The Art of Shaping Materials

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Abstract

Material perception — the visual perception of stuff — is an emerging field in vision research. We recognize materials from shape, color and texture features. This paper is a selective review and discussion of how artists have been using shape features to evoke vivid impressions of specific materials and material properties. A number of examples are presented in which visual artists render materials or their transformations, such as soft human skin, runny or viscous fluids, or wrinkled cloth. They achieve this by expressing the telltale shape features of these materials and transformations, often by carving them from a single block of marble or wood. Vision research has just begun to investigate these very shape features, making material perception a prime example of how art can inform science.

Keywords: Vision, material perception, visual arts, shape, shape features

1. Visual Material Perception

All objects in our environment are made of stuff and it is extremely important for us to be able to recognize and tell apart these different materials (Fig. 1) — for example, between water and ice when skating on a winter lake. Material perception serves different purposes such as estimation of material properties (e.g., soft vs. hard), anticipation of future material behaviors (e.g., bouncing vs. shattering) or motor affordances (e.g., grip and load forces in grasping) and feeds into cognitive judgments, for example, about quality, (aesthetic) value or edibility. Consequently, the recognition and categorization of materials in our visual environment, together with remembering or estimating their properties (e.g., soft–hard, light–heavy, smooth–rough, hollow–solid, fragile–durable, warm–cold), is presumably as important for interactions with our environment as perceiving objects (Adelson, 2001). For most of the time, we solve this visual and cognitive task with apparent ease, even though materials are of an enormous variety in shape, colors and textures within and between material categories (Fig. 1).

Figure 1. Images of material samples. Even though materials are enormously varied in shape, color and texture features, we can easily group together samples belonging to the same category: (A) stone, (B) wood, (C) plastic, (D) metal, (E) paper, (F) leather, (G) textile, and (H) glass. Images [C1, C2, D2, E1, E2, F1, F2, G1, H1, H2] were taken from the Flickr Material Database (Sharan *et al.*, 2009) and are published under Creative Commons License CC BY 2.0, the other images [A1, A2, B1, B2, D1, G2] were taken from the Material Image Database (Wiebel *et al.*, 2013) published under Creative Commons License CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/).

At the same time, within the field of vision research, which is concerned with how we see the world and why we see it as we do, the study of material perception is relatively young. Studying the perception of objects (e.g., of a chair or a face) has a long and rich research history, including the Gestalt school in the early 20th century (Koffka, 1935; Wertheimer, 1923) as well as contemporary neuroscience (e.g., Logothetis and Sheinberg, 1996; Pasupathy *et al.*, 2018) and computational modeling (DiCarlo *et al.*, 2012; Kriegeskorte, 2015; Riesenhuber and Poggio, 2002). On the other hand, the study of visual material perception was founded just about 20 years ago by a seminal article of Edward H. Adelson (2001). However, since then material perception has evolved into a recognized and proliferous research area in vision (e.g., Anderson, 2011; Chadwick and Kentridge, 2015; Fleming, 2014, 2017; Maloney and Brainard, 2010; Motoyoshi *et al.*, 2007).

There are different accounts at different levels of description of *how* we visually perceive materials. This article will use a slightly modified variant of a working model that was developed in our lab and which distinguishes between two major routes of material perception: the *association route* and the *estimation route* (Fig. 2; Fleming, 2017; Schmidt *et al.*, 2017; Van Assen and Fleming, 2016).

The association route, on the one hand, enables us to recognize materials via learned image features (e.g., folds and wrinkles suggest textiles), followed by retrieval of associated material properties from memory (e.g., textiles are rather soft and smooth than hard and rough; Fleming *et al.*, 2013; Goda *et al.*, 2014; Jacobs *et al.*, 2014; Paulun *et al.*, 2017; Schmidt *et al.*, 2017; Wiebel *et al.*, 2013, 2014). The power of the association

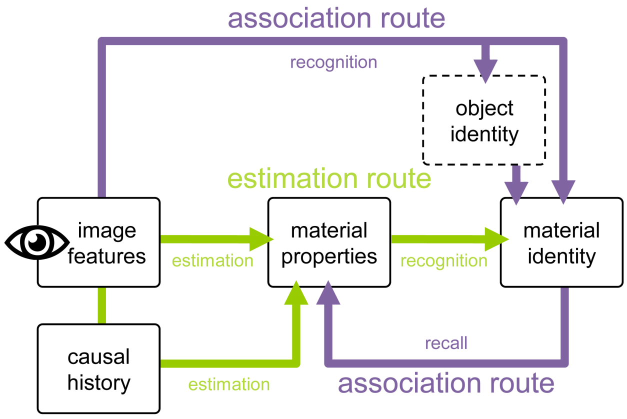

Figure 2. Working model of material perception that distinguishes between an association route and an estimation route for identifying materials (Fleming, 2017; Schmidt *et al.*, 2017; van Assen and Fleming, 2016). Modified from a figure kindly provided by Roland W. Fleming.

route is also evident from contemporary computational image recognition networks, that learn material representations from training sets of hundreds of thousands of labeled material images, and achieve impressive performance in recognizing the trained material classes when tested on novel material images (e.g., Bell *et al.*, 2015; Caesar *et al.*, 2018; Schwartz and Nishino, 2018). A sub-route is the inference of material identity from learned object–material associations (e.g., a table is most likely made of wood).

The estimation route, on the other hand, allows us to recognize materials by directly estimating material properties from image features — without the 'detour' of recognizing the actual material (e.g., when the material deforms easily under pressure it is soft rather than hard). Based on the entirety of the estimated properties, we can then infer material identity. For example, when a shiny, bright material is soft it is rubber rather than metal (cf. Paulun *et al.*, 2017; Schmidt *et al.*, 2017), when a transparent fluid is runny it is water rather than glue (cf. Kawabe *et al.*, 2015a; Paulun *et al.*, 2015; van Assen and Fleming, 2016; van Assen *et al.*, 2018), and when a cloth is easily whirled up by the wind it is silk rather than burlap (cf. Aliaga *et al.*, 2015; Bi and Xiao, 2016; Bi *et al.*, 2018; Bouman *et al.*, 2014). Gloss, which is based on surface reflectance properties, is a particularly well-studied material property that takes effect via the estimation route (Fleming, 2017). Another branch of the estimation route is the estimation of material properties from the inferred causal history of the object (e.g., when an object looks as if it has been twisted or bent it is soft rather than hard; see Section 3).

Of course, this high-level description model can just be an approximation of how material perception is implemented in the visual system. For example, under most circumstances the association route and the estimation route are not mutually exclusive: rather, we will use the available image features to directly estimate object and material identity as well as material properties, so that the two routes will typically complement each other. Also, material perception will be affected by contextual factors, for example, by the situational context, which is not part of the model (e.g., a flower in a restaurant is more likely to be made of plastic than a flower in a flowerbed; red liquid is ketchup rather than paint if it is in a ketchup bottle).

Still, the model can be used to discuss different aspects of material perception, and relate those to art. This paper will illustrate how art has been preceding and shadowing findings and theoretical ideas in material perception research. Specifically, it will focus (i) on shape as an important source of information about material identity, and (ii) on how artists have been using shape to create the impression of a particular material.

Why would artists like to do this? Of course, there is a plethora of reasons, ranging from a realistic depiction of the world (e.g., of human skin) or emphasizing particular material properties (e.g., fragility) to evoking particular cognitions (e.g., about value) or emotions (e.g., exhilaration) in the observer. For example, many artworks presented in this paper create an incongruity between perceived physical material identity (e.g., hard stone) and material behavior (e.g., twisting or melting). This 'dichotomy' (Pepperell, 2015) can lead to strong aesthetic effects (see Section 3).

In pieces of art, material perception from shape can best be observed in sculptures. Many sculptures are made of a single piece of material — such as a solid block of wood or marble — but skillful sculptors can convey a whole range of different materials by carefully forming the sculpture's shape. Consequently, the effect of shape for material identity can be appreciated independently from the effects of other image features (such as color or texture). In two sections, pieces of art will be presented that illustrate different aspects of (i) material from shape and (ii) material from transformations of shape (for an overview, see Table 1). The final section (iii) will identify future directions and open questions in the research of material from shape, inspired by the presented artworks.

2. Materials from Shape

Much, much earlier than vision science, artists realized that material perception is an indispensible aspect of how we see the world. Already some of the earliest sculptures known to mankind depict particular materials or material properties. For example, the surface of the head of the *Venus of Willendorf* (Fig. 3A) is carefully shaped into a pattern of horizontal bands that we see as braided hair or a woven cap. Also, the smooth and rounded shape of the Venus's body evokes the vivid percept of soft human flesh.

The detailed study and identification of visual material features through careful observation, together with previously unprecedented craftsmanship, culminated in the hyperrealistic sculptures of the 14th and 15th century, where artists like Italian Renaissance master Michelangelo perfected the rendering of soft human flesh from marble as in his *David* (Fig. 3B). Later famous examples include *Ugolino and his Sons* from Jean-Baptiste Carpeaux (Fig. 3C) or the *Veiled Virgin* from Giovanni Strazza (Fig. 3D) from the same period. From the viewpoint of vision science, these pieces beautifully illustrate the power of shape features in material perception. Indeed, it is difficult to distinguish between photographs of their details and grayscale photographs of actual human limbs or cloth. Also, these sculptures demonstrate how particular shape features cannot only convey material identity (via the association route; Fig. 2) but also allow us to estimate material properties (via the

Table 1. Overview of figures exemplifying the different shape cues (not included are the hyperrealistic sculptures of Figs. 4 and 5). The columns refer to the different types of shape cues, the rows refer to the different sections and the included figures. Colors indicate whether examples relate to the association (purple) or estimation (green) route of our working model (Fig. 2).

	Cues to material identity	**Cues to transformations**	**Cues to object identity**	**Interaction with other objects**
2. Materials from shape				
Figure 3A, B	✓		✓	
Figure 3C, D	✓	✓	✓	✓
3.1 Materials from Transformations: No Cues to Object Identity				
Figure 10		✓		
Figure 11		✓		
Figure 12		✓		
3.2 Materials from Transformations: Cues to Object Identity				
Figure 13		✓	✓	
Figure 14		✓	✓	
Figure 15	✓	✓	✓	
3.3 Materials from Transformations: Interactions with Other Objects				
Figure 16		✓		✓
Figure 17		✓		✓
Figure 18	✓	✓	✓	✓
Figure 19	✓	✓	✓	✓

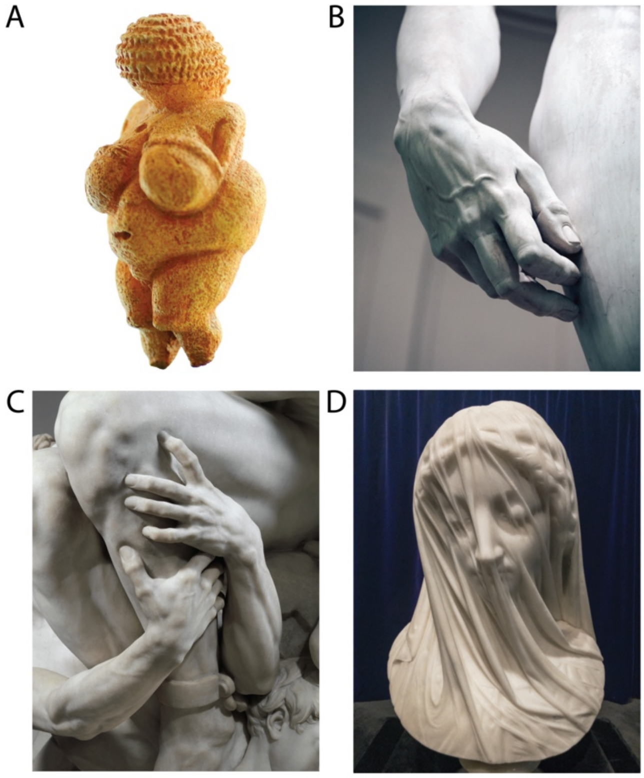

Figure 3. Four examples of sculptures illustrating how artists render materials by expertly mimicking shape features of real materials. (A) “Venus of Willendorf”. Sculpture by unknown artist (about 27,480 B.C.). Image © 2007 by Matthias Kabel published under Creative Commons License CC-BY 2.5 (https://creativecommons.org/licenses/by/2.5/). (B) Detail from “David” by Michelangelo (1501–1504). Image © 2013 by Accademia Gallery Guide (http://www.accademia.org/). Reprinted with permission. (C) Detail from “Ugolino and his Sons”. Sculpture by Jean-Baptiste Carpeaux (1865–1867). Image © by The Metropolitan Museum of Art (US) published under Creative Commons License CC0 1.0 (https://creativecommons.org/publicdomain/zero/1.0/). (D) “The Veiled Virgin”. Sculpture by Giovanni Strazza (about 1850). Image © 2007 by Shhewitt published under Creative Commons License CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0/).

estimation route; Fig. 2). For example, the veins seemingly showing through the surface of David's hand give the impression of a very thin and somewhat translucent layer of (skin) material (Fig. 3B). And the impressions in Ugolino's lower leg resulting from his son's grip let us see the flesh of the leg as soft and elastic (Fig. 3C). Finally, the way in which the veil is falling over the Veiled Virgin's face and through which much of the face is still visible let us perceive the veil material as soft, thin and airy (Fig. 3D). This also shows the remarkable capability of our visual system to use shape features to distinguish between two perceptual layers (veil and face) in just a single piece of marble (Phillips and Fleming, 2017).

In a nutshell, these sculptures demonstrate how the perception of particular materials and their properties can be evoked by (combinations of) particular features of shape. Later pieces of hyperrealistic art add additional material features such as color and texture to create perfect visual illusions. Of course, to create artworks with very high levels of realism, artists have to successfully mimic the materials that the real objects are made of. In other words, they have to fool material perception to let us interpret the depicted materials as real. In the following examples of hyperrealistic art, this material mimicry is combined with an exact reproduction of object shapes. As a result, the perception of material identity (via the association and estimation routes; Fig. 2) and object identity are mutually reinforcing each other in creating realistic impressions of particular objects made of particular materials.

For example, Tom Eckert makes sculptures of wood and paints them to meticulously re-create shape, color and texture features that imitate hard natural rocks, soft and semi-transparent cloth, or paper playing cards (Fig. 4). As a result, Eckert's illusions are cognitively impenetrable: even though we know that rocks or playing cards cannot float in mid-air, we still *see* them as being made from stone or cardboard.

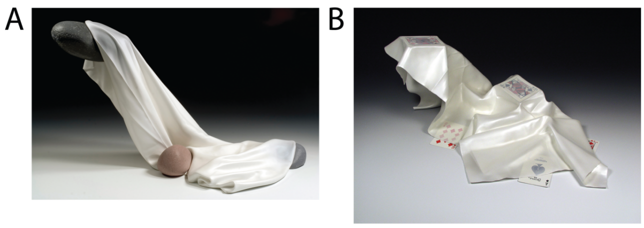

Figure 4. Both sculptures are carved from wood and painted using various spray and brush techniques. (A) “Gossamer Levitation” and (B) “Legerdemain”. Both sculptures and images © 2008 by Tom Eckert (http://www.tomeckertart.com). Reprinted with permission.

Another example is the Japanese art of *Sampuru*, where shape, color and texture features are imitated to produce sculptures of food items and materials. Since the early 20th century, these intricately decorated food models have been created for display in restaurant windows, initially from wax and later from plastic (Fig. 5A, B). Other examples for food sculptures are the detailed pieces from Shayna Leib who creates pastries completely from glass (Fig. 5C, D). Realistic food sculptures are especially fascinating as humans are very sensitive to whether food looks natural and appetizing.

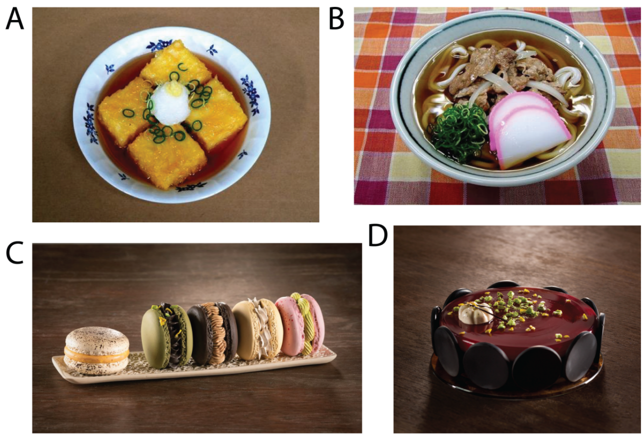

Figure 5. Examples of food sculptures. Even though they are made of plastic and glass, they illustrate perfect illusions of a whole range of different materials; from syrupy sauces, mellow pieces of meat and crispy spring onions to fluffy whipped cream, light cake and translucent jelly. The upper ones are Sampuru sculptures made of plastic: (A) "Age-dashi (Fried) Tofu Replica" and (B) "Niku Udon (Udon Noodle with Sliced Beef) Replica". Both images © 2011 by fakefoodjapan.com. Reprinted with permission. The lower ones are glass sculptures: (C) "La Macaron" and (D) "Forêt noire". Both sculptures by Shayna Leib (http://shaynaleib.com). Image © 2017 by Eric Tadsen. Reprinted with permission.

How do we resolve ambiguities arising from a mismatch between material perception and knowledge (as we *know* that there is no such thing as a floating stone or forever fresh-looking food)? Of course, we can use other senses such as taste or smell (e.g., to decide whether a flower is made of plastic). However, another powerful test is the observation of interaction behaviors of the objects or materials. For example, we can simply reach out and probe the material to test whether its visual appearance matches its internal properties (e.g., is it soft or hard; Baumgartner *et al.*, 2013, 2015; Drewing, 2014; Drewing and Kruse, 2014; Lezkan *et al.*, 2018; Metzger *et al.*, 2018; Zöller *et al.*, 2019) or we can observe its behavior in interaction with other materials, objects, or physical forces (Paulun *et al.*, 2017; Schmid and Doerschner, 2018; Schmidt *et al.*, 2017; van Assen *et al.*, 2018).

When making inferences about materials from observations, an especially powerful cue to material identity is motion or dynamic changes of shape. For example, different types of cloth can be distinguished by watching their responses to gusts of wind (Aliaga *et al.*, 2015; Bi *et al.*, 2018; Bi and Xiao, 2016; Bouman *et al.*, 2014). In fact, motion is more effective than color and texture features when pitted against each other (Paulun *et al.*, 2017; van Assen and Fleming, 2016) and is already used by five-month-old infants to make predictions about material behavior (Hespos et al., 2009, 2016). Also, material identity and properties can be estimated from point light movies (in which objects or fluids are represented by a sparse group of dots; Cutting, 1982; Kawabe *et al.*, 2015a; Paulun *et al.*, 2015), from dynamic flow movies (Morgenstern and Kersten, 2017), or even from artificial dynamic image deformations (Kawabe *et al.*, 2015b).

Interestingly, there is evidence that we can to some extent infer these dynamic changes of shape over time from the current, static shape of objects without watching the actual change (Arnheim, 1974; Chen and Scholl, 2016; Fleming and Schmidt, 2019; Leyton, 1989; Schmidt and Fleming, 2018; Schmidt *et al.*, 2019; Spröte *et al.*, 2016). In other words, we can infer the causal history of objects. What is the role of perceiving causal history in material perception? And how do artists make use of these inferences to convey perceptions of material properties and identity (cf. the causal history branch of the estimation route in Fig. 2)?

3. Materials from Transformations of Shape

The inference of causal history from current object shape — that is, the inference of the transformations that produced its shape — is an alternative route to estimate material identity and properties from image features (Fig. 2).

Every object in our environment is a result of some shape-transforming process, such as physical forces (e.g., heat, pressure) of non-human (e.g., wind) or human origin (e.g., manufacturing), biological growth, or self-organization. These processes shape objects and often leave transformation-specific traces (features) in their shapes. Similar to material perception the study of shape transformations is a relatively recent and emerging field in vision science (e.g., Arnheim, 1974; Chen and Scholl, 2016; Fleming and Schmidt, 2019; Leyton, 1989; Mark and Todd, 1985; Ons and Wagemans, 2012; Pinna, 2010; Pinna and Deiana, 2015; Pittenger and Todd, 1983; Schmidt and Fleming, 2018; Schmidt *et al.*, 2019; Spröte and Fleming, 2013, 2016). Again, much earlier, artists were fascinated by depicting shape transformations (e.g., between different natural shapes; Fig. 6) or documented semantic labels of transformation actions or effects (Fig. 7).

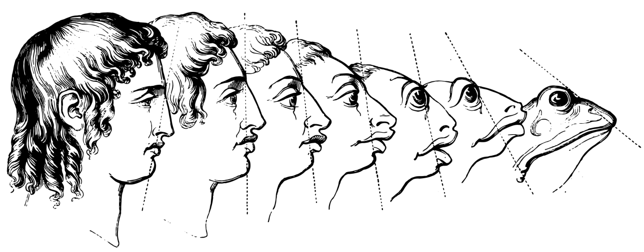

Figure 6. “Metamorphose” by J. J. Grandville. Magasin Pittoresque (1844). Image © by Morphart Creation/Shutterstock.com. Reprinted with permission.

Interestingly, there is a tight link between the visual perception of shape transformations and the visual perception of materials. Even though the same transformations can occur across different materials, and observers are able to recognize the features signifying the material and thosesignifying the transformation (e.g., wax, cardboard, and plastic might all be folded, crumpled, and twisted; Schmidt and Fleming, 2018), not all transformations will occur in all materials with the same probability. Particular shape features suggest a particular causal history, and this inference is putting constraints on material properties and identity. For example, parallel, spiraling creases suggests that an object has been twisted; and based on this inference we can assume that its material is soft rather than hard and is therefore paper or textile rather than metal or stone (estimation route; Fig. 2). Equivalently, tear-shaped drops suggest melting; thus we can assume liquid or easily liquefied material, and therefore water or wax rather than wood or textile. More generally, metal is not likely to crumple, cardboard will not melt, and water will not crack apart.

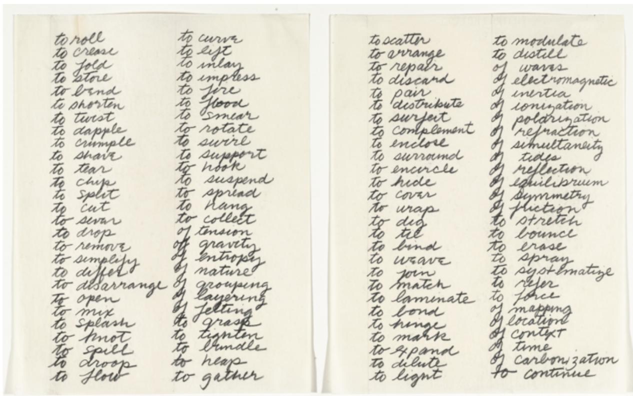

Figure 7. “Verblist” by Richard Serra (1967–1968). New York, Museum of Modern Art (MoMA). Graphite on two sheets of paper, 10 × 8 1/2" (25.4 × 21.6 cm) (each). Gift of the artist in honor of Wynn Kramarsky. Acc. n.: 843.2011.a-b. © 2019. Digital image, The Museum of Modern Art, New York/Scala, Florence. Reprinted with permission.

Material perception research has begun to pick up on this topic. For example, Pinna (2010; Pinna and Deiana, 2015) showed that observers consistently inferred material as well as causal history (‘happenings’) from a series of 2D squares with particular contour deformations (Fig. 8; the particular inferences are reported in the caption). In one of our own studies (Paulun *et al.*, 2017), we simulated interactions between 3D cube objects and a cylinder, and rendered the cubes with different materials (Fig. 9). We found that participants' ratings of softness were well predicted by the objective deformation of the cubes. Interestingly, we also found that perceived softness was purely determined by dynamic changes in object shape (differences between columns in Fig. 9) and not at all by the optical properties (differences between rows).

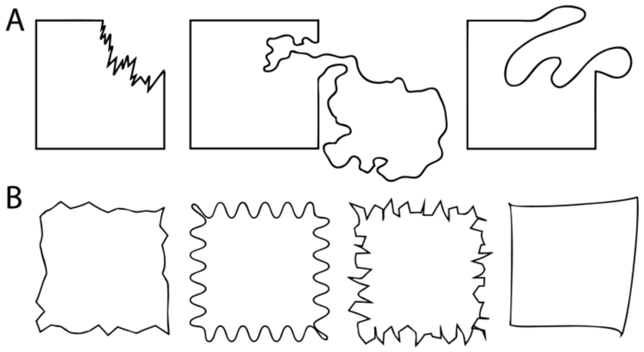

Figure 8. Deformed square contours. Participants spontaneously reported to perceive these stimuli as made of different materials, and subjected to specific transformations (when all were presented simultaneously and together with a standard rectangle). (A) From Pinna (2010): glass, broken; liquid and light material, erupting; and soft rubber, deformed by heat. (B) From Pinna and Deiana (2015): paper or cardboard, scrunched up; soft goods, undulated; aluminium, folded up; and tissue paper, swelled. All stimulus images generously provided by Baingio Pinna.

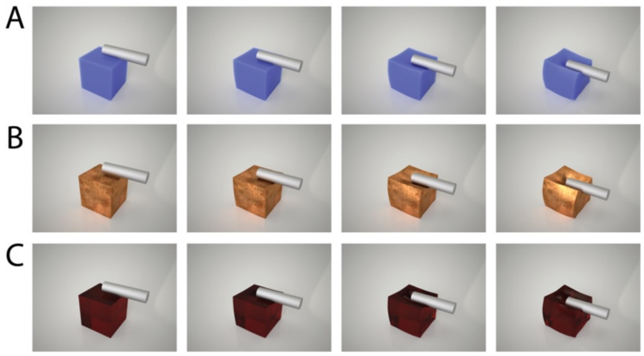

Figure 9. Example frames of movie stimuli from Paulun *et al.* (2017; frames 16, 21, 25, and 30 from 30-frame-movies). The different rows show different rendered materials: (A) plastic, (B) copper, and (C) gelatine. While static cubes of different materials were judged to have very different softness, movies with dynamic shape changes produced softness ratings independent of cube material and purely determined by objective deformation.

Again, artists preceded vision science in using the inference of causal history to create sculptures that do not only convey the look of a specific material but also of a particular transformation of that material. These sculptures demonstrate a deep knowledge of hallmark transformation shape features — which is especially striking when artists use this knowledge to dissociate (intrinsic) material properties and (extrinsic) transformation properties of objects (see Note 1). For example, they might re-create features of a soft material and a typical transformation of that material in a sculpture made of a particularly hard material.

Previous work described such “dichotomies” (Pepperell, 2015) between, for example, physical material and material behavior as the “coexistence of incongruent semantic stabilities” and argued for their basic appeal and production of affective reactions like exhilaration, irritation, surprise and aversion (Ludden, Schifferstein and Hekkert, 2008; Muth and Carbon, 2016). This paper shows images of sculptures that are especially intriguing in that respect and that let us reflect about our own expectations and visual inferences.

3.1. Materials from Transformations: No Cues to Object Identity

We start out with sculptures that do not provide many cues to object identity, but still allow us to see the mismatch between the actual material and the implied material or transformations (Figs. 10–12). In other words, material identity is inferred from material via the estimation route without contribution of the association route (Fig. 2). For example, the golden threads in Romain Langlois' sculpture (Fig. 10A) are of solid, hard bronze but their shape gives the impression of some sticky, soft material such as viscous liquid. Similarly, the sculpture by Hirotoshi Ito (Fig. 10B) is carved from a single piece of stone but its shape and glossiness gives the impression of a bowl filled with some runny liquid, splashing after something hit it. In both artworks, there are no definite cues to object identity; both do not seem to portray any particular real object.

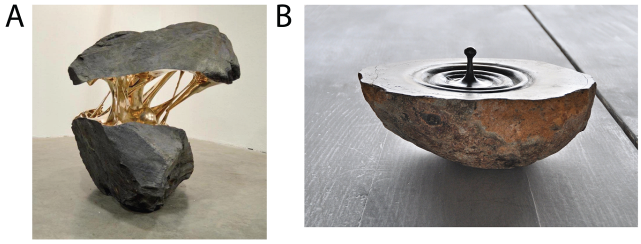

Figure 10. Examples of fluid sculptures made from metal and stone. (A) “Space attraction (L'attraction de l'espace)”. Sculpture and image © 2015 by Romain Langlois (https://www.romain-langlois.com). Reprinted with permission. (B) “Ripple”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

The same is true for the following two sculptures from José Manuel Castro López which are both made of solid stone. However, by carefully shaping its features, the first conveys the feeling of some soft, pillowy material that has been folded (Fig. 11A) and the second even suggests two materials: an inner, rather mushy one, enwrapped by an outer, rather tough skin material, which has been peeled away in one place (Fig. 11B).

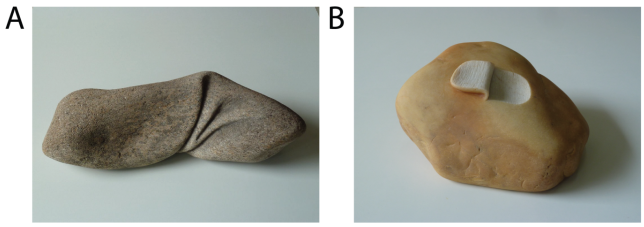

Figure 11. Examples of soft sculptures made from stone. (A) “Sin título” and (B) “Loncha”. Both sculptures and images © 2016 by José Manuel Castro López. Reprinted with permission.

Finally, the two wood and stone sculptures of Phil Young (Fig. 12A) and Hiorotoshi Ito (Fig. 12B) present typical shape features of folded cloth material. Also, they look as if pushed in and knotted, giving the impression of some soft, pliable cloth material, which persists even though color and texture features show the hard wood and stone materials.

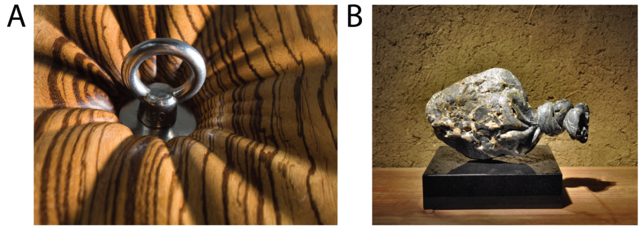

Figure 12. Examples of cloth sculptures made from wood and stone. (A) “Crush”. Sculpture by Phil Young (https://www.dendrophile.co.uk/). Image © 2010 by Lilly Holman (Lilyholman.com). Reprinted with permission. (B) “Bound”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

3.2. Materials from Transformations: Cues to Object Identity

Some artists add cues to object identity to create dissociations with material identity from shape. In the context of our working model (Fig. 2), this means that the artists use both routes simultaneously: they suggest a particular material identity by presenting shape cues in line with material properties (estimation route) but a different material by evoking learned object–material associations (association route). In the following, we show examples for this type of artworks with object identity cues of varying strengths.

First, the sculpture by Shayna Leib has relatively weak cues to object identity (Fig. 13A). The sculpture is made of glass, but gives the impression of some elastic, organic material, with particular physical forces acting on them (cf. Fig. 10B): the small limbs look as if they were swaying in wind or a water current. Both subsequent sculptures have strong cues to object identity: Daniel Webb’s wood sculpture (Fig. 13B) gives the impression of some soft, folding cloth material, with the shoes suggesting a blanket thrown over two persons. In contrast, Noémi Kiss used actual textile material (Fig. 13C) but formed it into the shape of spilled or splashed liquid, while color and texture features clearly give it away as a carpet.

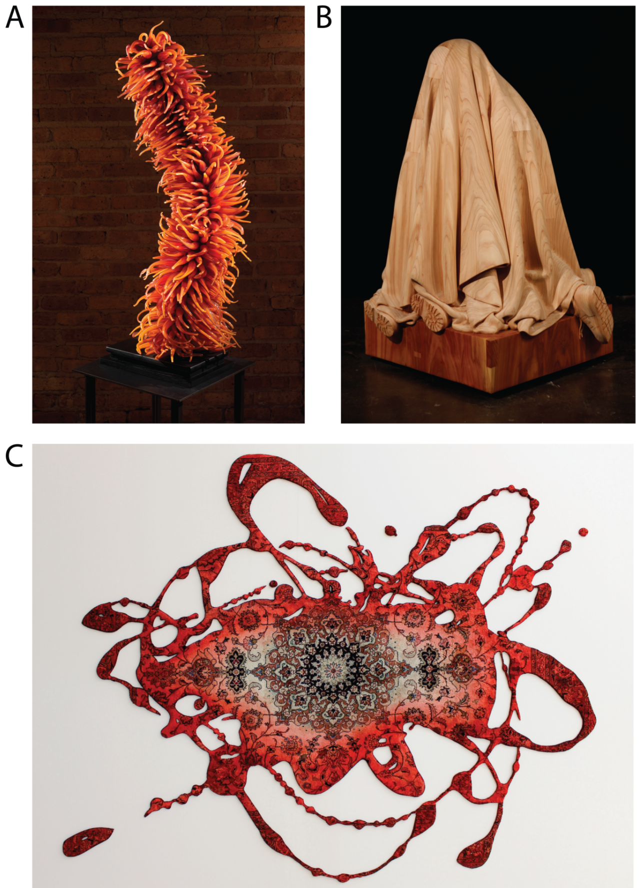

Figure 13. Examples of swaying, folding and spilling sculptures from glass, wood, and carpet. (A) “Cirrhipathes Anguina”. Sculpture by Shayna Leib (http://shaynaleib.com). Image © 2007 by Tom VanEndye. Reprinted with permission. (B) “Fortress”. Sculpture and image © 2010 by Daniel Webb (http://danwebb.squarespace.com). Reprinted with permission. (C) “Syrup”. Sculpture and image © 2017 by Noémi Kiss (http://www.noemikiss.at). Reprinted with permission.

There are even stronger cues to object identity in the following two porcelain sculptures: much of their shape, color, gloss and painted patterns are typical for porcelain dinnerware. However, Livia Marin formed part of her sculpture into a “puddle”, which makes it look like it melted (Fig. 14A). Equivalently, local shape features of the vase by Laurent Craste are modeled to give the impression of some soft material, which is melting or drooping under gravity (Fig. 14B).

The final sculptures discussed in this section (Fig. 15) are made of solid stone or glass. However, we see them as rather soft objects that were subjected to some transformation. The artists do achieve this

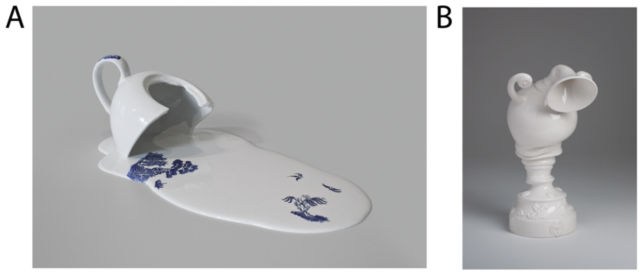

Figure 14. Examples of melting and drooping sculptures from porcelain. (A) “Nomad Patterns”. Sculpture and image © 2012 by Livia Marin (http://liviamarin.com). Reprinted with permission. (B) “Melting pot I”. Sculpture and image © 2012 by Laurent Craste (http://www.laurentcraste.com). Reprinted with permission.

impression by shaping global as well as local features together with particular color and texture features. The pillow by Håkon Anton Fagerås (Fig. 15A) is made of stone, but looks as if soft and sagged and crumpled under the influence of gravity. The same is true for Dylan Martinez's glass-blown sculptures (Fig. 15B) that look like water-filled plastic bags. Note that by conveying two different materials (water and plastic), the glass sculptures are similar to previous examples where the same physical material appeared as several materials simultaneously (Fig. 3D: skin and veil, or Fig. 5B: soup and meat). Finally, the two marble/stone sculptures by Hirotoshi Ito appear of similar softness: an ice-cream on a stick that is melting (Fig. 15C) and a handkerchief that was folded (Fig. 15D). All of these sculptures are made of materials that share texture and color features with the depicted object (e.g., the matte, white appearance of the stone in Fig. 15A resembles that of a pillowslip; the transparent glass in Fig. 15B resembles the appearance of plastic bags and water). As a consequence, they are close to being perfect material illusions. However, in contrast to our previous examples (Fig. 5), they do not only mimic particular objects and materials but also let us infer the particular transformations those objects were subjected to (i.e., their causal history).

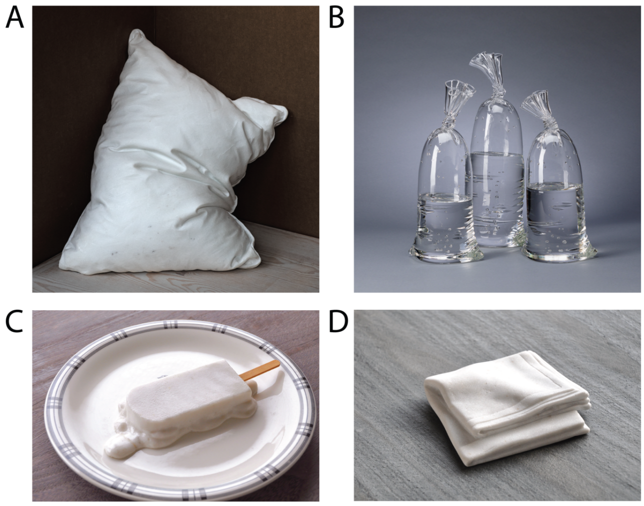

Figure 15. Examples of crumpled, sagged, melted and folded sculptures made from stone and glass. (A) “Down (no. 2)”. Sculpture and image © 2018 by Håkon Anton Fagerås (http://fageras.com). Reprinted with permission. (B) “H2O/SiO2”. Sculpture and image © 2018 by Dylan Martinez (https://www.dylanmartinezglass.com). Reprinted with permission. (C) “Melting” and (D) “Marble Handkerchief I”. Both sculptures by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

3.3. Materials from Transformations: Interactions with Other Objects

Also, artists can strengthen the impression of particular materials or transformations by including interactions between objects. These provide further visual evidence for a particular causal history and therefore, for a particular material identity (cf. the causal history branch of the estimation route in Fig. 2). In two sculptures by Phil Young and Hirotoshi Ito that are made from wood and stone, the interacting objects are fingers (Fig. 16A) and chopsticks (Fig. 16B) that appear to pinch the main objects, which makes them look soft and elastic. Also, the following wood and stone sculptures from the same artists are seemingly squeezed together by a tight cable (Fig. 17A) or a belt (Fig. 17B), again giving them a soft, elastic, cloth-like appearance.

The next sculptures (Fig. 18) strengthen the perceived incongruency between physical material properties and observed material properties by adding cues to object identity. The first sculpture, by Hirotoshi Ito, looks like stone (Fig. 18A) but its texture features (not so much the color) could also be that of a piece of ham or a loaf of bread. This impression is supported by the knife that seems to cut off a slice (a powerful visual illusion; see also Gerbino and Zabai, 2003) and makes the object appear somewhat soft and fleshy. In contrast, shape, gloss and color identify Laurent Craste's sculpture as porcelain vase (Fig. 18B); however, the baseball bat and the deformations it appears to have caused suggest a much softer material which was punched and carved in.

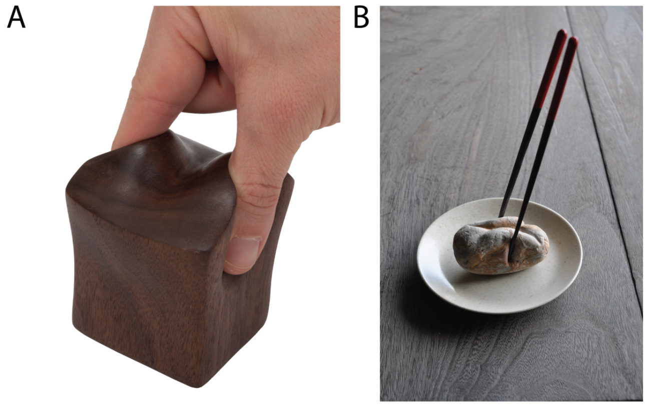

Figure 16. Examples of pinched sculptures made from wood and stone. (A) “Pinch”. Sculpture by Phil Young (https://www.dendrophile.co.uk/). Image © 2010 by Lilly Holman (Lilyholman.com). Reprinted with permission. (B) “Country of Chopsticks”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

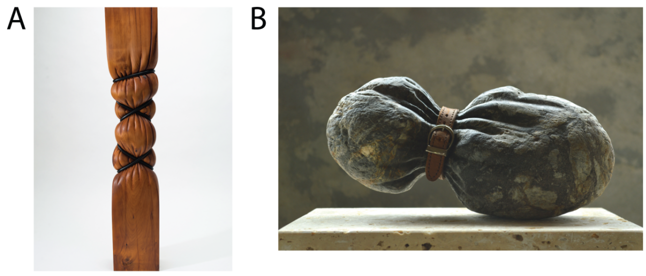

Figure 17. Examples of squeezed sculptures made from wood and stone. (A) “Rhytide”. Sculpture by Phil Young (https://www.dendrophile.co.uk/). Image © 2010 by Lilly Holman (Lilyholman.com). Reprinted with permission. (B) “Tied Tightly”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

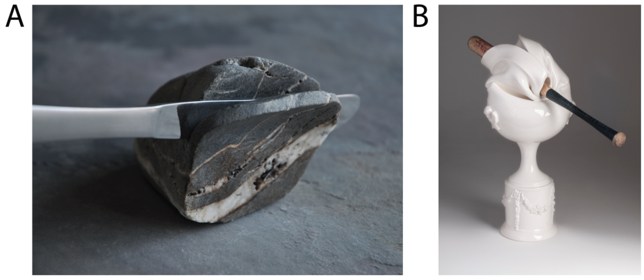

Figure 18. Examples of cut and punched sculptures made from stone and porcelain. (A) “Delicious Stone II”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission. (B) “Iconocraste au bat IV”. Sculpture and image © 2012 by Laurent Craste (http://www.laurentcraste.com). Reprinted with permission.

Finally, in the two sculptures by Carol Milne and Hirotoshi Ito (Fig. 19), the interacting objects are chosen to provide definite cues to object identity as well as causal history. The woven elements and the knitting needles of the glass sculpture (Fig. 19A) suggest some soft woolly material that has been knitted into a piece of wide-meshed ribbon (and knotted afterwards). The stone sculpture looks like stone (Fig. 19B) but the tab as well as the thin, opened lid, together with the spilling-out nuggets, clearly suggest a hollow can-like container of a hard and metallic skin material.

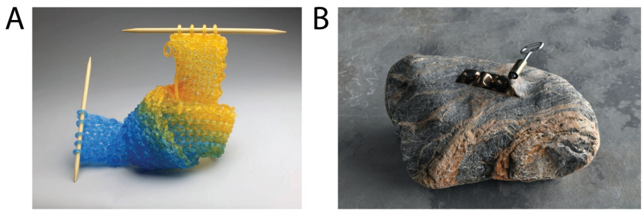

Figure 19. Examples of knitted and opened sculptures made from glass and stone. (A) “Knit Knot”. Sculpture and image © 2014 by Carol Milne (https://www.carolmilne.com). Reprinted with permission. (B) “Easy to Peel the Stone I”. Sculpture by Hirotoshi Ito represented by Paris Art Web Gallery (https://www.parisartweb.com/artists/sculpture/hirotoshi-ito). Reprinted with permission.

4. Visual Arts and Material Perception Research

Visual artists rely on careful observation and intuitive insights to learn characteristics of the real world that can inform many areas of vision science (Arnheim, 1974; Gombrich, 1960). Most painters, sculptors, designers, illusionists and other visual artists create their works to be visually experienced by an audience. As a consequence, they implicitly or explicitly strive to understand how visual perception works and how they can use perceptual principles to create the desired effects. This might be, for example, to imitate reality or to produce particular cognitive effects like interest or surprise in their audience (Ludden *et al.*, 2008) — for example, by creating inconsistencies between texture and shape cues to material.

As a consequence, visual arts can inform vision science (Daneyko *et al.*, 2011; Grossberg and Zajac, 2017; Leymarie and Aparajeya, 2017; Pinna, 2012, 2013; Rubin, 2015) or even preempt later scientific findings (Ekroll *et al.*, 2017; Macknik *et al.*, 2008; Tse, 2017). For example, children's paintings can teach us about their cognitive development and the associated predominant way of seeing the world (e.g., with increasing age children assign more importance to volume and illumination; e.g., Pinna, 2013). Paintings in general can be used to (i) demonstrate different aspects of visual perception, such as boundary and texture grouping or spatial attention, and (ii) compare these effects to predictions from cognitive or neural theories (e.g., Grossberg and Zajac, 2017). Finally, visual arts often also preempts vision science: for example, Tse (2017) describes how American illustrator Coles Phillips (1880–1927) used principles of illusory contours and completion in drawing his signature “fadeaway girls” — principles which vision science picked up on only several decades later (Kanizsa, 1979).

Consequently, in recent years, there is an increasing interest in bringing together vision science and art, exemplified by an increasing number of publications on the topic (e.g., Cavanagh, 2005; Cavanagh *et al.*, 2008;

Cutting, 2002; Gregory and Harris, 1995; Hecht *et al.*, 2003; Kemp, 1990; Kubovy, 1986; Livingstone, 2014; Mamassian, 2008; Pinna, 2007; Ramachandran and Hirstein, 1999; Zeki, 1999).

It seems that especially material perception — which is a relatively young field of research but has a very long tradition in visual arts — can learn from artists and their artworks (e.g., Di Cicco *et al.*, 2018; Sayim and Cavanagh, 2011; van Assen *et al.*, 2016). The current paper highlighted this by showing how sculptors use principles of material perception from shape which research has just begun to uncover. Together with considerations based on our model — which emphasizes the different routes and sub-routes of material perception (Fig. 2, Table 1) — the presented artworks point to future directions and open questions in the research of material from shape that will be outlined in the following.

Material perception research will need to (i) identify relevant shape features in material and transformation perception (e.g., shape features signifying particular material properties or transformation identity; e.g., Paulun *et al.*, 2017), and (ii) test the relative importance of particular features (e.g., highlights and their characteristics for perceiving an object as glossy; e.g., Chadwick and Kentridge, 2015). Specifically, for shape features it is not yet clear which features are absolutely necessary to let us perceive particular materials: what are the heuristics we rely on to identify materials?

Furthermore, material perception research should test interactions (iii) between cues (such as optical and shape features) in determining material perception (e.g., Kersten *et al.*, 2004), as well as (iv) between perceived transformations and materials. Also, there is a lack of research investigating the roles of (v) object familiarity, as well as (vi) context effects on material perception (e.g., interacting objects or scene environment). Finally, there is little research on the consequences of material perception. To a large extent, it still has to be investigated what (vii) aesthetic, emotional and cognitive effects follow from looking at particular materials or transformations (e.g., which materials and transformations are experienced as surprising, funny or sad? Why? What makes food look appetizing and skin look natural?).

These questions are just a few potential future venues for material perception research that were at least partly inspired by the presented artworks. Other intriguing examples of how research and visual arts can inform each other are collected in this special issue of *Art & Perception*; in the long run they will help to combine insights from science and art to advance knowledge in both areas.

Note

1. Intrinsic properties ‘belong to’ the object; they tend to persist over time and to originate from the object itself rather than from external events (e.g., object material and typical shape). Extrinsic factors or events are rather circumstantial, variable, and come from outside the object (e.g., position, orientation, lighting conditions, viewpoint, motion caused by outside events or shape transformations; Schmidt and Fleming, 2018).

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Competing interests

The author declares no competing interests.

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