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The Legacy of Willem Beurs – Bridging the Gap between Art and Material Perception

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Abstract

Dutch Golden Age painters could convincingly depict all sorts of materials. How did they do it and how do we perceive them as such, are questions that only recently have started to be addressed by art historians and vision scientists, respectively. This paper aims to discuss how a booklet of pictorial recipes written by the Dutch painter Willem Beurs in 1692 constitutes an index of key image features for material depiction and perception. Beurs' recipes connect different materials according to their shared visual features, and offer the profiles, i.e., the optimal combinations, of these features to render a wide range of materials. By combining representation and perception, the knowledge of painters about the depiction of materials can help to understand the mechanisms of the visual system for material perception, and these in turn can explain the pictorial features that make the pictorial representation of materials so convincing.

Keywords

Art and perception, material perception, material depiction, pictorial cues, Willem Beurs, seventeenth-century paintings

1. Introduction

As for many other phenomena that are of interest to vision scientists, e.g., the perception of depth, color, and lightness (Spillmann, 2007), the discoveries made by the artists over the centuries about the appearance of materials largely preceded its systematic scientific investigation.

Dutch Golden Age paintings, in particular, are prominent examples of the effective visual communication of materials and their properties. In this paper, I will discuss the work of Willem Beurs (1656–1700), a painter who compiled an *ante litteram* index of key features for material perception by writing a simple painting manual. Son of a shoemaker, Beurs soon followed his passion for painting, and in 1671 he became a pupil of Willem van Drillenburgh. Under his teaching, he was quickly able to paint a “sweet landscape” (Houbraken, 1718). He then moved to Amsterdam where he started to paint portraits, and finally to Zwolle where he mainly focused on flower still lifes. It was in Zwolle that Beurs started to make a living from teaching painting to four wealthy ladies, for whom he wrote his treatise on the mixtures and treatment of oil paint, with declared didactic purposes. The book, written in 1692, is called “*De Groote Waereld in ’t Kleen Geschildert, of schilderagtig tafereel van ’s Weerelds Schilderyen kortelyk vervat in Ses Boeken verklarende de Hoofverwen haare verscheide mengelingen in Oly, en der zelve gebruik. Omtrent de meeste vertoningen van de zigtbare nature. Leerzaamelyk den liefhebbers en leerlingen der Ed. Schilderkonst medegedeelt van Wilhelmus Beurs, Schilder*” which means “The Big World Painted Small, or painterly tableau of the World in Paintings concisely presented in Six Books explaining the Main Colors, their various mixtures in Oil and their use. Concerning most phenomena in visible nature. Instructive for lovers and pupils of the Noble Art of Painting, set forth by Wilhelmus Beurs, painter” (Beurs, 1692; Lehmann and Stumpel, in press) (Fig. 1).

Beurs’ treatise is rightly valued in the field of (technical) art history as an important record of pictorial procedures (De Keyser *et al.*, 2017; Pottasch, 2020; Stols-Witlox, 2017; Wallert, 2012; Wiersma, 2020), but it has never been considered, or even known, outside the realm of art history. Here, I will argue that its content contributes to the understanding of the mechanism of material perception, fostering the collaboration between the fields of art history and visual material perception.

Vision scientists and art historians have devoted a large body of research to the rendering and the perception of depth in art and its revealing cues (Brooks, 2017; Cavanagh, 1999; Pepperell and Ruschkowski, 2013; Saxena *et al.*, 2008; Spillmann, 2007; Zimmerman *et al.*, 1995), but paid less attention to the rendering of materials (Dupré, 2011; Gombrich, 1976). Gombrich (1976) advised the art historians to take interest in the depiction of the appearances of

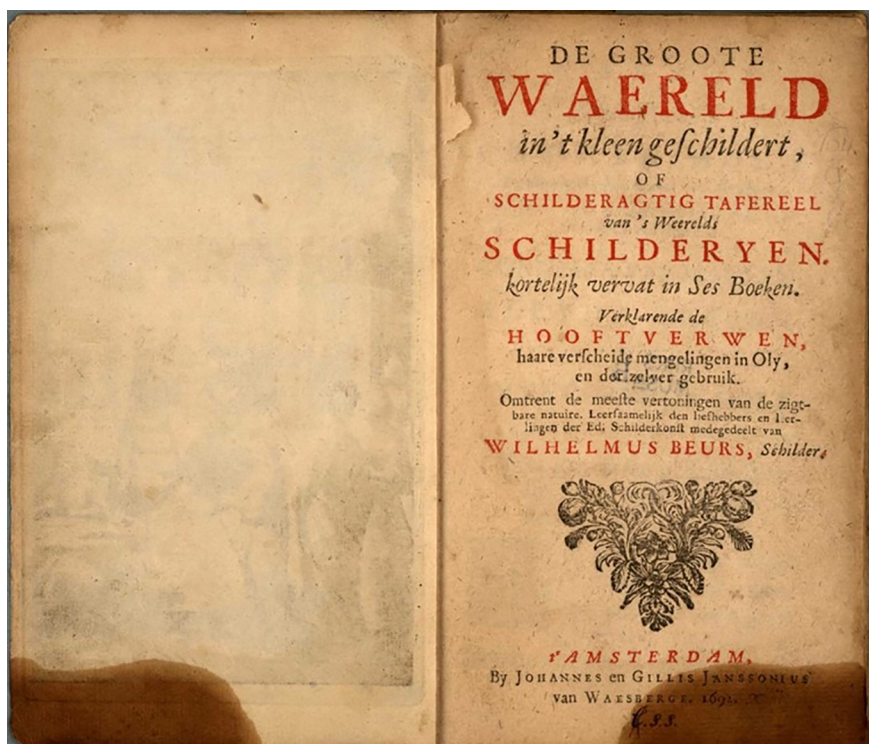


Figure 1. Title page of the treatise *The Big World Painted Small* (1692) by Willem Beurs.

materials, to connect styles and their evolution of formulae to render reality. For example, before the 15th century, Gombrich (1976) noted, the distinction between diffuse and specular reflections – what he called “illumination and sparkle” – was avoided altogether. The lustrous appearance of jewelry and precious metals, or the texture of silk and velvet, were not rendered through the use of image features but via the direct application or stencil of the real materials on the canvas.

To gain a holistic understanding of materials’ depiction and perception, bridging the fields of vision science and (technical) art history is necessary.

Sayim and Cavanagh (2011) investigated the knowledge and the image features used by artists over the centuries to depict transparency. Apart from the often-used luminance constraints, that match well the X-junctions theory of Metelli (1974), they also identified material constraints. In particular, the material property of glossiness can be diagnostic for transparency. Sayim and Cavanagh (2011) illustrated how in the pictorial practice, the presence of highlights on a surface can constitute the only revealing cue of its transparency. Fleming and Bülthoff (2005) and Motoyoshi (2010) came to similar

conclusions about the role of the highlights for the case of translucent objects made via computer rendering, i.e., the perception of translucency can be enhanced by the presence of specular reflections. Wijntjes *et al.* (2020) identified the Number of Distinguishable Levels (NDL) and a set of image cues for translucency perception of sea waves in paintings. They found that different levels of translucency could be retrieved according to the shape of the waves, e.g., bigger waves afford more and clearer cues. Van Zuijlen *et al.* (2020) carried out a big-scale experiment of material perception in paintings. After testing the perception of a set of properties for different materials depicted in paintings, they concluded that the mechanism of material perception is independent of the medium of representation, as their results were in agreement with previous studies conducted on photographs (Fleming *et al.*, 2013) and computer renderings (Zhang *et al.*, 2019). A similar conclusion has been reached more recently by Delanoy *et al.* (2021) who found no significant perceptual differences between computer renderings and paintings for the judgment of low- and mid-level material properties.

Koenderink and van Doorn (2001) investigated the issue of shading in the case of translucent materials. They suggested that it is not necessary to know the exact physics of the subsurface scattering of the radiation at every point and direction, but rather establish some general rules that can help to render the effect of translucency, as much as painters were able to do via image features and shortcuts.

Perception-driven approaches are also rapidly gaining relevance for computer graphics, a field that strives to “generate an image that evokes from the visual perception system a response indistinguishable from that evoked by the actual environment” (Hall and Greenberg, 1983). However, in realistic image synthesis, there is no agreed standard of realism to judge the success or failure of the final result (Ferwerda, 2003). Computationally expensive, physically-based renderings are increasingly replaced by perceptually-relevant renderings, approximating details that would anyway go unnoticed by human observers (Ferwerda, 2003), especially in the case of real-time and interactive renderings, like virtual reality (Bartz *et al.*, 2008) and video games (Barla, 2017). Khan *et al.* (2006) have used such a perception-driven procedure in photo-editing applications to automatize the process of materials’ manipulation. Motoyoshi *et al.* (2005) demonstrated that material appearance can even be altered via luminance re-mapping, a quick and effective method to transform opaque materials into translucent or metallic materials, relying on perceptually-relevant image features not dissimilar from pictorial techniques.

This paper aims to discuss the relevance of Beurs’ treatise for material depiction and perception. I will start by presenting how Dutch Golden Age painters became experts in seeing and depicting materials.

2. Science and Art in the Dutch Golden Age

2.1. Learning to See

The main trait of the Dutch Golden Age paintings can be summarized with the word *realism*. Realism not only in the thorough reproduction of everyday life scenes and sights (which compiles an invaluable record of the Dutch 17th-century culture), but also realism in the rendering of the depicted materials. Realism though is a problematic term, firing semantic debates when applied to art, as it can take on several meanings (De Vries, 1991; Slive, 1962; Westermann, 2016). And, as argued by Hoffman (2019), there is no such thing as the “true perception” of the real world, there is only our efficient interface shaped by evolution for the sake of the survival of the human species. A more appropriate term in the present discussion will be *convincingness*, to clearly distinguish its subjective and perceptual nature from an ‘objective’ reality.

The development of the convincing depiction of the world’s appearance pursued by Dutch 17th-century painters coincides with the occurrence of a combination of factors, the first being the Scientific Revolution happening at the time. This is in line with the idea of “synchronicity of change” typical of a metabletic shift (van den Berg and Croes, 1961), i.e., the changes in human activity throughout history correspond to simultaneous changes in related fields (Mook, 2009). Craftsmanship, like that of painters, is considered to be at the core of the Scientific Revolution and the new empirical science (van Berkel, 2010). The act of painting was regarded not to be different from a scientific inquiry since both were aimed at understanding and describing the world. By learning to see, painters claimed their role “as observers, representers, and knowers of nature” (Smith, 2006), conducting their experiments and testing their theories via the production of images.

Dutch 17th-century painters’ knowledge of the various ways in which light can interact with surfaces and materials was built on the observation of nature and rooted in the contemporary scientific writings on optics. At the beginning of the 17th century, Karel van Mander (1548–1606), Dutch painter and art theoretician, in his most famous work, *Het Schilder-Boek* (1604), had already discussed several terms to describe the interaction of light with surfaces – mirroring (*spiegeling*), reflection (*reflectie*), polish (*glans*), re-reflection (*weerschijn*), and reverberation (*reverberatie*) (Dupré, 2011). Similarly, Beurs distinguishes between *glans* and *reflexie* in his manual, while demonstrating a keen interest in contemporary optical theories. For example, in the second and third chapters of the fourth book of his treatise (Beurs, 1692; Lehmann and Stumpel, in press), details of the wave theory of light formulated by Christiaan Huygens (1629–1695) in the *Traité de la Lumière* (1690) emerge within the pictorial recipes for metal and glass.

The (re)discovery of optical tools, like mirrors and lenses, and instruments like microscopes and the camera obscura allowed these 17th-century painters to investigate nature in the greatest number of details, such that even the invisible world became visible. The use of camera obscura by Dutch 17th-century painters has been most extensively investigated for the case of Johannes Vermeer (Fink, 1971). Jelley (2013), for example, provided a detailed description of a studio experiment that demonstrates how projections from the camera obscura could have been used by Vermeer during his painting process. Jelley (2013) proposed that the projected images could have been traced on oiled paper, to then be transferred onto the canvas during different stages of the painting (the underdrawing, the addition of highlights, etc.). This method allows for the rendering of the features characteristic of Vermeer's style, like the skillful transitions between tonal values and the variable focus.

2.2. *The Importance of the Medium*

Next to the observation of nature and the employment of optical devices, the compelling, life-like rendering of materials in Dutch Golden Age paintings has been ascribed to the use of oil paint and its methods of application. The paint-handling techniques were heavily dependent on the physicochemical properties of oil paint. As suggested by Lehmann (2015), “materials cannot be separated from representation”. During the 15th century, following the leading efforts of Jan van Eyck (1390–1441), painters started to transition from the use of tempera to oil paint, discovering a whole new range of possibilities. Lehmann (2015), building on the theory of affordances formulated by Gibson (1979), offered a novel understanding of how oily pigments could be translated on the canvas into skin, fur, or bronze.

The list of oil's affordances begins with transparency, the foundation of glazing (see Note 1). The glazing technique consists in applying a translucent layer, made of little pigment and much oil, on top of an opaque layer of paint. Glazing allows for the creation of new tints of deep, saturated colors, otherwise impossible to achieve. Colorimetric measurements (Elias, 2012) and modeling functions (Elias and Simonot, 2006) have shown that the exceptional level of color saturation allowed by glazing cannot be achieved by merely mixing pigments. This effect is due to the optical mixing mechanism. Glazing also smooths the asperities on the surface of the painting which are due to the protruding pigments' particles, thus producing a glossy effect on the surface. Such smoothing of the surface also increases the contrast and saturation of the colors. This effect has been reported for the varnish layer (De la Rie, 1987), but it has never been investigated for the glaze, to the best of my knowledge. With the addition of a number of glaze layers of different thicknesses, the painter could modulate the apparent values of lightness and

saturation, creating a glowing effect, as if the light was radiating from within the painting (Elias and Simonot, 2006). It is no coincidence that Arnheim (1974) compared the glaze to the illumination of the object, i.e., “the perceivable imposition of a light gradient upon the object brightness and object colors”.

The following oil’s affordance is malleability, due to its adjustable degree of viscosity. The manipulation of the rheological properties of oil was determinant to achieve both the smooth and invisible touch of the *fijnschilders*, by mixing the oil with thinning agents, as well as the rough and plastic style of Rembrandt or Rubens, by thickening the oil (De Viguerie *et al.*, 2009). Finally, the slow-drying process of oil allows for the attainment of smooth color transitions and retouching.

However, the binding medium, i.e., the oil, is not the sole cause of a convincing visual effect. Other elements play a role. For example, the absorption and scattering properties of the pigments and their interaction with oil need to be considered according to the desired visual outcome. A translucent glaze requires the use of pigments with a refractive index close to that of the oil medium, for the light to be mostly absorbed; vice versa, an opaque layer of paint is made by using pigments with a higher refractive index so that most of the light is scattered. Finally, the layers’ building up should not be ignored. It is easy to think of a painting as a 2D image, and overlooking its complex, 3D nature resulting from the superimposition of several layers that interact with each other (see the Kubelka–Munk theory for the formalization of the optical interaction between paint layers; Kubelka and Munk, 1931) and all serve a visual purpose.

De Ridder and Wallert (2011), in this regard, presented the case of the depiction of human skin by Adriaen van der Werff (1659–1722), who developed a quantitative painterly procedure for the successful rendering of skin. This procedure was based on mixing and layering the proper pigments and binders in exact amounts, to accurately mimic the optics of skin, meaning that the ordering of the layers of paint found a qualitative correspondence to the reflection, scattering and absorption phenomena happening between the layers of human skin.

The study of the materials, left out of the realm of art history (Note 2), was integrated in the fields of technical art history and painting conservation. This trend, however, started to be inverted in the 1990s, with what Lehmann (2015) called a “re-materialization” of art theory. To contribute and further develop this new role of materials, Lehmann formulated a “theory of materials”, starting from Arnheim’s idea (1957) that the properties of the medium help to mold the description of reality. The starting point of this theory happens to be oil, the medium that revolutionized Western painting with all its new affordances and possibilities, but which, at the same time, was not granted the full

attention of scholars until Stumpel began to investigate it in 2007 (Note 3). The historical written document that most aligns with this central view of oil as a tool to render reality, providing practical advice and how-to instructions, is the booklet written around the end of the 17th century by the painter Willem Beurs.

3. Willem Beurs and “The Big World Painted Small”

According to Beurs (1692; Lehmann and Stumpel, in press), his treatise intended to fill the “lamentable” gap “about the materials, the mixing and use of oil paints”. This book is of particular interest and importance because it is the first written source completely devoted to oil painting, offering concrete instructions to both amateurs and experts painters. Similar to a cookbook of recipes to be found in a kitchen, the treatise begins with the basics and the tools: how to prepare the mixtures of oil and pigments, which brushes to use, how to prepare the support, and which colors go or do not go well together. Throughout the rest of the chapters, Beurs instructs the reader on how to paint all sorts of materials, starting from snow to illustrate the purest white one can find in nature, up to the skin of human beings, “who – being wise and intelligent – can make amazing use of the visible world” (Beurs, 1692; Lehmann and Stumpel, in press).

Akin to empirical research, painters believed that the first step of artistic creation was the close observation of the natural world (Snyder, 2015). Sketching and painting *naer het leven* (from life) was a regular practice (Westermann, 2016), and Beurs was no exception to such advice. Already in the preface, he mentions that the content of the treatise was not meant to be fruitful only for the painters who are willing to practice, “but it is also useful for all types of persons if they only want to observe and investigate visible things more closely” (Beurs, 1692; Lehmann and Stumpel, in press). When instructing on how to choose the best color combinations, Beurs recommends “the diligent observation of the supreme teacher, nature” (Beurs, 1692; Lehmann and Stumpel, in press).

Throughout the treatise, he demonstrates a deep knowledge of the scientific theories and discoveries of the time about light and colors, mentioning the work of Robert Boyle, Christiaan Huygens, and René Descartes. In a sort of literature review, he refers to several scientific facts to support the reader in better understanding the nature of things. For example, he mentions the fact that colors “owe all their diversity to the composition of the surfaces of the objects on which light falls and acts in various ways” (Beurs, 1692; Lehmann and Stumpel, in press), or that objects are usually seen under different light depending on the time of the day, and from different viewpoints, changing their appearance. Knowing how light reflects and refracts when interacting

with different materials, like snow or glass, would give intellectual satisfaction to the painter, but this would be of “little or no relevance for painters, as long as they have a good understanding of the pigments and how to prepare them and paint with them” (Beurs, 1692; Lehmann and Stumpel, in press).

Painting *naer het leven* was not the only approach, and not always feasible, especially with quickly decaying subjects like food and flowers, or with expensive goods like jewels and luxurious fabrics. The detailed observations could be enhanced and dramatized in the studio as desired, by painting *uyt den gheest* (from memory), and by relying on established recipes and conventions like the ones to be found in Beurs’ treatise. A famous example is the *Vase with Flowers* painted by Bosschaert (Fig. 2), portraying an impossible bouquet meticulously rendered but illuminated by impossible lighting. In this painting, the mastery of Bosschaert in the *stofuitdrukking* or ‘expression of stuff’ (Wiersma, 2020), of each flower is the center of attention, at the expense of



Figure 2. Ambrosius Bosschaert the Elder, *Vase with Flowers in a Window*, 1618, Mauritshuis, The Hague, The Netherlands. The image was downloaded royalty-free for non-commercial use from www.mauritshuis.nl

realistic lighting and composition. As reported by Slive (1995), each flower in this painting is like a portrait which has been the subject of an individual study: “no flower is thus left in the shadow, every corolla emerges clear and radiant, in its own local color, in the same ‘impartial’ light”.

The incoherent lighting distribution is an example of an optical phenomenon that can be rendered wrong without bothering the eye of the observer or even being noticed, revealing the tolerance of the human visual system for illumination incongruities. Such tolerance, found and exploited by painters, was later confirmed in perceptual experiments in which participants failed to quickly identify inconsistent illumination directions (Ostrovsky *et al.*, 2005). These results indicate that the lighting does not need to be globally consistent to estimate the local illumination of the objects as convincing, validating Beurs’ teaching approach on how to paint. In the book, each object or material is treated separately, describing how they should appear under a standard, “neutral light”, meaning that one side of the object – usually the left (Mamassian and Goutcher, 2001; McManus *et al.*, 2004; Stone *et al.*, 2009) – reflects the light while the other side is shaded. Such standard chiaroscuro is also the most effective of the four illumination types proposed by Beurs (1692; Lehmann and Stumpel, in press) (in sunlight, in a neutral light, in shadow, at night), to obtain the most powerful rendering of depth. It has been shown in psychophysical experiments that shape and relief perception depend on the lighting conditions (Christou and Koenderink, 1997; Ho *et al.*, 2006). The individual pieces, thus rendered with the illumination that best serves their most convincing rendering, can be combined in the final composition, as is the case of Fig. 2.

What matters most in Beurs’ treatise, beside the teaching of the correct use of pigments and oils, is the knowledge of the image features in the build-up of the layers, the patterns of light relevant to our visual system, which resonate with our previous knowledge of materials and thus trigger the convincing appearance. The pictorial procedure embodies the knowledge of the visual shortcuts responsible for the convincing visual outcome as much as the affordances of oil, that is why they need to be studied together (Lehmann, 2015; Wallert, 2012).

4. An Index of Key Features for Material Perception

According to Van Eikema Hommes (2002), the pictorial recipes written between the 15th and the 18th century, including Beurs’, provide “systems [...] to render the modeling of the objects and their textural characteristics in the quickest, best and easiest way”, and “[t]he great advantage of following these and other instructions was that the rendering of effects did not continually have to be reinvented”.

The ‘system’ offered by Beurs in his treatise, which may not come across so explicitly from a first reading, consists of an index of key features to depict materials.

The term ‘key features’ here means that the established image features proposed by Beurs to render different materials work as perceptual cues regardless of the illumination and viewing conditions. For example, when painting a polished ceramic jug with a shiny metal cap, it does not matter whether one places it in an outdoor shaded patio, as in Fig. 3 (above), or even behind the shadow of a hung duck, as in Fig. 3 (below). The jug invariably shows sharp, high-contrast specular reflections on the cap, and these cues will always



Figure 3. Examples of key features for material depiction and perception. The ceramic jugs show sharp and bright, window-like specular reflections on the metal cap despite the illumination conditions. On the left is shown the detail with the jug and, on the right, the entire painting. (Above) Jan Steen, *The Dancing Couple*, 1663. National Gallery of Art, Washington, DC, USA. The image is available in the public domain. (Below) Joachim Beuckelaer, *Christ in the House of Martha and Mary*, 1568. Museo del Prado, Madrid, Spain. Authorized download of the image was granted by the Image Bank of the Museo del Prado.

trigger the intended material perception despite the (in)consistency with the illumination field or viewing direction. Moreover, both jugs in Fig. 3 show a conventional window-shape reflection on the metal cap (Pirenne, 1970).

I argue that there are two main reasons to explain why Beurs instructs to use the specific features reported in his recipes, and why they work so effectively on our perception.

The first reason is that they capture the most likely appearance of the objects. According to Brunswik's (1952) Theory of Probabilistic Functionalism (TPF), organisms (including humans) are continuously engaging in probabilistic processing of the ambiguous information provided by the environment. Such ambiguity could be resolved by choosing the most likely option based on expectations and previous experiences. As noted by Gombrich (1976), the likelihood of a given optical phenomenon heavily influences our perception. As an example, he discusses the long-known artistic convention which states that something hollow has to be painted black, in contrast to something protruding which needs to be painted white, since the former is a receding color and the latter is advancing. Such mode of representation, Gombrich (1976) continues, was deemed valid for paintings, because it was taken for granted to also happen in nature, i.e., "hollows are dark and ridges are light". Concave or hollowed surfaces are subject to the vignetting effect under diffuse ambient illumination, which causes hollows to appear darker since part of the light has been occluded (Langer and Zucker, 1994). However, Langer and Bülthoff (2000) demonstrated that the dark-is-deep heuristic cannot fully account for shape from shading perception under diffuse illumination, as participants perceived the points of luminance maxima deeper in the concavities. Nonetheless, expectations make the most likely appearance also the most plausible and convincing representation. Fleming *et al.* (2003) reasoned that the visual system exploits the regularities of natural illumination to discard unlikely interpretations of materials (e.g., a blurry surface reflection is unlikely to be interpreted as a sharp reflection of a blurry world). Under such natural illumination conditions, different materials can be recognized through their signature features profile, the set of key image features that trigger their characteristic appearances.

The second reason is that these key features not only trigger the most likely appearances, they also allow for the best visual communication of the material properties. Consider again the examples of the ceramic jugs in Fig. 3. It has been shown that different illumination fields can make the same object look more matte (under diffuse light) or shinier (under collimated light) (Pont and te Pas, 2006). So, if the painter had to create a strict, one-to-one correspondence between the physics and the depiction to achieve a convincing result, the most accurate rendering of the reflections on the jugs' caps would probably look dimmer and blurrier, thus losing their convincing shiny appearance. By following the physics, the artist would depart from the most effective and convincing representation of the material he intended to show.

Like painters had a system to depict materials in the “quickest, best and easiest way” (Van Eikema Hommes, 2002), similarly, the human brain has a system to perceive materials in a way that is fast, efficient, and effortless. That is why perceptually-relevant recipes were taught and preferred by the artists.

Beurs in his book foresaw elements of ecological optics by laying the foundations of materials’ depiction onto the observation of natural illuminations and natural environments. He also understood the relevance of grasping the physics of optical phenomena, while at the same time acknowledging that there is no need for complex mathematical computations. For example, he remarks that the painter is not required to embark on the calculations of refractive indices to paint a smooth, fragile and transparent glass of wine (as the one in Fig. 4) (Beurs, 1692; Lehmann and Stumpel, in press).



Figure 4. Detail of Willem Claesz. Heda, *Still Life with Gilded Beer Jug*, 1634. Rijksmuseum, Amsterdam, The Netherlands. The image is available in the public domain.

Likewise, according to the modern theory of vision science that regards inverse optics as ill-posed and unfeasible (Fleming, 2017; Nishida, 2019; Purves *et al.*, 2011), the brain has no need (and no way) to compute the physical parameters of a Bidirectional Reflectance Distribution Function (BRDF) (Nicodemus, 1965) to estimate the reflectance of that same glass.

Van Zuijlen *et al.* (2021) reported an example of such perception-based, standard material depiction. They found that the rendering of wine glasses in paintings, like the one in Fig. 4, was based on perceptually invariant cues, i.e., the consistent locations of the window-shaped reflections on the glass. In comparison, the photos of wine glasses taken nowadays by amateurs, under different lighting conditions, and from diverse viewpoints, reveal no consistent patterns for the location of the reflections. This finding expands on the well-known artistic convention of placing a bright window reflection on objects no matter the environment, which according to Pirenne (1970) demonstrates how vision relies on preconceived ideas and previous experiences.

Even though ecological environments allow for a wide variety of appearances, professional photographers, who aim like painters for the best representation of materials' appearance, might be more prone to capture the light in a way similar to the pattern used by painters (see Fig. 5).

It was noted by Hagen (1980) that applying the theory of ecological optics of Gibson (1961) to the representation and perception of pictures, means that “pictorial styles succeed as representations only to the extent that they capture invariant information for the objects and scenes pictured.” The hypothesis



Figure 5. Professional photographers tend to prefer a pattern of specular reflections on wine glasses similar to that used by Dutch 17th-century painters to depict glasses. Images downloaded from Unsplash.com, released under free license.

proposed in this paper is that Beurs seized and listed in his book the key features of the structure of light to render and perceive material properties.

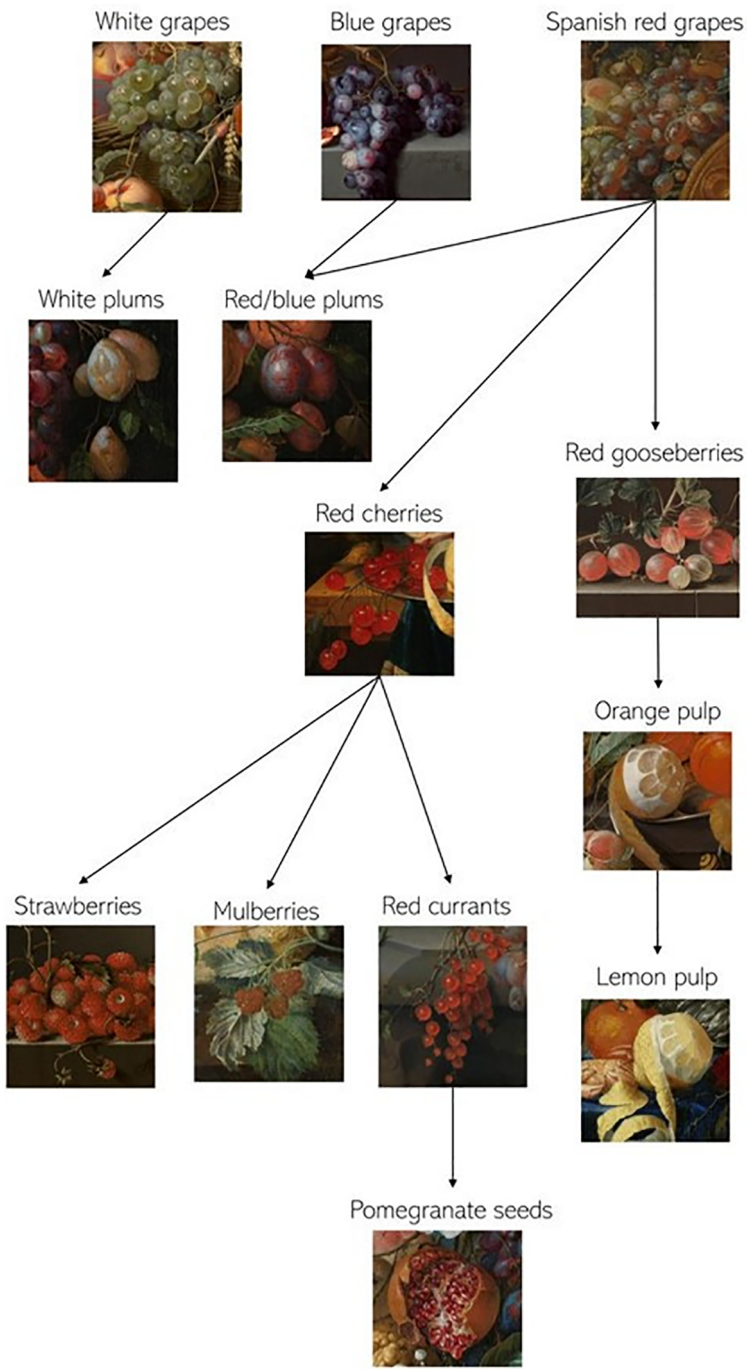
He describes the features of each material under a natural, standard illumination condition, which he calls “neutral daylight” or “midtone” (Beurs, 1692; Lehmann and Stumpel, in press), corresponding to *chiaroscuro*, i.e., transitions of light and shade on the surface of the object. In such neutral daylight, Beurs also considers the effect of interreflections on the appearance of the surfaces, in this case, self-interreflections, as each object is treated separately.

Another interesting element of Beurs’ treatise is that the key features that he provides are organized in a sort of taxonomy of appearances. Very different materials are grouped in the same class according to their key image features. For example, snow, flowers, fabrics, worms, butterflies, and caterpillars all belong to the same class. Another example is the class that contains hairs, tree trunks, wood, masonry, straw, stones, chestnuts, olives, and capers. Grapes introduce another class which includes the visual formulae for plums, cherries, berries, pomegranate seeds, oranges, and lemons.

A schematic representation of the connections between materials in this last group is shown in Fig. 6.

White grapes, rendered in neutral daylight, need a light color mix on the lit side and a dark one on the shaded side, to create depth via *chiaroscuro*. Next, the reflections are applied, i.e., the light re-emerging after subsurface scattering at a different location from where it entered, thus to be placed opposite to the specular reflection. The latter will be most likely placed top left; therefore, the reflections will be rendered at the bottom right. Then, a whitish, opaque layer, corresponding to the bloom, is distributed over the surface, taking care to use a darker color for the grapes in the shadow. The distribution of this opaque layer needs to be somewhat random, leaving free spots here and there but especially making sure to leave enough space to apply the specular reflection. This is placed on the lit side, where the light hits the surface and it is partially absorbed and scattered and partially reflected. The highlight needs to be high contrast but with blurry edges. The final step is to make the seeds of some grapes visible through the fruit. This is done again on a spot on the surface free from the opaque layer so that the see-through effect is more convincing.

This first visual formula is rich in details because it lays the foundation of the key features for all the following fruits in the group. Therefore, blue and Spanish red grapes will need the same features as white grapes, but rendered with different colors. The same is true for white and red/blue plums, and no additional instructions are needed. In Fig. 6, it can be easily seen that a plum is just a very big grape, slightly less translucent, thus with smaller reflections, because, due to the increased size of the object, the light has a longer path to



travel and fewer chances to re-emerge after subsurface scattering. The features profile of red cherries is also the same as that of grapes, with again a difference in colors. But cherries are shinier, so less or no bloom is needed, and they need more saturated colors. Red currants are made exactly like cherries, adding just the seeds to be seen through. And the seeds of a cracked-open pomegranate are rendered like red currants. Each segment of the mulberries is rendered like a tiny cherry. For the strawberries, the base is like the cherries, which are like the grapes, so they need a lit and a shaded side and reflections. Instead of applying one strong specular reflection, though, strawberries need small highlights to render every seed on the surface, and their body color is less saturated than that of the cherries. Red gooseberries need the same key features as the grapes, plus the veins on the surface. They also need a brighter color, so less to no bloom rendered by the whitish opaque layer. The pulp of an orange is rendered like an orange gooseberry. This means that first, they require a lit and a shaded side, followed by the reflections for the translucency. Like gooseberries, they do not need bloom. As in the case of strawberries, there is not a single specular reflection, but the highlights are used to mark the cells of the pulp. Their arrangement, though, still follows the scheme of the grapes, opposite to the translucent reflections. The veins of the gooseberries are used to trace the slices of the orange. The last material in this class is the lemon pulp, which is exactly like the orange, with a color change.

A similar description would apply to the other groups of materials described in the book. Within each group, Beurs proposes features profiles that trigger material perception, and each profile is derived by a weighted combination of key features. Such a layered combination of features is similar to the optical

Figure 6. Schematic representation of the connections between different materials that, according to Beurs, can be rendered using the same image features. *White grapes*: Abraham Mignon, *Still Life with Fruit, Fish and a Nest*, 1675. National Gallery of Art, Washington, DC, USA. *Blue grapes*: Jacob van Walscapelle, *Still Life with Fruit*, 1675. National Gallery of Art, Washington, DC, USA. *Spanish red grapes*: Abraham Mignon, *Still Life with Fruit and Oysters*, 1660–1679. Rijksmuseum, Amsterdam, The Netherlands. *White plums*, *Red/blue plums* and *Pomegranate seeds*: Jan Davidsz. de Heem, *Festoon of Fruits and Flowers*, 1660–1670. Rijksmuseum, Amsterdam, The Netherlands. *Red cherries*: Johannes Hannot, *Still Life with Fruit*, 1668. Rijksmuseum, Amsterdam, The Netherlands. *Red gooseberries*: Adriaen Coorte, *Gooseberries on a Table*, 1701. Cleveland Museum of Art, Cleveland, OH, USA. *Red currants*: Jacob van Walscapelle, *Still Life with Fruit*, c. 1670–c. 1727. Rijksmuseum, Amsterdam, The Netherlands. *Mulberries*: Jan van Huysum, *Still Life with Fruit*, 1700–1749. Rijksmuseum, Amsterdam, The Netherlands. *Strawberries*: Adriaen Coorte, *Still Life with Wild Strawberries*, 1705. Mauritshuis, The Hague, The Netherlands. *Orange pulp*: Cornelis de Heem, *Fruit Still Life*, c. 1670. Mauritshuis, The Hague, The Netherlands. *Lemon pulp*: Pieter de Ring, *Still Life with Golden Goblet*, 1640–1660. Rijksmuseum, Amsterdam, The Netherlands. All images were downloaded from open-access galleries.

mixing (Griffin, 1999; Pont *et al.*, 2012) of canonical material modes proposed by Zhang *et al.* (2016, 2018, 2019, 2020), in which the key features are related to a limited range of common but mutually distinct appearance modes.

In previous studies, Di Cicco *et al.* (2019, 2020a, b, 2021) have shown that the key image features in Beurs' pictorial recipes are exploited by the visual system to perceive materials and their properties. For example, when describing how to paint grapes, Beurs provides in terms of key features all the optical phenomena that define their appearance. By manipulating the weights of the image features listed by Beurs – highlights, edge reflections, and bloom – Di Cicco *et al.* (2020a) inferred a causal relationship with the perception of the material properties glossiness, translucency, and bloom. The highlights were used as perceptual cues for glossiness and translucency perception, in agreement with the literature (Chadwick and Kentridge, 2015; Fleming and Bühlhoff, 2005), and the edge reflections also increased the translucent appearance, again in agreement with literature about the cues for translucency (Fleming and Bühlhoff, 2005; Gigilashvili *et al.*, 2021; Gkioulekas *et al.*, 2015; Nagai *et al.*, 2013; Wijntjes *et al.*, 2020; Xiao *et al.*, 2020), whereas the image feature of the bloom was the direct trigger of bloom perception. Di Cicco *et al.* (2019) further showed that the glossiness of grapes is predicted by high contrast, blurry highlights, in agreement with Beurs' instructions.

These findings might seem limited since they were derived for grapes only, but because Beurs grouped the materials according to their communal features, I assume that they will hold valid for all the materials which share the same features as grapes (see Fig. 6). This was confirmed for the perception of juiciness and translucency of citrus fruits (Di Cicco *et al.*, 2020b), for which the main perceptual cues that were identified – highlights for juiciness and light gradient (or edge reflections) for translucency – are also to be found in Beurs' grapes recipe.

As noted by Van Eikema Hommes (2002), the use of standard recipes offers the advantage of not having to re-invent the right image features for the convincing rendering of materials every time. Accordingly, I propose that the study of material perception could greatly benefit from consulting Beurs in order to identify candidate image features, then to be tested with psychophysical methods, without having to re-invent the wheel every time. Such an index of diagnostic features to be derived from Beurs could enrich and complement theoretical models, such as the statistical appearance model proposed by Fleming (2014, 2017; Fleming and Storrs, 2019), or the linear weighted combination of canonical modes of material and lighting elaborated by Zhang *et al.* (2016, 2018, 2019, 2020).

Considering Beurs' book as a list of key image features also contributes to filling the gap in art history about the depiction of materials. By relating the image features found in paintings and listed by Beurs to their perceptual

effects, the question *How did painters achieve the convincing rendering of materials?* could be answered (Di Cicco *et al.*, 2020a). Information about the functioning of the visual system can be used to understand the pictorial procedures. For example, the following step in Beurs' grapes recipe (Beurs, 1692; Lehmann and Stumpel, in press):

"The reflections, however, require only a little ash but somewhat more yellow lake"

instructs that to render the edge reflections, a lighter color (yellow lake) should be applied. This step will create the visual impression of the light re-emerging from the edges of the grapes, which is what happens after subsurface scattering. Since the edges are the regions of an object most affected by variations in light scattering and diffusion, they constitute also the quickest and best shortcut to depict translucency. By adding knowledge of optics and perception, art historians could reach a comprehensive understanding of the artworks and the historical recipes.

Another point of convergence between art (history) and vision science should be on the use of quantitative analysis and image statistics in art. Doing quantitative image analysis in vision science is no breakthrough, but applied to uncontrolled stimuli, such as paintings, it offers the possibility to uncover unexpected findings because it allows variations across a range of unknown features. Most of the research on visual material perception has in common the use of well-controlled, computer-rendered stimuli. It is easy to see why that is the case since rendered stimuli allow systematically manipulating the specific parameters under investigation. However, these stimuli are often simple or unfamiliar shapes presented in isolation against a neutral background, therefore lacking the complex interactions between shape, illumination, and materials encountered in real life, and potentially missing out on relevant cues and structures.

When investigating the highlights features for gloss perception of grapes, Di Cicco *et al.* (2019) found, outside the primary scope of that study, that painters could break the fundamental rule of congruence of highlights' orientation (Anderson and Kim, 2009; Beck and Prazdny, 1981; Fleming *et al.*, 2004; Kim *et al.*, 2011; Koenderink and van Doorn, 1980), without hindering the perception of glossiness. This was demonstrated by applying quantitative image analysis to the highlights, by measuring and correlating the orientations of ellipses fitted onto the highlights and the grapes, for different levels of perceived glossiness. Van Zuijlen *et al.* (2021) performed an annotation experiment of highlights depicted on drinking glasses using images of paintings and found a consistent stylized pattern resulting in the convincing rendering of glass. When using only computer-rendered stimuli it is more difficult, if not

impossible, to reveal hidden information because all the features available in the stimulus are carefully tuned and controlled by the input parameters during the rendering. I suggest using computer renderings in combination with more uncontrolled and ecologically-valid stimuli, like paintings or photos, to maximize the availability of potential visual cues.

Quantitative analysis of image features in paintings can also advance the art historical inquiry on the depiction of materials (Wiersma, 2020). For example, it has long been observed that 17th-century painters could adopt a neat and precise brushwork, typical of the *fijnschilders* like Gerard Dou and Adriaen van der Weff, or use loose and coarse brushstrokes, like the late Frans Hals and Rembrandt. What might have gone unnoticed, though, is that both pictorial manners employ the same image features to depict, for example, the shininess of fabrics, i.e., high coverage and high luminance highlights (Di Cicco *et al.*, 2021). Future research in the art history of materials depiction should include quantitative analysis of the paintings, to relate the image features to their deviation from the optics, and consequently to the evolution of pictorial styles.

There is a strong link between art and visual perception, which has often been acknowledged but rarely pursued. With this paper, I hope to have sparked the curiosity of art historians to incorporate theories and findings of visual perception into their work, and for the vision scientists to consider that since paintings provide a forty thousand-year-old corpus of perceptual experiments, they better start looking at them.

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Notes

1. Note that glazing is also possible with transparent media other than oil, like watercolors, but discussing the properties of other painting media is out of the scope of the present paper.
2. Note that when I mention ‘art history’ or ‘art’ throughout the paper, I refer exclusively to the art history of paintings and paintings, respectively. I acknowledge that in other forms of art, like sculpture, materials have received much more scholarly attention. However, that is outside of the scope of the present discussion.

3. Stumpel, J. (2007). The impact of oil; a history of oil painting in the Low Countries and its consequences for the visual arts, 1350–1550. <https://www.nwo.nl/en/projects/360-55-060>.

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