and an important practical ability.

3. The empirical study of material perception

It is only with the publication of Adelson's (2001) seminal "On seeing stuff" that material perception has grown into an active and recognized branch of vision science.[1] Research has tended to focus on the two aspects of the phenomenon highlighted earlier: (i) how do we visually recognize material categories? and (ii) how do we infer material properties from visual cues? After reviewing some of the research on these topics, we touch on some theoretical issues and open questions of this burgeoning field.

3.1 Recognizing material categories

Only very recently has human facility at material recognition been quantified. People can label close-up photographs of materials like fabric, paper, and plastic (Figure 2) by their correct material categories with an average accuracy of 85% (Sharan et al 2013). For comparison, the best available modern computer vision models reach only 64-69% accuracy (Wieschollek & Lensch 2016, Bell et al. 2015). Observers can even successfully recognize materials during ultra-rapid presentations of ~40 ms (Sharan et al. 2014; Wiebel et al. 2013), and when presented with samples identify materials far more accurately by sight (90% accuracy) than by touch (66%; Baumgartner, Wiebel

[1] The first attempts to objectively measure material properties arose from industrial scientists wishing to quantify, for example, the glossiness of paper stocks produced by different manufacturing processes (Ingersoll, 1921). These studies prompted attempts to catalogue the different aspects of the concept of "glossiness," from the physical to the subjective (Hunter, 1937).

& Gegenfurtner, 2013). Performance also seems to improve throughout the lifespan, as children tend to perform worse on material categorization tasks than adults (Balas, 2017).

A useful comparison can be made here with object recognition, which is a compelling visual phenomenon because it occurs rapidly and effortlessly across infinite variations in pose, illumination, distance, or self-occlusion (DiCarlo et al. 2012). Yet, although viewing conditions can vary widely, the properties of objects themselves, such as shape, only change in constrained ways. In contrast, materials can be formed, and transformed, by myriad physical processes, so that the same material can take on radically different appearances. Thus, examples of the same material category can appear very distinct, and examples of different material classes can share many similarities (Figure 2). Our ability to recognize materials suggests that we are able to use even more ephemeral and mutable visible features than required for object recognition (Adelson, 2001).

Figure 2. *These photographs are grouped into columns based on material type: fabric (left), paper (middle) or plastic (right), yet images within a row appear more visually similar. Reproduced from the Flickr Material Database (Sharan, Rosenholtz & Adelson, 2014) under a Creative Commons (CC) BY 2.0 license.*

Recognizing a familiar material brings with it expectations about the properties that material typically has (Figure 3). People reliably associate different material categories (e.g., stone, wood, glass) with different properties (e.g., hardness, roughness, transparency), and a material's category can be predicted with 90% accuracy from such properties (Fleming et al. 2013). This impacts how we interact with an object or substance. For example, people decide how firmly and where to grasp an object depending on whether they expect it to be slippery, fragile or heavy (Johansson & Westling 1984; Paulun et al. 2014, 2016). Such prior expectations are exploited in the "material-weight illusion" (Seashore, 1899) where objects of equal size, shape, and mass have been manipulated to appear to be of different materials (e.g. brick vs wood) and are reported as having different weights (Buckingham et al 2009; Paulun et al. 2019).

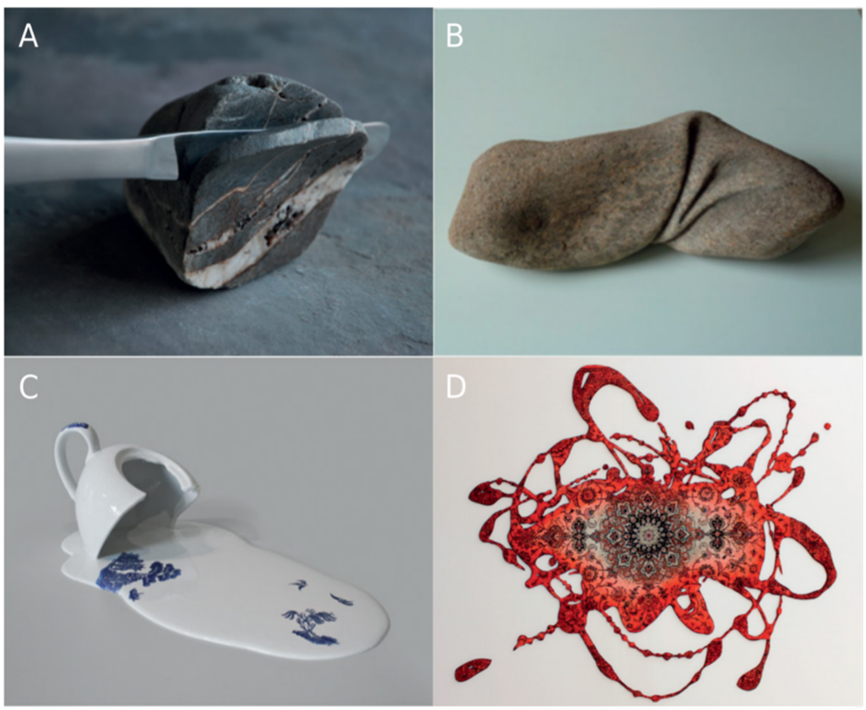

Figure 3. *By identifying the type of material, we form expectations about what properties it will have. These artworks play with our expectations by pitting the apparent properties of objects against those usually associated with their materials: (A) "sliced" stone; (B) "folded" stone; (C) "melted" porcelain; (D) "splashed" rug. All images reproduced with permission: (A) "Delicious Stone II" sculpture by Hirotoshi Ito, image © 2017 Paris Art Web; (B) "Sin Título" sculpture and image © 2016 José Manuel Castro López; (C) "Nomad Patterns" sculpture and image © 2012 Livia Marin; (D) "Syrup" sculpture and image © 2017 Noémi Kiss.*

3.2. Seeing material properties

Recognising familiar materials is not the only way to visually infer material properties. We also use visual information to more directly perceive such properties. Research on perceptible material properties has tended to focus on those that are either closely associated with surface reflectance (e.g., glossiness, transparency, and translucency) or dynamic interactions (e.g., elasticity, softness, and viscosity). We shall refer to these loosely as *optical* and *mechanical* properties, respectively. These properties are often independent. Gelatin and glass are both transparent, but one is soft and the other hard. However, mechanical properties can influence optical ones. A surface that is rough, for instance, is generally not glossy, because a physically uneven surface scatters light in many directions, producing a diffuse matte appearance.

Optical properties of course depend on light striking a surface, where it can then be absorbed, reflected, or transmitted. When surfaces are opaque, their reflectance properties can be fully described by the bidirectional reflectance distribution function (BRDF) (Nicodemus, 1965). The BRDF describes the proportion of light that is reflected from a surface in each direction, relative to the light arriving at it from each direction. Similar to how surfaces absorbing different wavelengths of light tend to produce different colour experiences, surfaces with different BRDFs tend to produce experiences of different optical properties, appearing matte, glossy, or mirror-like (Figure 4).

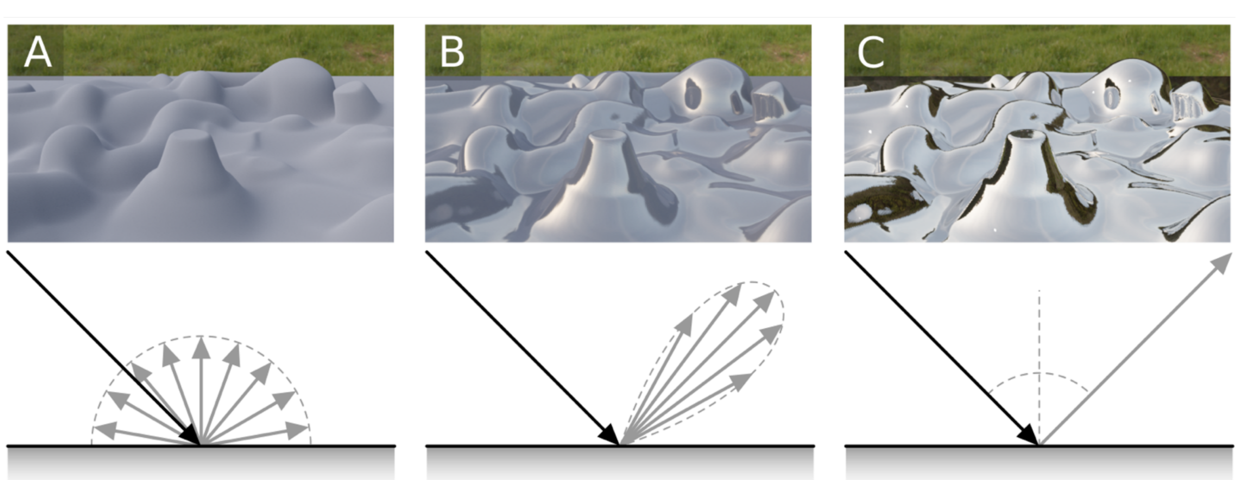

Figure 4. *Surface materials with different reflectance properties often create different perceptual impressions. Here the same 3D surface shape is rendered using computer graphics three times, simulating different reflectance properties. If incoming light reflects diffusely in all directions, a surface appears matte (Figure 4A); if it reflects multiple directions but partially follows the same angle of arrival, it often appears glossy (Figure 4B); and if the angles of arrival and reflection are identical, it appears mirror-like (Figure 4C).*

However, there is no direct mapping between the parameters of the BRDF and perception. Identical materials can look differently glossy when seen from a different angle, under different lighting, or applied to a surface with a different shape (Nishida & Shinya, 1998). In other words, observers do not show perfect gloss constancy, in the same way they do not show perfect colour constancy. Gloss constancy is generally better when a surface is seen in natural outdoor lighting than when lit more simply, such as by a single lamp (Fleming et al. 2003; Motoyoshi et al. 2011; Pont et al. 2006), and when a surface is moving, and viewed with both eyes (Wendt et al., 2010). Our perception of glossiness also seems to depend on the sharpness, contrast, and complexity of highlights as materials that reflect light in a less scattered way tend to have highlights with these characteristics (Marlow et al. 2012; van Assen et al., 2016). However, highlights are *also* affected by illumination conditions and surface shape, leading to failures of gloss constancy (Ho, Landy & Maloney, 2008; Marlow, Kim & Anderson, 2012). In sum, perception of gloss depends on a complex (unknown) function of the reflectance properties, the illumination, the observer's viewing angle, and the shape of the surface (for review see Chadwick & Kentridge, 2015).

When it comes to mechanical properties, our perception depends primarily on motion and shape information. For example, more smoothly flowing motion patterns look more liquid-like (Kawabe et al., 2015), and the viscosity of a poured liquid can be judged from just a static snapshot by the shapes it forms (Figure 5B; Paulun et al., 2015). Motion and shape cues often work in concert, arising from interactions between materials and the environment or external forces (Van Assen et al., 2018). For example, the way a piece of cloth folds is diagnostic of its stiffness (Bi and Xiao, 2016; Bouman et al. 2013; Schmidt et a. 2017), and viewers can use observed deformations of objects to judge their softness (Kawabe & Nishida, 2016; Paulun et al., 2017), or their bounce behaviour to estimate elasticity (Nusseck et al., 2007; Paulun & Fleming, 2020; Warren et al., 1987). Dynamic clues to mechanical properties usually dominate perception if they are experimentally brought in conflict with prior expectations (Figure 5A; Paulun et al. 2017). Reliance on dynamic cues requires great flexibility though; the amount of spread or piling, while useful for discerning viscosity when a liquid is poured onto a flat plane is not useful as a cue when it is being stirred in a container.

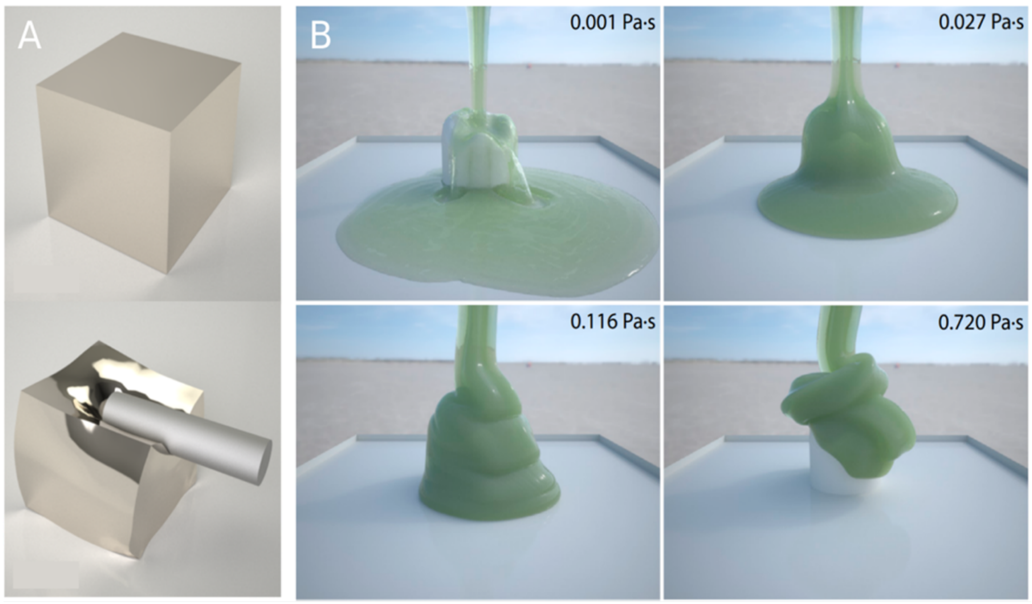

Figure 5. *Mechanical properties can be inferred from the way materials behave when forces act upon them. (A) A metal-looking cube that appears soft once it is deformed by a rod (Paulun et al., 2017). (B) Frames from videos of simulated liquids that appear to vary in viscosity based on their shape and motion cues (van Assen, Barla & Fleming, 2018).*

Our perception of both optical and mechanical properties showcases our prowess at disentangling the visual effects of multiple, complexly interacting physical causes. The presence of highlights depends not just on the reflectance properties of a surface, but also its shape and illumination. How much a material deforms when pressed depends not just on its softness but the amount of pressure that is exerted. What the above research makes clear is that attributing material properties to things in the visible world requires the visual system to solve a cascade of causal attribution problems.

3.3 Issues in the explanation of material perception

The studies we have reviewed contain important insights about material perception yet leave many questions unanswered. Little is known about the developmental trajectory of material perception (Balas et al. 2020), its neural basis (for a review see Schmid and Doerschner, 2019), or how we predictively reason about materials (Bates et al. 2019). Indeed, the diverse – even heterogenous – nature of the phenomenon has frustrated the development of unifying theoretical approaches. This is reflected in the fact that we as yet do not have a good answer to the question: how are material recognition and property perception linked?

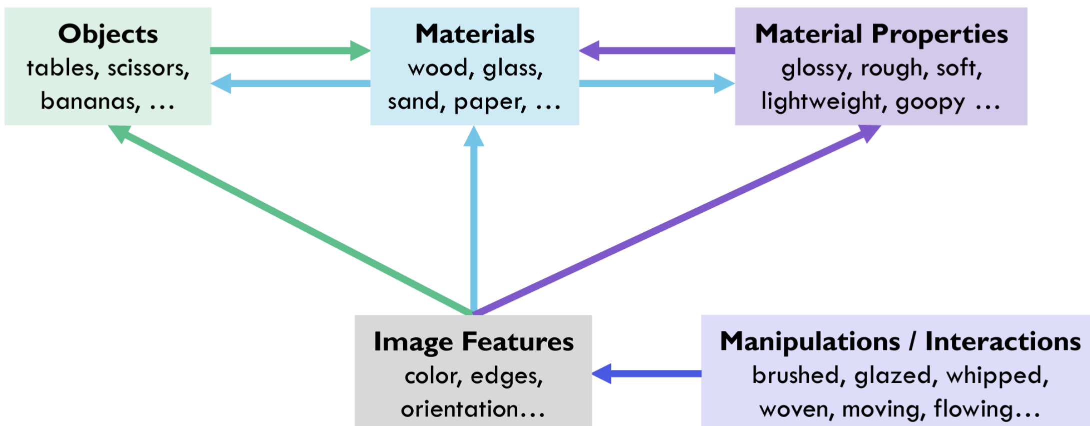

Figure 6. *Schematic of some of the ways in which object recognition, material recognition, and material property estimation are interlinked, and arise from visual features, which are in turn caused by physical interactions between materials and their environment.*

Whatever the relationship, it is complex and dynamic. What visual cues we rely on when seeing materials may vary depending on the task, such as recognizing familiar materials, estimating properties of unfamiliar ones, planning to grasp an object, or predicting how it will respond to interaction with the environment (cf. Fleming, 2017). Furthermore, because the space of materials and their properties is so diverse, the visual dimensions used to identify one material type or property might be useless or inappropriate for another. In a recent study, Schmid et al. (2020) found that people judge how glossy an object is differently depending on what material category it appears to have. It may be useful to think of the relationship between recognition and property perception as going in both directions, in the sense that material category recognition can influence material property estimation, and vice versa (Figure 6; Fleming, 2017; Schmidt et al. 2017; van Assen et al., 2016). We can connect certain profiles of visual features to certain types of material (in some cases via a connection between object types and material types; e.g., tables are typically made of wood). Having recognised the material, we understand through association what material properties it likely has, along with characteristics that otherwise are only accessible through other senses, or through wider world knowledge (e.g., having visually identified a liquid as ketchup, we can recall its taste, and the fact that it tends to come in bottles or sachets and is associated with fast food). Alternatively, we can connect certain profiles of static or dynamic visual features to certain optical or mechanical material properties (e.g., a "bouncing" pattern of motion creates an impression of an elastic material). Having estimated the material properties, we may in turn understand the material type. Each connection between these elements invites further exploration.

Although much work remains to be done, discoveries about material perception have nonetheless raised important issues that speak to how vision is explained more generally. Here we will briefly touch on two of them.

Figure 7. *An illustration of textural representation. The two cut-out regions of grass look to have the same texture or be "made of the same stuff". Yet, they don't consist of any simple repetition of pattern elements and could not be spatially aligned with one another. Their perceptual similarity likely lies in their similar statistical properties, such as in terms of how the orientation, colour, brightness, and spatial frequency of line segments are distributed in the two images.*

The first concerns the nature of the visual system's representation of the visible world. One way of thinking of what and how we see encourages us to think of the visible world as segmented into discrete objects of different shape against scene backgrounds. Such a perspective is reflected in the Gestalt tradition, with its focus on principles of perceptual organization for figure-ground segmentation and grouping (Wagemans et al. 2012). However, materials emphasize a different perspective, according to which the visible world is represented in terms of continuous statistical *texture*, relating to different materials in a scene (Beck, 1983; Julesz, 1975). This alternative approach is popular in computer vision analyses that decompose an image into local and global statistical properties of orientation, contrast, and spatial frequency (Campbell and Robson, 1968; Nishida, 2019; Oliva and Tarralbo, 2001). In natural environments for example, large swathes of the visible scene often appear to be made of the same "stuff"— grass, foliage, river rocks—yet do not have any directly repeating spatial elements (Figure 7). When artificial images are computer-synthesised to have the same high-level image statistics as regions of natural scenes, they are often indistinguishable from one another and even from natural images (Freeman & Simoncelli, 2011; Wallis et al., 2017). This suggests that the visual system relies on a textural representation of the summary statistics within image regions, rather than a precise spatial parsing (although effortful scrutiny can allow an observer to compare the spatial arrangement of elements in textures). An important question is the extent to which seeing materials and their properties relies on the visual system representing statistical properties of images. For example, Motoyoshi et al. (2007) suggested that perceived glossiness could be explained by a simple statistic summarising the distribution of bright and dark points on a surface (glossy surfaces tend to have just a few very bright points, where highlights lie). However, other studies found that surfaces with an identical distribution of brightness can have very different apparent gloss, depending on their apparent 3D shape (Figure 8; Marlow et al. 2012, 2015; Olkkonen and Brainard, 2010).[2] Nevertheless, more complex statistics may play an important role in material perception.

[2] A separate issue is that the very same region of an image can appear as a material texture or scene. Thus, whether a region appears as a material in the first place cannot simply be a result of image statistics or textural representations (Ritchie and van Buren, 2020).

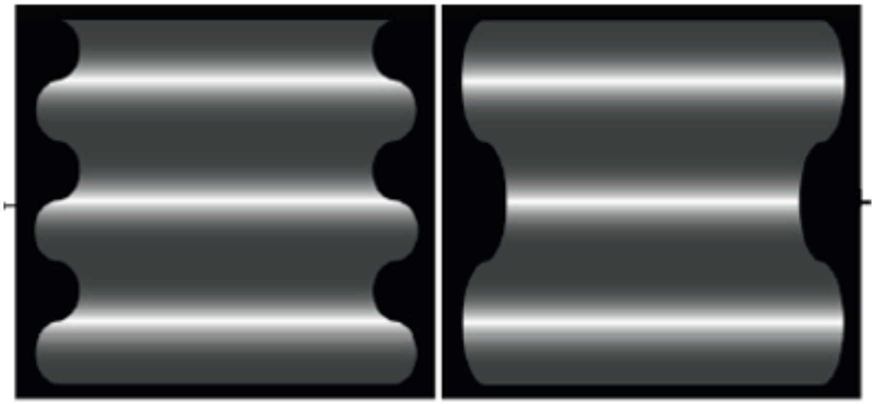

Figure 8. *The effect of 3D shape on gloss perception. The surface on the left is perceived as less glossy than the surface on the right, even though the contrast gradients are identical, due to the alignment between the gradients and the curvatures of the bounding contours, which determine the perceived 3D shape of the stimuli (from Marlow et al. 2015).*

The second issue is perhaps even more fundamental, and concerns whether the visual system "estimates" physical material properties at all. One can imagine a framework according to which the visual system carries out a procedure of "inverse optics" to approximate true physical characteristics (e.g., surface BRDF, mechanical elasticity) as closely as our finite brains will allow, and then recognises the type of material that best matches the profile of estimated properties. However, the complexities of material perception do not easily fit this picture. An alternative perspective is that we learn the ways in which visual appearance and behaviour varies across materials, leading to representations that both cluster materials by type, and form dimensions of material properties based on these types (Fleming, 2014). In other words, under this alternative, our perception of material properties, and their forms of variation, is in a sense by-product of material recognition.

Both these issues are crucial for building models of material perception as illustrated by the use of deep neural networks (DNNs) in vision science. DNNs can be trained to label material categories without first estimating material properties (Bell et al. 2015; Wiesschollek and Lensch, 2016) and can learn complex regularities from images that are diagnostic of perceived gloss without receiving any information about physical surface reflectance (Fleming and Storrs, 2019; Storrs, Anderson, and Fleming, 2021). In this way, recent interests in the representational capacities of DNNs for shapes and texture, which are of interest to philosophical discussions of learning and abstraction (Buckner, 2018), are also foundational to current attempts to explain how we see materials.

4. Material perception and the history of thought

While the empirical study of material perception has only recently taken off, it is striking that (to our knowledge) historically there is virtually no acknowledgment by (natural) philosophers of materials as a visual subject matter. Consider examples drawn from two important epochs in the philosophical discussion of perception.

In the Ancient Period, material properties featured in theories of perception but not as a visual phenomenon being explained. Presocratics like Alcameon of Croton and Anaxagoras claimed seeing is manifested by the reflective properties of the eye as a "gleaming" surface. Theophrastus, in his *de Sensibus*, criticizes this theory on the grounds that many surfaces (such as water or bronze) are reflective, but do not perceive. Aristotle famously held that seeing involved an emanation of form, but not matter, from objects to the eyes and posited a transparent external medium while acknowledging, in *de Anima,* that some solid bodies are also transparent. In both cases our ability to see reflective and transparent materials is not recognized as a perceptual phenomenon also demanding explanation.[3]

In the Early Modern Period, many philosophers followed Locke (including Boyle, Galileo, Hobbes, and Reid) in making extensionally similar distinctions between primary sensible qualities, which reflect the fundamental structure of reality, versus those that do not, and are therefore secondary, including color. Although the distinction was typically grounded in a mechanical or materialist philosophy, for which primary qualities included shape, size, or motion, again materials and their properties did not feature as examples of either type of quality.[4]

[3] An interesting case is Democritus' lost work on colour, for which Theophrastus is a major source. Different material properties such as smoothness, fragility, and hardness feature in his analysis of brightness (Rudolph, 2020).

[4]Though according to Reid we can learn to see anything we might also perceive by touch, including hardness. See Copenhaver (2010).

These examples are by no means exhaustive and we welcome any attempt by philosophers of history to find evidence of material perception discussed in the philosophical canon. However, unlike philosophy, there can be no question of the centrality of material perception to the history of art, in which the aim has long been to depict not just objects, but materials, like the granite of the bowl in Figure 9A. Indeed, some of the most celebrated works in art history, such as van Eyck's *Arnolfini Portrait* (1432) and Sanmartino's *Veiled Christ* (1753), are remembered precisely because of the fidelity of their rendering of materials (Figure 9B - C). One cannot produce these works without (at least implicit) attention to some of the principles that govern material perception – a fact that was known both during the Ancient and Early Modern periods.


A
B
C
D
E
F

Figure 9. *Artistic depictions of materials and their properties. (A) Die Grantischale in der Schleifmaschine (1931), by Johann Erdmann Hummel. (B) Detail from The Arnolfini Portrait (1434), by Jan van Eyck. (C) Detail from Cristo Velato (1753), by Giuseppe Sanmartino. (D) Detail of fresco from the Great Tomb at Lefkadia (3rd Century BCE). (E) Detail of the Charioteer of Delphi (5th Century BCE). (F) Detail of Still Life with Fruit and a Lobster by Jan Davidsz. De Heem (1640 – 1700), used as a stimulus by Di Ciccoci et al. (2019).*

In *the Republic,* Plato makes passing reference to *skiagraphia,* or "shadow-painting", which was an important artistic practice in antiquity and involved depicting surface highlights, as in Figure 9D (Tanner, 2016),[5] Also sculpting to imply mechanical properties was clearly already mastered (Figure 9E). Similarly, at roughly the same time that philosophers were distinguishing primary and secondary qualities, artists like Wilhelmus Beurs (1656 – 1700) were developing detailed manuals for convincingly painting the material properties of objects like grapes (their gloss, translucence, and bloom) in the interest of mastering *stofuitdrukking*, or the "rendering of texture" of materials (Figure 9F).

Increasingly, artistic practice has itself become the source of insights for the science of material perception. For example, a series of studies have investigated the depiction of material properties like glossiness in still life and the fidelity of paintings that follow Beurs' instruction (di Cicco et al. 2019, 2020), and Phillips and Fleming (2020) investigated the ability of subjects to distinguish apparent layers of different materials in stimuli inspired by sculptures like the *Veiled Christ*. This reflects a more general belief that the scientific study of material perception has something to gain from artmaking, both past and present (Schmidt, 2019).[6]

5. Materials and puzzles of perception

Material perception is an exciting and rapidly developing branch of vision science, as we have seen. In this section we illustrate how, on the one hand, careful attention to how we see materials

[5] Another related, but obscure notion, is that of *poikilia,* which was associated with many properties of artworks originally applied to textures and fabric (see Grand-Clement, 2015).

[6] The Presocratics also looked to art to inspire their theories of perception. Democritus wrote a (lost) treatise on painting, and Empedocles' theory of color was heavily influenced by color mixing (Ierodiakonou, 2005).

has the potential to bring new insights to a number of philosophical issues related to perception, and on the other, how greater philosophical scrutiny of the phenomenon can in turn benefit scientific practice.

5.1 The subject matter of perception

Minimally, research on material perception makes clear that the subject matter of perception includes *stuff* (Adelson, 2001). However, theories of the individuals picked out by perception are generally object focused: what we primarily see are "bodies" that are bounded, cohesive, rigid, solid, and have three-dimensional shape (Burge, 2010), or are structured and mereologically complex individuals (O'Callaghan, 2016). Moving beyond these views, Green (2019) suggests that groups that conform to Gestalt principles are perceived as perceptual objects as we can visually track things that violate conditions like cohesion, such as shapes that appear to "pour" from one location to another, so long as they move in a tightly clustered unison (Howe et al. 2013; vanMarle and Scholl, 2003). Such a conclusion comes naturally from thinking about material perception directly, as we can also readily predict and reason about liquid-like materials (Bates et al. 2019), even if it is in a manner that is different than for objects. Indeed, if stuff is also a fundamental subject matter for vision, then the fact that our ability to track substance-like stimuli that expand and contract is diminished in comparison to tracking rigid bodies may simply show that the wrong standard is being used to measure perceptual object-hood.

Appreciating materials as a distinct type of perceptual subject matter (a term we prefer to "individuals") also opens new avenues for exploring the contents of material perception. Typically, perceptual content is characterized in terms of attribution of a property to a particular, or quantified-over entity (Burge, 2010, Davies, 1992). How does this picture map onto materials? One issue concerns what property is attributed to what thing. Recall the familiar puzzle of material constitution presented by the statue and the clay; when the one object, the statue, is destroyed, the other object, the clay, persists. Vision may trade in a similar bifurcation: we see a statue made of clay, but we can also a see a portion of clay take the shape of a statue. In such cases, how do we capture the shift in perceptual content?

Another issue concerns *where* material properties are attributed. Many optical properties are attributed directly to an object's surface (for opaque materials) or to its whole mass (for transparent or translucent materials). Mechanical properties such as viscosity or springiness may have a similar "depth". In the case of material types, however, the localization is less clear. If we look at a block of clay, do we see the whole mass as made of the material, or does the attribution end somewhere near the surface and the interior remains undifferentiated (Koenderink, 2015)? Vision science may benefit from philosophers exploring such questions.

5.2 The ontology of material properties

Under contemporary usage, "secondary" qualities are those that are mind-dependent, with color being the prime example. In light of this, color ontology has become a major topic in its own right in the philosophy of perception (Chirimuuta, 2020), and it is not unusual to develop theories of color ontology that are then generalized to other, non-visual examples of secondary qualities like musical pitch or odors (e.g., Isaac, 2014). Some material properties may be secondary qualities as well. For example, how glossy or "shiny" something looks can be dissociated from its reflectance properties, just as with color (Figure 10). Thus, while whether something is wooden or stone does not seem mind-dependent, gloss, and other material properties, may present as much of a "problem" of realism as color (cf. Hilbert and Bryne, 2003).

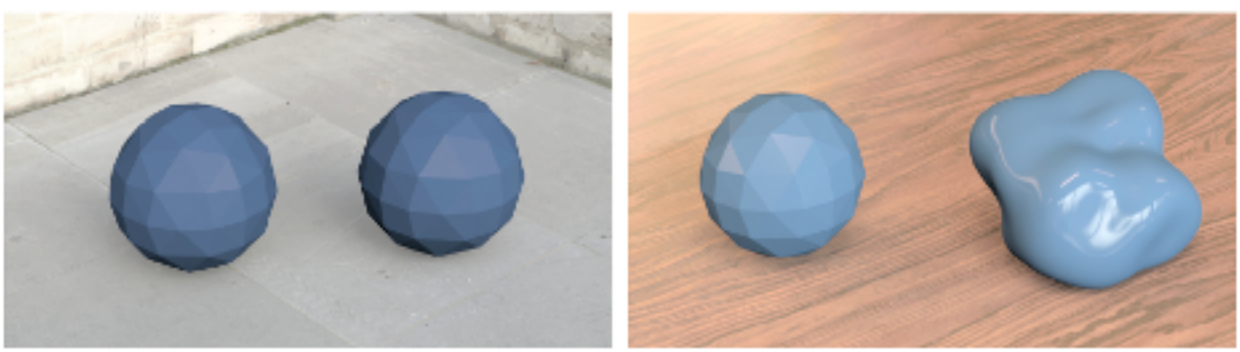

Figure 10. *Left two rendered objects that appear identical in surface gloss, but with different BRDFs. Right two rendered objects that appear to have different surface gloss that are composed of identical material. Reproduced with permission from Vangorp, Laurijssen, and Dutre (2007, Figure 1).*

The same range of theoretical positions about color ontology may be available for gloss. One possibility is to endorse gloss eliminativism or revisionary realism (Gert, 2008; Hardin, 1993), or alternatively, to treat gloss as relational or response-dependent as with other secondary qualities (Cohen, 2004). According to pragmatic views, the visual system is not structured to represent colors as such but rather to treat chromatic properties of surfaces as one of many cues for object recognition (Akins and Hahn, 2014; Chirimuuta and Kingdom, 2015). Extending such a position to gloss may fit well with the view, described earlier, that rejects the idea of material property estimation as inverse optics. Another possibility is that material properties like gloss may not easily be characterized as either a primary or secondary quality, and instead straddle the division.

Material perception may also require re-evaluation of theories of secondary qualities more generally, and color in particular. Minimally, gloss perception can also modulate color constancy (Granzier et al. 2014; Wedge-Roberts et al. 2020), which theories of color ontology may also need to take stock of as has been the case for color science (Maloney and Brainard, 2010; cf. Chirimuuta, 2020). But more provocatively, it is notable that colorfulness is often treated as itself a material property that is diagnostic of material type (e.g. Fleming et al. 2013; Baumgartner et al. 2013). From such a perspective, color is just one of many optical properties revealed by the interplay between illuminations and surfaces.

There are also other material properties we see that do not neatly qualify as optical or mechanical, an instead seem emotional or aesthetic in nature. For example, our appreciation of the sculptures in Figure 3 clearly involves attributing aesthetic properties based on the materials utilized (Schmidt, 2019). One interesting branch of material research has been framed around the Japanese concept of *Shitsukan* (“quality / texture / feel”), which defies neat physical correlates. A piece of sushi may have the Shitsukan of being moist, translucent, delicious, cold, and fresh – only some of which translate to physical dimensions (Komatsu & Goda, 2018; Spence 2020). Here insights may be gained from work at the intersection of philosophy of perception and aesthetic experience (Nanay, 2016).

5.3 The perspectival character of material perception

An ever-present feature of visual experience is that we always see things in a particular way. For example, there is some sense in which a rotated coin looks similar to an ellipse viewed head-on, or a white surface in a shadow appears similar to a grey surface directly illuminated. Such experiences may even seem contradictory; that the coin looks both round and elliptical or the surface both white and gray. While the example of the coin may point to the underappreciated topic of spatial perception (Green and Schellenberg, 2018), the perspectival character of perception is highly salient in the case of material perception as well (Figure 11).

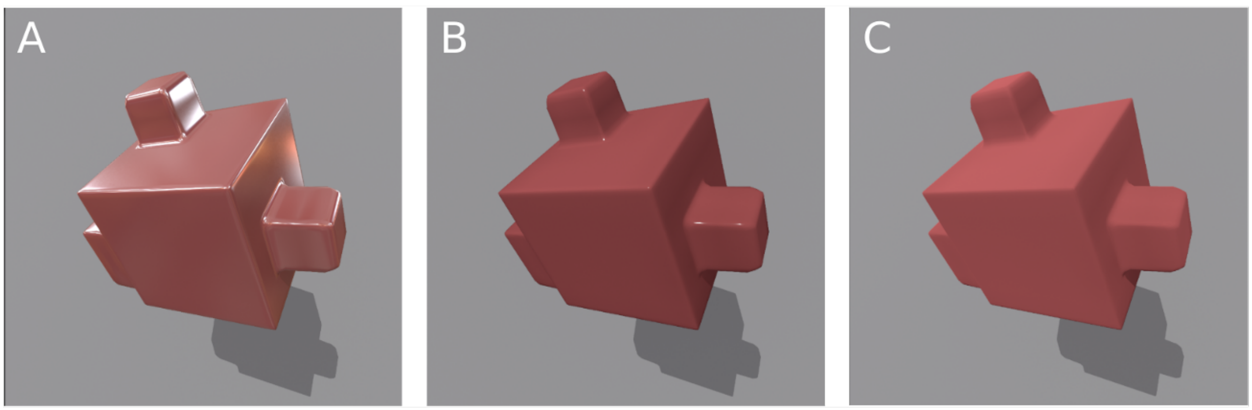

Figure 11. *The perspectival character of material perception. Images (A) and (B) are renderings of an identical material – the only difference is that (A) is illuminated by a complex natural environment, while (B) is illuminated by a lamp emitting light in only one direction. The glossiness of the material is far more apparent in (A), where the complex illumination allows the surface to manifest many highlights. In some ways, the image in (B) looks more similar to the matte material in (C), which is illuminated by the same natural environment as (A).*

Such a case may have consequences for theories of the perspectival character of visual experience. One common proposal is to associate this character directly with representations of relational properties between observers and their environment, which is contrasted with representations of visual attributes such as the actual shape or color of an object (Cohen, 2010; Schellenberg, 2008). Alternatively, it may be that it is the structural relationship between these representations of relational properties and visual attributes that accounts for such cases (Lande, 2018). At a more fundamental level, examples like Figure 11 also show that the perspectival character of material perception is closely tied with how we represent optical properties like gloss (cf. Morales, Bex, and Firestone, 2020).

Here again philosophical work remains to be done in terms of what it is we see when we look at highlights, which are themselves a reflection of the illuminating scene. If we can literally see through mirrors and pictures (for example Yetter-Chappell, 2018), then does the same hold for highlights in which the structure of the scene is partially visible? Or in the case of mirrored, irregular surfaces, does this require switching between seeing surfaces as mirrors to the scene, or as the scene as a reflected texture that contains important diagnostic distortions for resolving surface shape (Fleming et al. 2004)? Such questions once more remain to be explored.

5.4 Multimodal material perception

Although we have focused on vision, material perception is clearly multimodal: we can distinguish between paper and plastic not just by sight, but by how it feels to the touch (Baumgartner, Wiebel & Gegenfurtner, 2013), or the sound it makes when deformed (Giordano & McAdams, 2006). In light of this, material perception relates to a number of philosophical topics concerning multimodal perception.

First, the topic of the subject matter of perception is also a multimodal one (Green, 2019; O'Callaghan, 2016), and it is worth considering again whether objects provide the appropriate theoretical foundation. While it may be obvious the subject matter of touch includes stuff (not just objects), it is worth considering whether sounds *themselves* should be better thought of as acoustic *substances* that flow, form, dissolve, an undulate, and how such a position relates to the influential view of sounds as events (O'Callaghan, 2007). Second, touch has in part been difficult to define as a sense, in part because of the heterogeneity of what it detects (de Vignemont and Massin, 2015; Fulkerson, 2020). But as we have seen, many of these properties, such as texture, hardness, and solidity, are available to vision as well, and appreciating this overlap may help in delineating sense modalities. Finally, material perception also offers a different perspective on Molyneux's problem: would a formerly blind person, given the ability of sight, readily recognize distinct shapes that they previously only perceived from touch? While this question is multifaceted (Matthen & Cohen, 2020), the same question can be posed as to whether mechanical properties revealed by touch would also be quickly matched with vision.[7]

5.5 Categorizing materials and the nature of perception

In our discussion we have characterized recognizing material categories as a perceptual phenomenon. Such a position is potentially philosophically controversial in several related respects.

First, we have implied that attributing material categories to what we see is a facet of our visual *experience*. However, it is openly debated whether visual experiences are so rich that they include representing properties not just of shape or color but also object categories like being a tree (Siegel, 2006). Thus, it may similarly be debated whether visual experiences represent material categories as we have suggested. Second, we have assumed that material categorization is largely proprietary to the visual system. This position has been taken to entail that visual categorization involves *conceptualization*, whereas others assert that vision only involves representations with non-conceptual content (Gauker, 2017; Mandelbaum, 2018). Finally, we have emphasized that material categorization can modulate material property estimation (Schmid et al. 2020; Figure 6). Such feedback relations have also featured in discussions of whether vision is cognitively penetrated (Tuefel and Nanay, 2017), with some questioning whether visual recognition is itself a perceptual phenomenon precisely because of its recruitment of memory (Firestone and Scholl, 2016).

Underlying these inter-related topics is the issue of how we differentiate perception from cognition (if at all). Does the division depend on the format of the representations they trade in (iconic vs abstract) or their information-processing architecture such as informational encapsulation or stimulus dependence (Quilty-Dunn, 2020)? Greater attention to material perception may offer important case studies for these debates. For example, the material-weight illusion (Seashore, 1899) could be taken to provide evidence either that material categorization is perceptual, or that the estimation of weight—a material property—is cognitively penetrable.

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[7] Newly sighted individuals are much better at discerning the number of objects in a scene when motion cues are present (Ostrovsky et al. 2009). It remains unknown whether such individuals would be able to discern mechanical properties from presentation of stimuli like in Figure 5.

6. Conclusion

Almost all our visual impressions arise from the interaction between light and materials, only some of which form objects. We recognise rich repertoires of material types and perceive subtle distinctions in material properties. Both science and philosophy have long focussed on seeing *things*, to the neglect of *stuff* (Adelson, 2001). Greater attention to material perception may require a shift in how we think of what, how, and why we see.

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