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RESEARCH ARTICLE

COLOR RESEARCH AND APPLICATION WILEY

Colored skins and vibrant hybrids: Manipulating visual perceptions of depth and form in double-curved architectural surfaces through informed use of color, transparency and light

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Abstract

The past decades of research on color and light yielded vast knowledge supporting their informed use in architectural design. While there currently exists a rich body of knowledge and methods geared to affect the perception of depth and form in tiled, opaque architectural surfaces, not many such methods have been developed for double-curved, transparent, in-mass colored surfaces. The perception of depth and form in these surfaces relies on a complex blend of parameters, such as color combinations, illumination source, angle of viewing, location of shadows and reflections, material thickness and grade of transparency. To determine the visual effects caused by some of these parameters, experiments based on visual observations were carried out involving handcrafted, in-mass colored, undulant architectural surfaces. The insights from the experiments then served to develop four color strategies for architectural surface design harnessing the discovered effects in diverse ways. Through this, the study has sought first to observe and understand the effects of color and light in perceiving undulant surfaces, and second to highlight the potentials of harnessing these effects in the design of expressive architectural elements. The main insight from the study is that informed and deliberate application of color and light yields a wide range of potentially interesting perceptual effects in double-curved architectural surfaces, such as spatial filtering, gradient screening, vibrant massing and animate reshaping. Such effects, applied in an architectural context, can help to fulfill the demand for physical environmental enrichment in the digital era.

KEYWORDS

architectural surface design, double-curved surfaces, form and depth perception, in-mass color and light interactions, translucent and transparent color

1 | INTRODUCTION

Today, the use of color as a medium for enhancing the physical experience of the built space promises to address the emerging need to diminish the negative effects of digitalization on human health. Prolonged exposure to digital stimuli on handheld devices and computer screens followed by reduced interaction with the physical environment are suggested to lead to worsened physical and mental wellbeing.[1,2] Consequently, it is believed that richly articulated physical architectural elements and built spaces that encourage multisensory interactions with real-world materials are desired to counterbalance these effects in many architectural contexts—from elderly homes and workplaces to public buildings and healthcare facilities.[3] Specifically in healthcare architecture design, they could be an effective aid in rehabilitation of disorders such as autism, stroke and dementia.[4] The observations concerning richly articulated surfaces in this study reveal that color, geometry and light effects, if united in an informed manner, can become powerful tools in achieving such utility goals.

Color in architectural design has been applied for millennia, with the first written mentions by Vitruvius dating back to the 1st century.[5] Among historical precedents, Antonio Gaudi's informed employment of translucent color in the glass windows of the La Sagrada Familia Church in Barcelona, producing spectacular atmospheric effects, is one of the well-known examples.[6] Today, color in architecture is applied to a variety of elements and scales, such as roofs, facades, urban screens, interior walls and furnishings.

A closer look at contemporary architectural projects employing color suggests that it is primarily applied on a component-to-component basis, for example as planar tiles or other types of smaller individual elements assembled to form larger entities, such as colorful facades, roofs and canopies.[7] Thereupon, an architectural surface is divided into compartments, each with its own color, which allows for variation of hues at the global scale of an architectural surface. It can be noticed in many contemporary buildings, such as the multicolored roof of the Santa Caterina Market in Barcelona by Enric Miralles and Benedetta Tagliabue,[8] the experimental enclosures with colored stripes by architect Marc Fornes,[9] and textile structures by Jenny Sabin,[10] in which patches of fabric with uniform color are sewn together to create a chromatic effect. Similarly, in color research, the majority of precedent studies investigating color and light interactions in architectural surfaces focus on surfaces comprised of either flat, two-dimensional tiles and wall planes, or tessellated three-dimensional (3D) structures.[11–14]

The fact that both architectural applications as well as color research have primarily focused on the abovementioned component-to-component coloring principles suggests the existence of a knowledge gap, concerning other ways of applying color onto architectural surfaces. Of particular interest for this study is a coloring strategy based on in-mass color gradients. The research of architect Neri Oxman and the team from Massachusetts Institute of Technology can be regarded as one of the precedents of this approach. Therein, 3D printing was used to achieve an effect of in-mass coloring in architectural objects from a soft, synthetic material.[15]

The findings of leading color theorists, such as Lois Swirnoff, clearly show that color composition is a powerful tool for shaping and manipulating the perception of depth and form in tiled, 3D architectural surfaces.[16] Prompted by this premise, this study aimed to determine how different color compositions affect the perception of depth and form in the particular case of in-mass colored, smooth, double-curved architectural surfaces. With this, the purpose of the investigation was to formulate architectural surface design strategies that prompt further research and encourage novel applications in architecture and interior design.

2 | METHODS, MATERIALS, THEORY

2.1 | Setups and prerequisites for the observations

The study embraced two sets of qualitative observations aimed at describing the visual effects in handcrafted physical models with moderately and strongly undulant features. Figure 1 diagrammatically summarizes the physical setup for observations involving these models.

In each experiment, a model was exposed to two different illumination sources, positioned at two locations relative to it—at the side and from behind. The sources were set up to resemble lighting conditions present in architectural settings. The first illumination type was daylight from a window on a sunny day, filtered through a white photo studio light reflector, mimicking a light filtering effect of a sheer window curtain. This type of illumination was applied always from the left side of the model. Each model was placed on an opaque, matte, white paper background.

The second setup for the observations embraced backlighting, which was important to investigate as it is relevant in architectural settings. Most commonly, it can be observed in translucent building façade elements and window screens that are backlit with artificial light sources during nighttime. To simulate such an effect, eight linear LED light fixtures, each 80 cm long, with luminous flux of

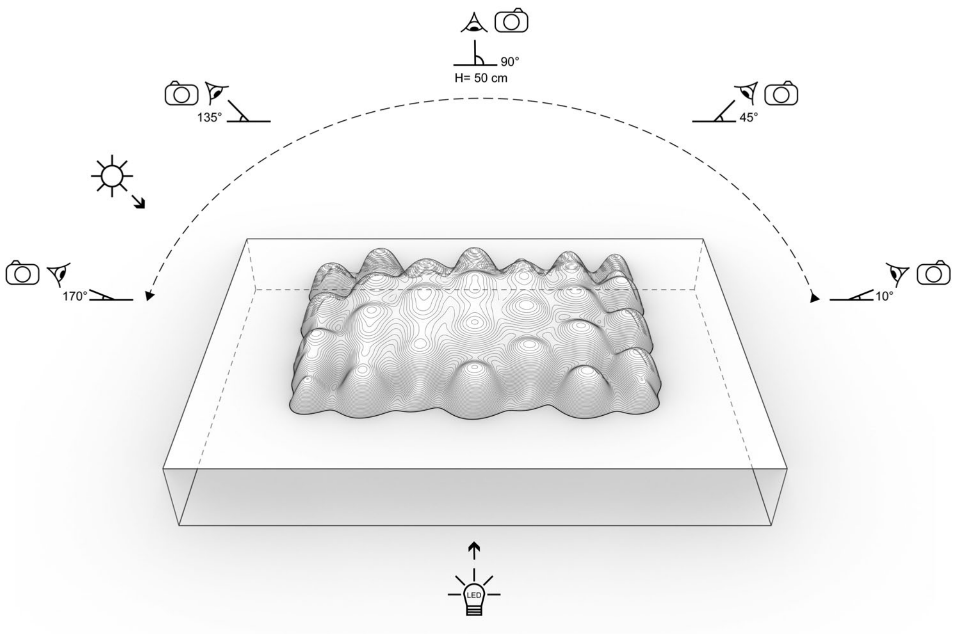


FIGURE 1 The physical setup for the observations

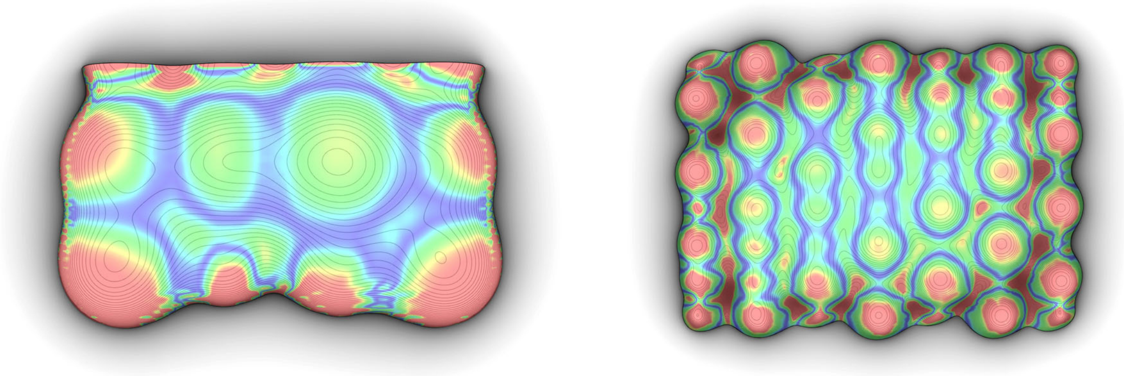


FIGURE 2 Digital analyses of mean curvatures in the studied models. Red indicates zones with the largest curvatures, yellow, orange and green indicate zones with moderate curvature and blue indicates the flattest areas

400 lm and color temperature of 3000 Kelvin were placed 10 cm underneath a white, translucent Plexiglas sheet.

Moreover, for both illumination setups, to examine the transparency, translucency, opaqueness and gloss of the studied objects, they were placed on a contrasting background of a square grid, according to similar procedures used in prior color research.[17–19]

After placement in the illumination and background setups described above, the researchers examined each model visually from multiple angles, at an approximate distance of 50 cm from the model. As shown in Figure 1, the viewing angles were kept in a panoramic range of 10°–170°, with the viewing plane perpendicular to the background plane on which the model was placed. The most pronounced effects at characteristic viewing angles were documented in photographs taken with a digital camera.

To enable qualitative comparisons between the perceived and the actual curvatures, digital curvature maps of the original digital 3D models were generated (Figure 2).

Furthermore, to structure and guide the visual observations of each model, the following questions were formulated:

1. *Depth perception*: Which areas of the surface protrude and which recede visually? How does the observed effect correspond to the actual topography of the surface?
2. *Curvature perception*: Which areas of the surface appear concave, convex and which seem flat? How

does the observed surface topography correspond to the actual curvatures of the surface?

3. *Form perception*: How are the boundaries of global form, silhouette and internal boundaries between the color gradients defined? Which other visual effects and material properties influence the perception of the surface's geometric form, silhouette and outer boundary?

The answers to these questions were registered in an experiment log.

2.2 | Theoretical frameworks underpinning result formulation

The results of the abovementioned observations of in-mass interactions of color and light and their effect on the perception of depth and form in the studied models were formulated in relation to established color and light theories. How juxtapositions of particular colors interact with each other and how this interaction affects the perception of a surface were examined in the context of Josef Albers's and Johannes Itten's findings on colors applied to flat surfaces.[11,20] Lois Swirnoff's observations concerning dimensional appearance of color[14] were a key reference regarding the perceptual effects in multicolored architectural surfaces. Regarding other important factors related to color and affecting the perception of materials interacting with light, such as transparency, translucency, opacity, specularity and gloss, Jose Caivano's theory of the cesia[12] was included in the qualitative interpretations of the observed effects. Moreover, the early concepts of David Katz on different modes of color appearance, i.e. surface color, film color, volume color and transparent color,[21] affecting the perception of form and depth of objects, have informed the interpretations of experiments involving the contrasting grid background. Wherever relevant, other research findings from the field of color and optics were also recalled to support the drawing of conclusions from the visual observations.

2.3 | Study model design and materialization

To enable the visual studies, 18 artistically handcrafted physical models were made, representing two typologies of double-curved surfaces: moderately undulant and strongly undulant. To materialize the models, two double-curved surfaces were first 3D modeled using software Rhinoceros 3D and Grasshopper (Figure 3). The 3D models were then used as input for digital manufacturing of physical molds from a PET-G plastic. The employed mold manufacturing techniques were CNC milling, vacuum thermoforming and robotic single-point incremental forming.

Importantly, the chosen manufacturing techniques generated two types of textures on the surfaces of the molds: a rugged one in the moderately undulant model, and a linear one in the strongly undulant model (Figure 4). These textures were transferred onto the surfaces of the final models cast from the molds. As the later observations revealed, this texturing influenced the perceptions of depth and form in the examined surfaces. In addition, the fact that both molds, apart from the abovementioned textures, had overall smooth surfaces, resulted in the final cast models exhibiting high glossiness.

The last materialization stage involved handcrafting of the final models by manually casting addition-cure silicone into the molds. Prior to casting, dedicated silicone pigments, in liquid and powder form, were mixed into the material while it was still in liquid state. Because the curing of silicone can start only if a catalyst is added to a base, the color intensity, hue and transparency levels in the material could be evaluated qualitatively prior to casting by ocular inspection of the liquid mass against a source of light and, if necessary, adjusted to obtain the

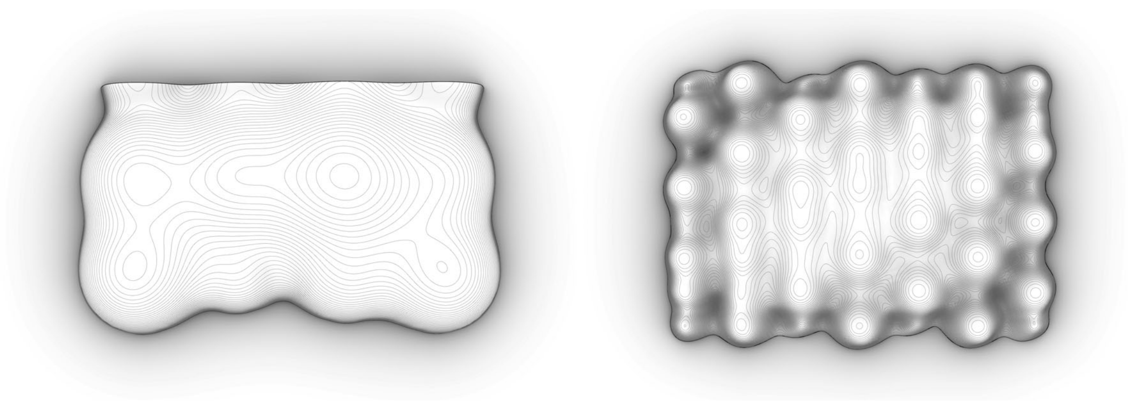


FIGURE 3 Digital 3D models with moderately undulant (left) and strongly undulant (right) features

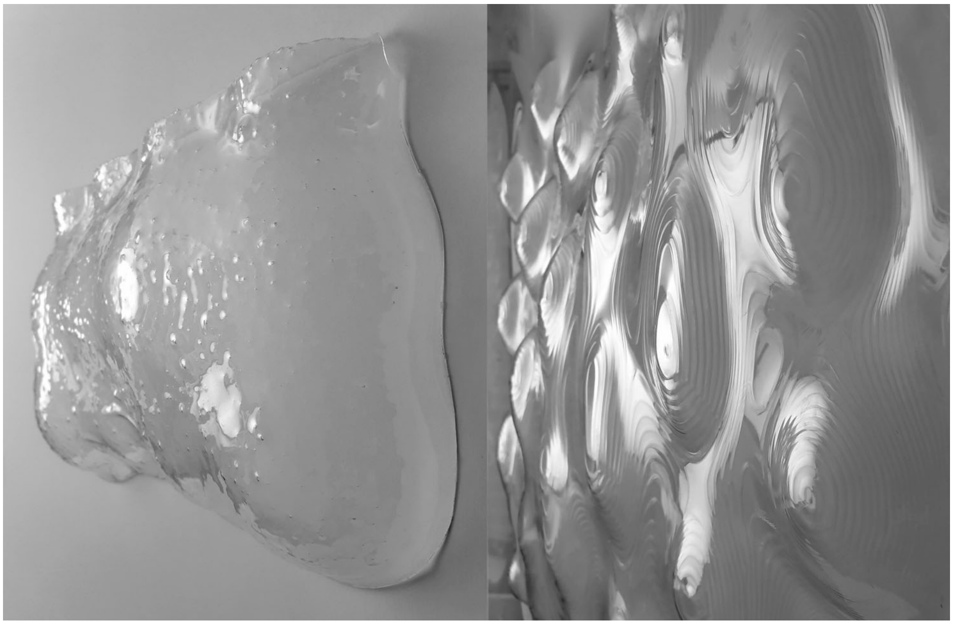


FIGURE 4 Textural features of molds used to produce the final study models—rugged texture of the moderately undulant model (left) and curvilinear texture of the strongly undulant model (right)

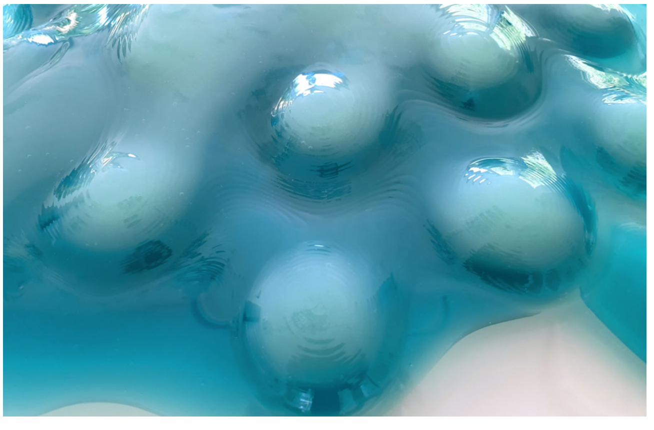


FIGURE 5 Color saturation and translucency gradients in the material mass, caused by the undulant characteristics of the mold and the optical properties of the material cast into it

anticipated coloring effects. After adding the catalyst to the pigmented silicone base, the material would coagulate. After approximately 2–3 h, it solidified and dried completely, forming pliable, form-stable models that could be easily removed from the molds.

2.4 | In-mass coloring and model transparency variation approach

The silicone material chosen to make the final models is a highly translucent material that can be pigmented and cast in layers. At first in liquid form, with time it coagulates and hardens, producing form-stable models. The cast layers smoothly bond with each other, forming a coherent material mass.

In both geometric types of the produced models, due to large variations in surface curvature angles and topographical depth, the material in the initial liquid state accumulated in thicker and thinner zones. These thickness variation effects, after initial experiments with the material, led to the discovery that the overall surface mass can be visually differentiated by introducing color saturation and translucency gradients, achieved through informed material layering (Figure 5).

Therefore, a systematic method of in-mass coloring through layered casting was developed to control the final colors and transparency levels in the material. An overview scheme of the method is presented in Figure 6. The method embraced gradual filling of the mold with material layers, with each layer having specific proportions between the total material volume and the quantities of introduced pigments. This allowed to achieve low color saturation and transparency by sparse use of pigments and low surface thickness, moderate saturation and translucency by moderate increase in pigment amount and material thickness, and high color saturation and opacity by using a large quantity of colored pigment or by adding white pigment to the colored base. In addition, the described method allowed to generate color blending effects for transparent and translucent color layers cast on top of each other.

When it comes to the choices of pigment hues, to limit the virtually endless possibilities for composing colors into mixtures, this study followed a pigmenting approach based on a color harmony classification by Frank H. Mahnke, featuring monochromatic, analogous, complementary and asymmetric color harmonies.[22] For each harmony type, a select number of representative

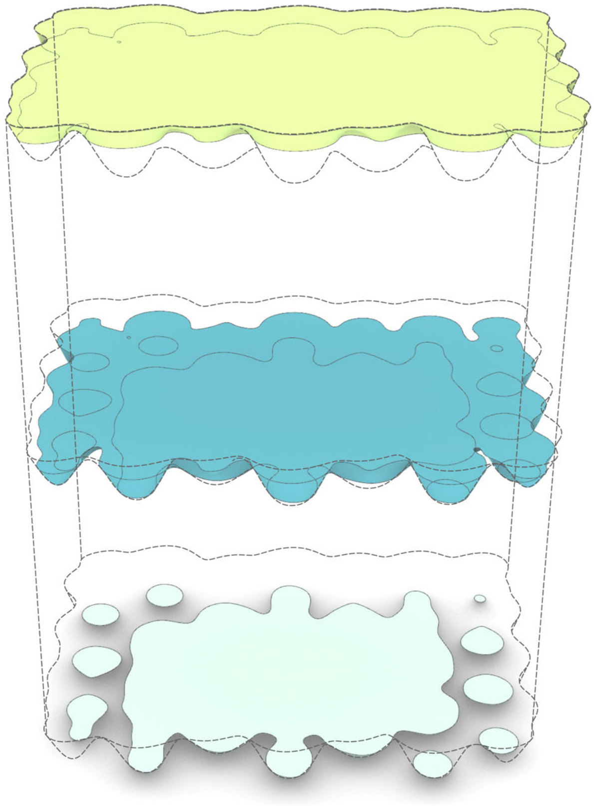


FIGURE 6 An overview scheme of the developed in-mass coloring method, with exemplary pigmenting formulas employed to control the colors and levels of translucency in one of the examined surface models

color combinations was examined. The colors were explored in single, double and triple layers of differently pigmented material, with hues applied in diverse combinations and orders.

In the first experiment series, the models were pigmented with yellow, red and blue. For experiments in series two, this palette was broadened by introducing colors derived from their mixing, and by including a white pigment for opacity and color brightness modulation. While the color pigments to be combined as layers were selected based on the color harmony categories mentioned above, the actual color effect in the material was fluctuant. This was due to the inherent translucency of the material, causing the superimposed pigmented layers to interact with each other, producing additional colors and color volumes that varied in hue and brightness in various illumination conditions and viewing situations.

3 | EFFECTS OF COLOR AND LIGHT ON THE PERCEPTION OF DEPTH AND FORM IN MODERATELY UNDULANT SURFACES

The aim of this part of the study was to determine how translucent color compositions affect the perception of depth in moderately undulant, thinner architectural surfaces, viewed from various angles under differing illumination conditions. All models were made by casting silicone into the vacuum formed mold featuring the rugged texture. The observations were carried out for natural lighting and artificial backlighting, to allow for comparisons between the studied cases. The color harmonies examined in these models were monochromatic, non-uniform, complementary and analogous, with optical properties of the layers varying between transparent and translucent characteristics. The formulation of the results of the observations was guided by the questions listed in the previous section, with the most characteristic effects registered in photographs and in an experiment log.

3.1 | Effects in monochromatic surfaces: Depth erasure and depth inversion

The models examined in this category constituted of one color layer, cast into the vacuum-thermoformed mold. Two models of this kind were produced, representing cool and warm colors, obtained by using blue and red pigments. The pigment quantities differed between the models, to explore colors with two different saturations. In the model with the red pigment, a small quantity of pigment was added, resulting in a light orange color with low color saturation and a high level of transparency (Figure 7). For the blue model, a large quantity of pigment was added, producing a

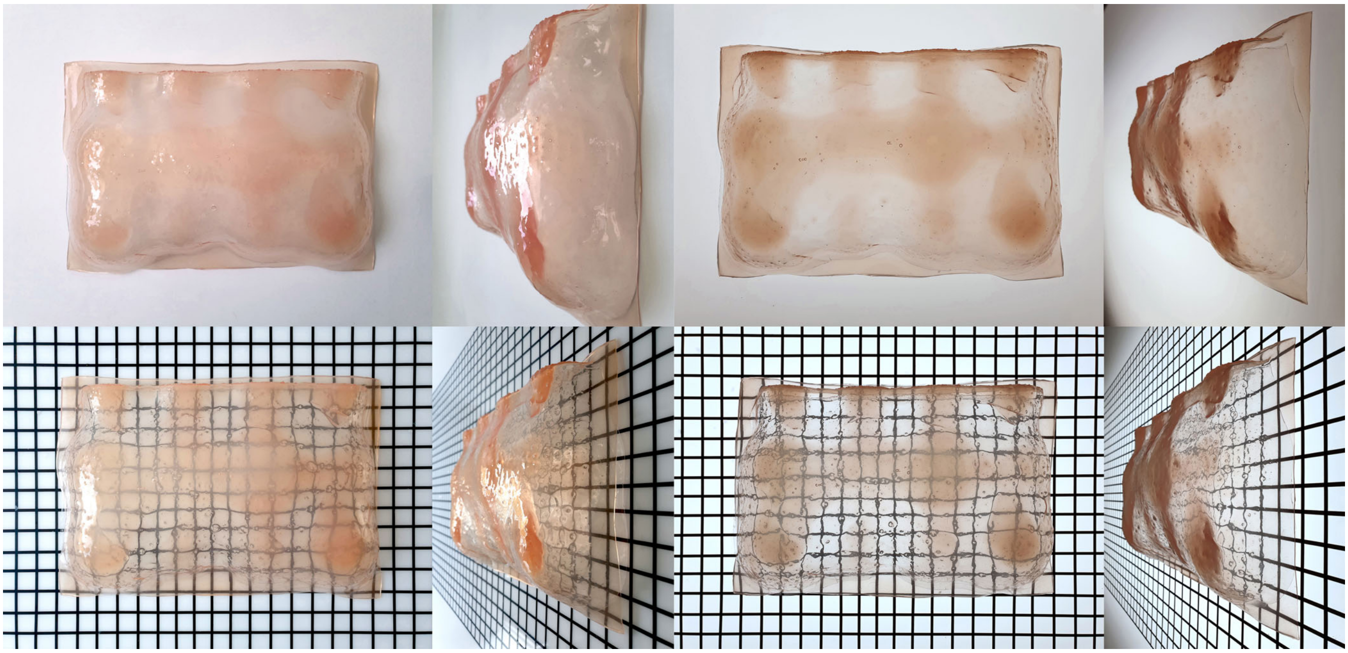


FIGURE 7 Monochromatic surface colored using a small quantity of red pigment. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

dark color with high saturation and an almost opaque surface (Figure 8).

One of the most striking effects observed in these models were depth erasure in the light red model and depth inversion in the dark blue model, both occurring in the frontal viewing situation. For the former, in front view, regardless of light source type or location, the surface appeared rather flat. The presence of reflections, especially for the side illumination case, additionally increased the difficulty of understanding the surface topography upon frontal viewing. Only the edges of the surface were easily discernable as curved, and the rugged texture of the surface helped to emphasize this reading, making it accurate in relation to the actual form.

The accuracy of perceiving the actual depth of that surface, its thickness and variation of curvatures was improved upon non-frontal viewing, that is, viewing from the sides, in ranges of approximately 0°–45°. Viewing at these angles with the illumination source positioned opposite to the viewer, regardless of illumination type, revealed surface depth and thickness and emphasized the third dimension of the material cross-section. This effect relates to the effects in volume color observed by Albers and further studied for fluid materials such as water.[11,23] New forms appeared within the material mass, with sharpened boundaries revealed by this way of viewing. This effect was further enhanced by the color becoming more saturated in the thicker zones of material accumulation and less saturated in the thinner ones, helping to associate these color cues with the surface thickness. These positioning and light transmittance effects also enhanced the perception of the global surface silhouette, which clearly appeared as curved.

In the second, dark blue model, upon frontal viewing and in the side illumination situation, the undulant topography of its form could be identified to a certain extent. The visual cue helping in this was the darker color in the thicker zones, and the specular reflections in the zones that protruded and that had more pronounced curvature. The reflections were amplified by the presence of the rugged texture, which also seemed to be a valuable depth cue, helping to understand the topography of the model. The outside boundary of the model was also discernible. In the angular viewing and side illumination situation, the presence of reflections partially helped to understand the topography of the surface due to the sharp contrast between the pseudo-matte and glossy, reflective zones. At the same time, the zones occupied by the reflections became almost white, which erased their depth and made them appear flat.

In the backlighting option, upon frontal viewing the geometric variations in the topography of the form became well emphasized, and the color intensity grading resulting from the smooth transitions of material thickness. However, an accurate understanding of how the form was shaped was distorted by the presence of a strong contrast between the thick dark zones and thin light ones. This caused an illusion of the dark zones receding and the light ones advancing toward the viewer, which somewhat inversed the perception of actual depth.

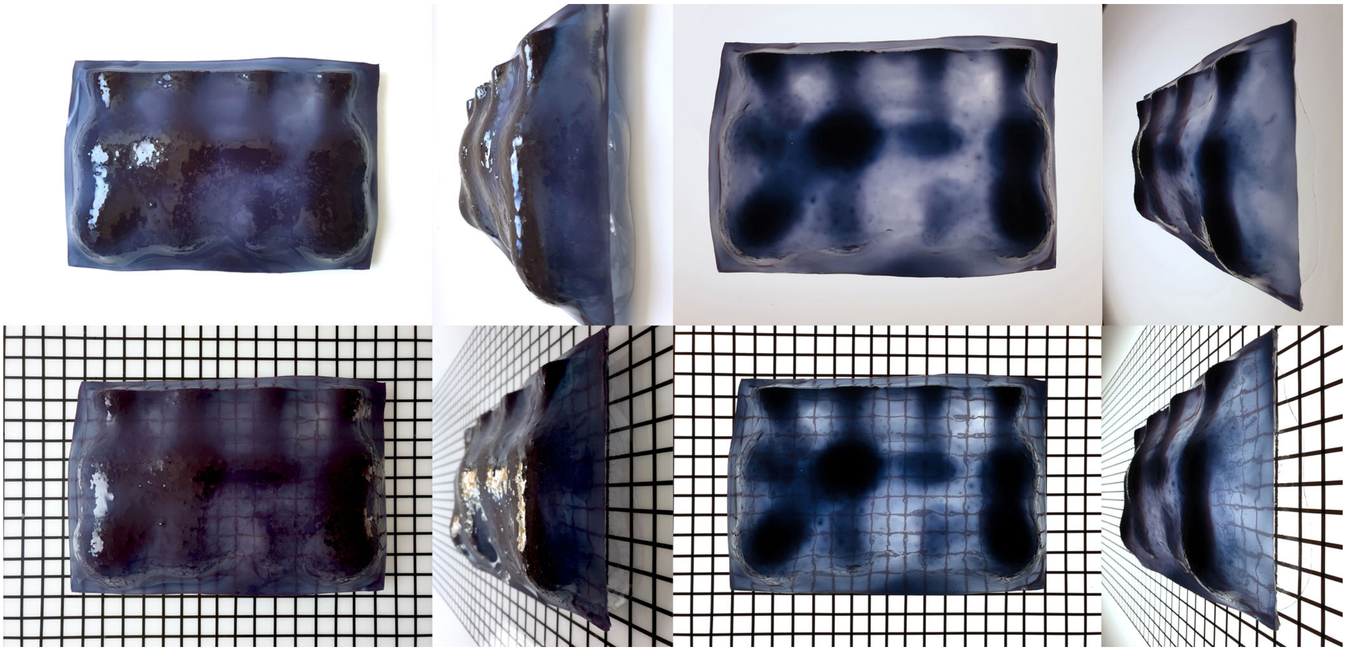


FIGURE 8 Monochromatic surface colored using a large quantity of blue pigment. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

The gloss effect was less evident in this case but in the areas where it appeared, it had a similar flattening effect as for the side illumination. Upon non-frontal viewing in ranges of approximately 0°–45° and backlighting, a similar effect was observed as for the earlier model. Namely, it revealed surface depth and thickness and emphasized the third dimension of the material.

To summarize, the transparent, moderately undulant surfaces with monochromatic coloring, both dark and light colored, need careful consideration when locating them in rooms and architectural settings with regards to the positioning of the viewer and illumination source. The most optimal placement that will emphasize their tectonic qualities seems to be on room walls located perpendicularly to the viewer, for example, at the side walls of an entrance to a room, with the illumination source such as a window located opposite the entrance. In this way, viewing at sharp angles when entering the room will activate surface depth perception. In addition, these surfaces can be illuminated from the back with artificial lighting, to either enhance or intentionally distort the perception of their depth in a frontal viewing situation.

3.2 | Effects in non-uniformly colored surfaces: Depth infusion

To counter the observed effects of form, depth and curvature flattening of the monochromatic coloring scheme, two additional models were made that featured intense-colored streaks of pigment stirred into the monochromatically colored material mass. The models represented the warm and the cool color schemes (Figures 9 and 10).

The stirring of these saturated, irregularly shaped pigment streaks into the material mass where it was the thickest and where it initially appeared as the flattest, proved to be a very effective strategy for enhancing the depth perception. The presence of streaks prompted to examine the volumetric outlines and thickness of the material at locations where these streaks occurred. These effects correlate with the research findings concerning thick, irregular in shape, transparent objects, suggesting that an important cue signaling the presence of thickness in such objects are the distortions in the perceived shape of other objects in the scene.[24] In the case presented herein, although refractive distortions are not evident, the very existence of other objects, that is, pigment streaks spatially distributed in the translucent material mass, can be seen as cues signaling the presence of its depth.

For the studied models, the streaks of pigment embedded in the translucent material revealed its thickness upon all viewing situations, both frontal and sideways. These enhancements were most striking visually when the surfaces were backlit and when the pigment streaks had differentiated hues, as was the case in the light orange model with yellow and red streaks. Importantly, the described depth accentuation effect, although positively enhancing the perception of the global surface, did not seem to enhance the perception of its curvatures and form.

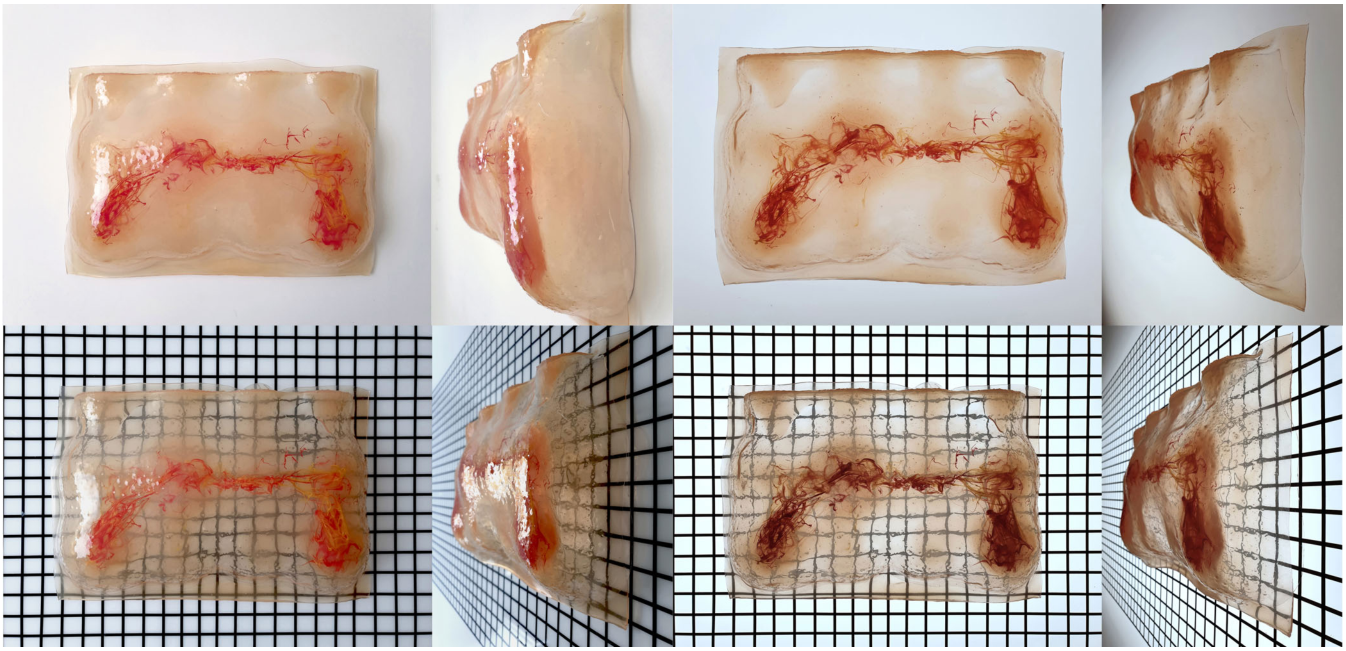


FIGURE 9 Monochromatic surface colored using a small quantity of blue pigment, featuring intense-colored streaks of concentrated blue pigment. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

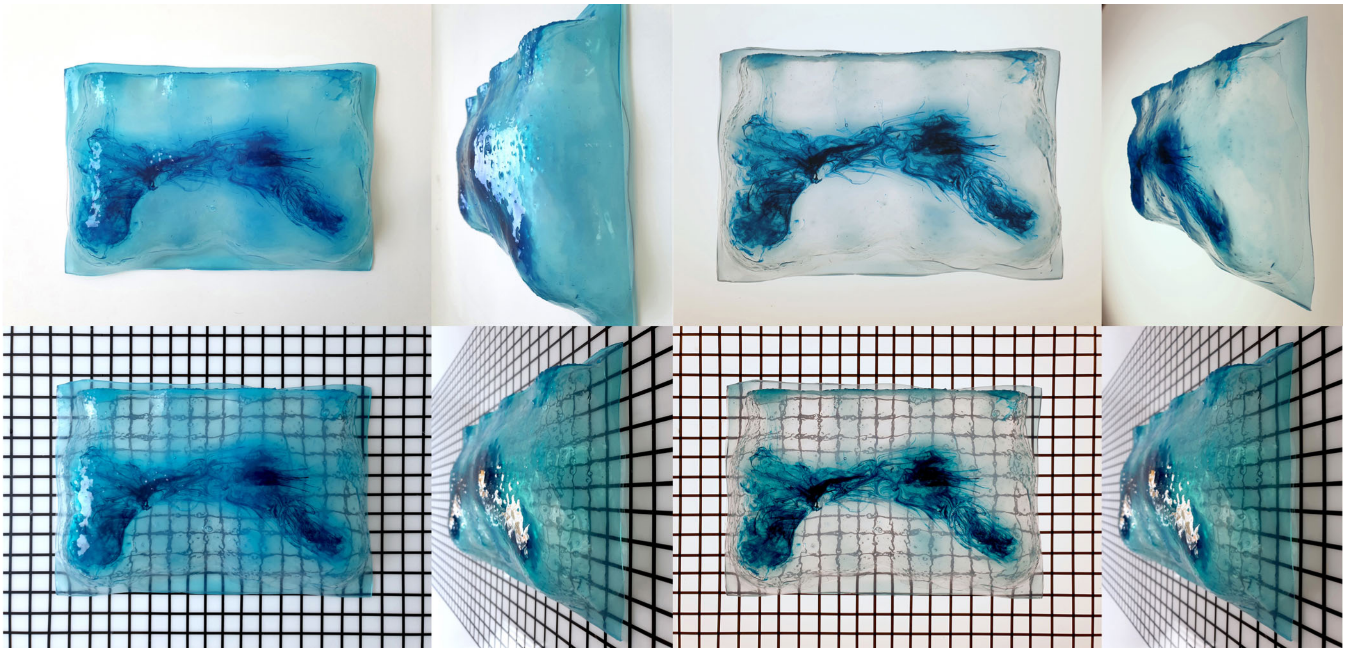


FIGURE 10 Monochromatic surface colored using a small quantity of red pigment, featuring intense-colored streaks of concentrated red and yellow pigments. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

To summarize, the additional introduction of pigment streaks into the mass of moderately undulant monochromatic surfaces creates an interesting effect that can accentuate the thickness, depth and volume of the material. The range of optimal placements of such surfaces in architectural space is potentially broad as the effect is visible both in frontal and angular viewing. An important factor to consider, however, is the preferable illumination of these surfaces from the back, to highlight their decorative depth infusion effects, as well as their overall coloring kept bright and having a high level of transparency.

3.3 | Effects in complementary color surfaces: Depth amplification and thickened depth

For the four models representing the complementary color scheme, dual and triple colors that lie opposite or asymmetrically opposite to each other on the color wheel were chosen. This included models colored using red-blue, orange-blue, and blue-yellow-red pigments. As in the case of the monochromatic models, the quantity of added pigment was differentiated between the models, from small to large, to investigate a wider range of effects.

In these models, the most evident effects were depth amplification and depth thickening. Depth amplification was caused by color contrast and differences in color brightness, which additionally emphasized the curvilinear features of the form. This effect was evident in the model featuring bright red pigment, accurately following the known observation coined by Itten[20] of the warm color raising toward the viewer and the cool one receding (Figure 11). Somewhat surprisingly, however, the red zones contained a large quantity pigment and therewith appeared opaque, which caused their actual concave curvature to appear as rather flat. This effect was, to some extent, counterbalanced by the presence of other depth cues, that is, local specular reflections accentuating the material texture and the local darkening of the boundary between the red zone and the blue underlay.

The second observed effect was the thickened depth, which revealed itself due to the layering of colors with smaller pigment quantities and therewith translucent. This effect can be seen in orange-blue and orange-green models. The bright orange zone overlaid against a darker blue and blue-green passed light through to the underlay, causing the effect of a correctly perceived thickening of the material mass. This observation aligns with the findings by Fleming and Bülthoff,[25] stating that color can amplify the sensation of translucency and make the translucent object appear to glow. Such a glow effect can be noted in the orange-blue model, in which the orange color translucent zone stands out and slightly glows from within (Figure 12).

In the backlighting setups for all models in this series, the boundaries between the layers featuring varying hues became sharply defined, revealing outlines of additional shapes within the otherwise uniform material mass. For all models except the ones featuring saturated pigments, the backlighting did not cause the effect of depth inversion observed previously in the monochrome blue model. Rather the opposite, the strongly translucent orange zones of these models in the backlighting situation still appeared as closer to the viewer that the other areas of the surface.

An additional interesting effect observed in the models was the color mixing occurring in frontal viewing in both side illumination and backlight situations. At the

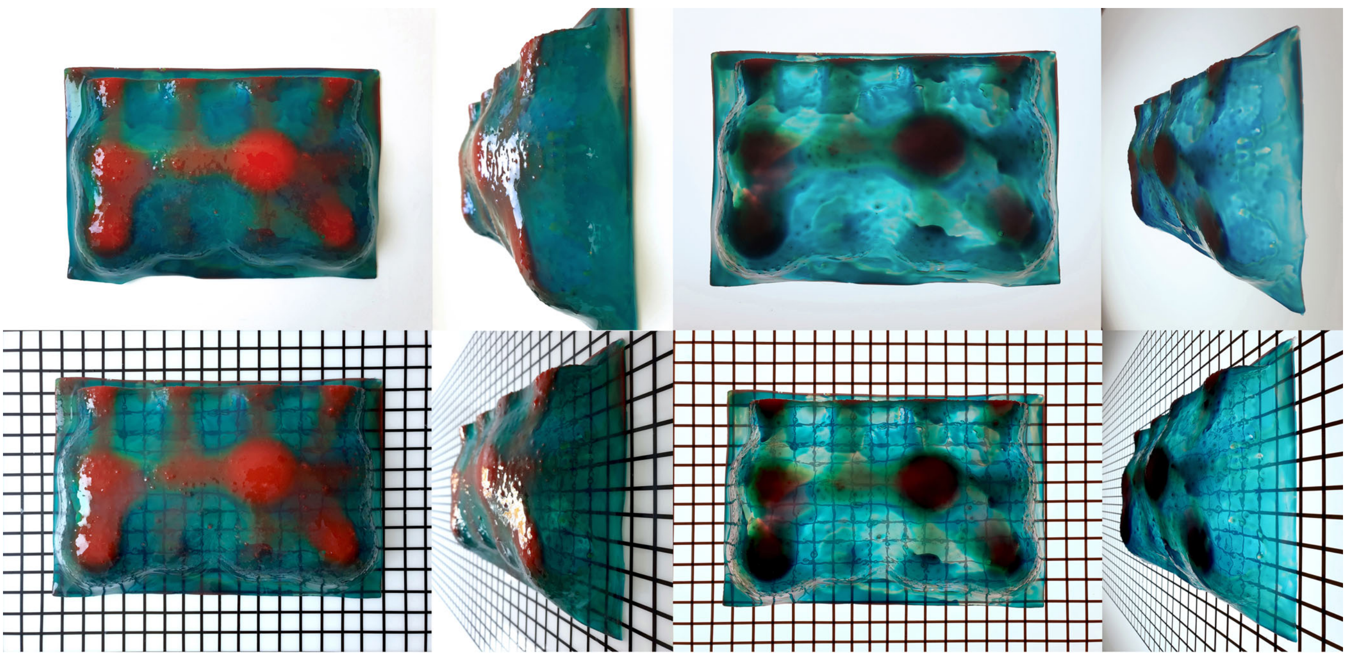


FIGURE 11 A surface featuring the complementary color scheme, colored using large quantities of red and blue pigments. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

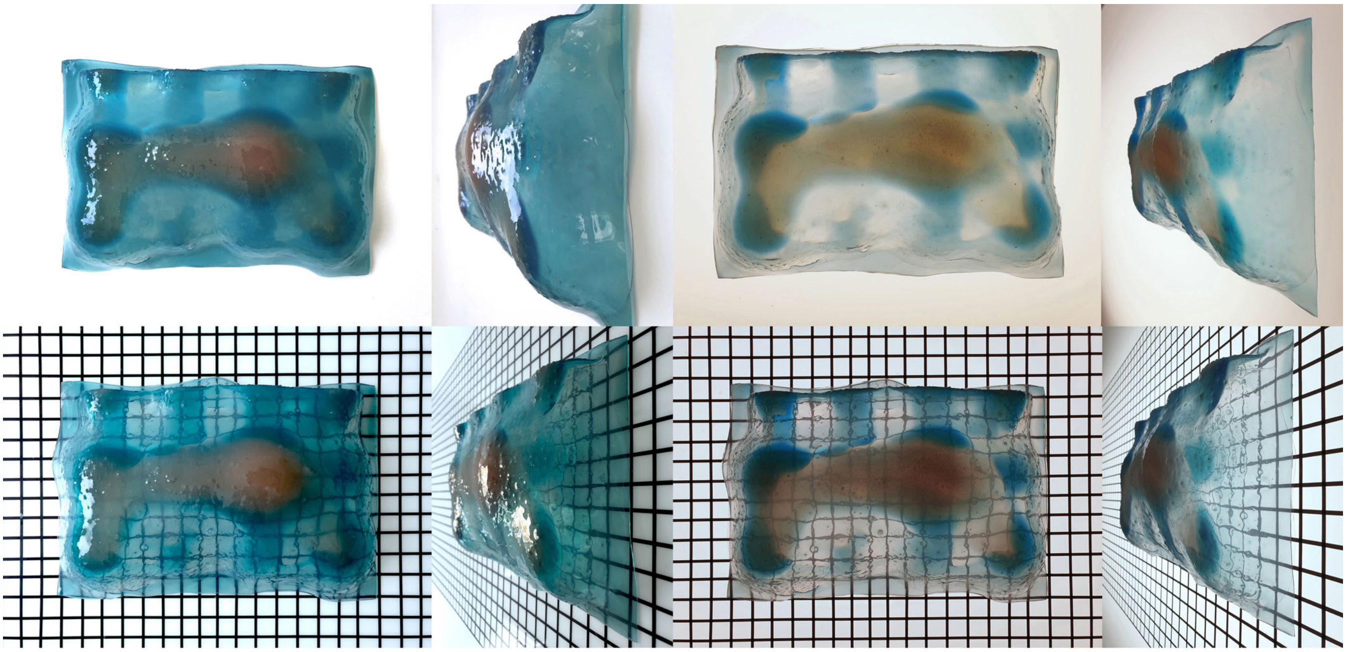


FIGURE 12 A surface featuring the complementary color scheme, colored using small quantities of red and blue pigments. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

same time, upon angular viewing, the primary colors constituting the layers of the surface could be discerned, contributing to the correct understanding of depth in the surfaces. The presence of gloss and texture also helped to understand surface curvatures, both within and at the perimeter of the forms.

To summarize, the surfaces featuring complementary color schemes can be employed to invigorate the perception of undulant architectural surfaces. When locating them in rooms and architectural settings with regards to the positioning of the viewer and illumination source, it seems that they can be located in versatile ways, as their perceptions both in frontal and side viewing situations offer a wide range of interesting effects, both in side illumination as well as in lighting from behind. However, due to the pronounced effects related to light and color depth interplays offered by these surfaces, they could be dominating and overwhelming, and therewith should be used with care as accents rather than as main surfaces defining entire façades or room enclosures. To diminish the visual tension caused by these color combinations, a decrease in their saturation and brightness can be considered, which opens the possibility of applying the described effects on larger surface areas.

3.4 | Effects in analogous color surfaces: Depth with diffuse glow

For the two models featuring this color scheme, colors that lie in proximity to each other on the same half of the color wheel were selected. Primary color overlays of yellow and blue were applied in two different orders, with the color mixing yielding emerald and lime hues.

In principle, these two models exhibited depth, curvature and form effects similar to the models of the complementary color scheme. In frontal viewing and side illumination, depth and surface curvatures were amplified by the differences in color brightness, supported with specular reflections and texture roughness effect accentuated by them. In the model featuring the bright lime color accent followed by a darker emerald green underlay, the surface depth was better accentuated than for the model featuring the opposite ordering of color hues. Angular viewing of this lime-emerald model against the source of light also in a more pronounced way revealed the primary colors constituting the layers of the surface (Figure 13).

In the backlighting setups, the sub-shapes of the layers constituting the mass of the surface were clearly defined. Here, however, a difference was noted in relation to effects in the models featuring complementary colors. The difference was that the boundaries of color layers were not clear-cut in this case but rather diffused. This effect was influenced by the gradual decrease in material thickness, which caused the edges of these forms to visually dissolve. The edge dissolution effect was further promoted by the colors interacting, forming new hues and gradually decreasing in saturation and increasing in brightness, causing a diffused glow effect.

The use of this scheme in architectural surfaces allows for achieving similar depth effects as for the complementary scheme. An additional feature offered by the analogous scheme is the relief from the tension caused by the complementary scheme in favor of a more calm color composition. The placement of such surfaces in architectural contexts seems therewith unrestricted. The only element to consider could be to make sure that the selection of analogous colors does not tend toward a monotonous scheme resembling the monochromatic one, and that it creates a differentiation that is legible and esthetically attractive to the viewer of the surface.

4 | EFFECTS OF COLOR AND LIGHT ON THE PERCEPTION OF DEPTH AND FORM IN STRONGLY UNDULANT SURFACES

The aim of this part of the study was to determine how color and light affect the perception of depth upon frontal viewing of strongly undulant, thick-layered, variably transparent architectural surfaces. All models were made by casting silicone into the robotically formed mold featuring the curvilinear texture. The observations were carried out for natural lighting and artificial backlighting, to allow for comparisons between the studied cases. The color harmonies examined in these models were analogous and asymmetric, with optical properties of the layers varying between transparent, translucent and opaque characteristics. A new feature introduced in this experiment series were color transitions achieved using thermochromic pigments, which change to colorless when warmed up to a temperature of over 30°C. As in the previous series of experiments, the formulation of the results of the observations was guided by the questions listed in the methods section, with the most characteristic effects registered in photographs and in an experiment log.

4.1 | Effects in an analogous color surface 1: Depth dissolution

The first study model comprised of five transparent layers of analogous colors (Figure 14). The first layer was colored using a green pigment, the three middle ones were colored using blue pigment with gradually decreasing pigment quantity, and the fifth and final layer was cast as colorless.

In daylight, the observed effect embraced strongly dissolved boundaries between the differently colored layers, causing a seamless transition from highly saturated color at the highest peaks of the surface to desaturated color in the valleys. This helped to perceive correctly the overall surface topography, and to accurately discern the locations of the most protruding and most sunken extremes of the surface. This effect was further supported by the presence of specular reflections emphasizing the curvilinear surface texture, demarcating the inner outlines of surface topography. Finally, the seamless color gradients

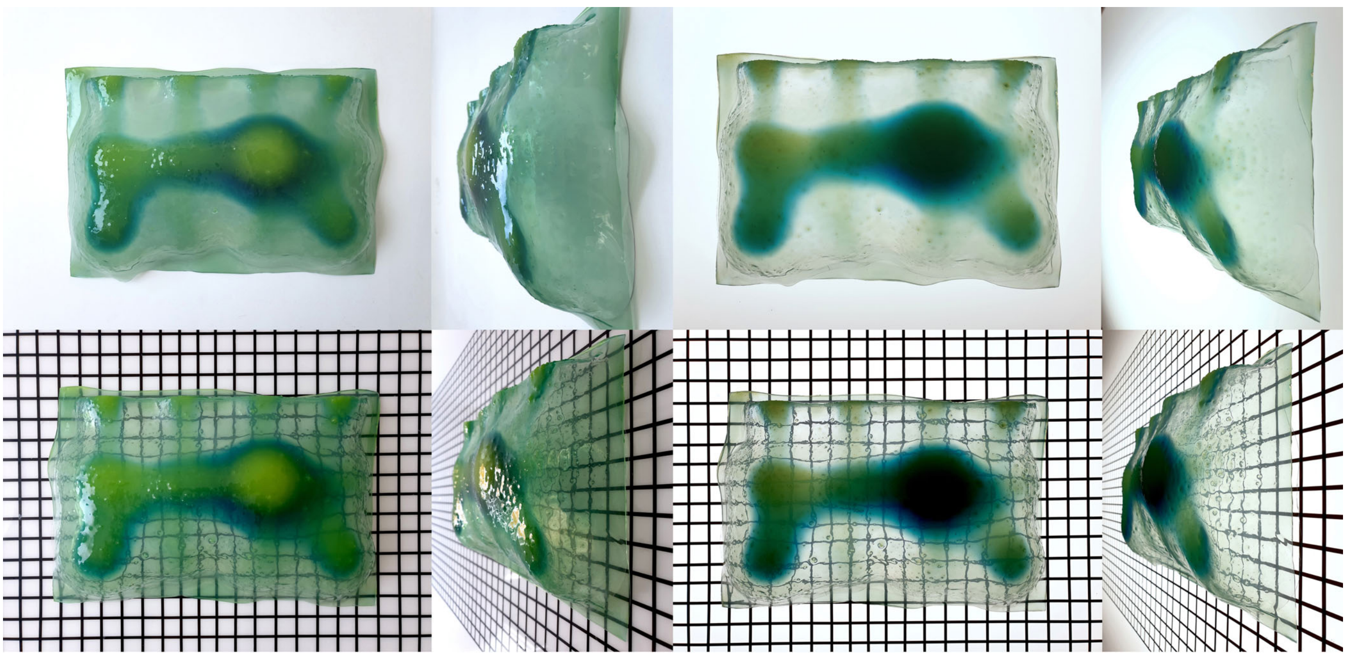


FIGURE 13 A surface featuring the analogous color scheme, colored using yellow and blue pigments, blending and producing a lime-emerald color effect. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

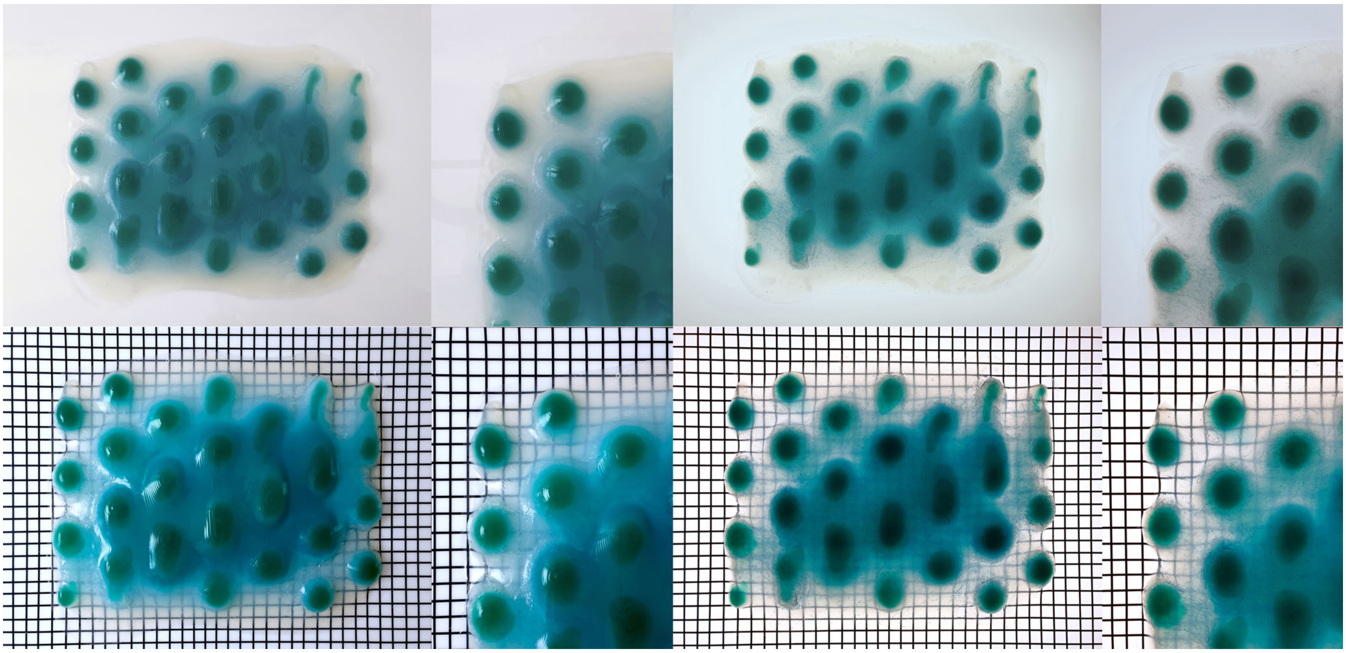


FIGURE 14 A thick, strongly undulant surface featuring the analogous color scheme and grades of transparency. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

made the form appear unified, with no strong definition of other inner forms or shapes within the surface.

In the artificial backlighting situation, an observable difference from the daylight-illuminated model resided in the stronger differences between the hues of the respective layers, accompanied by more pronounced boundaries between them. At these boundaries, a glow effect was observed resulting from the large differences between dark and bright areas, caused by a large amount of light passing through the translucent material from behind. Because of the strong effect of translucent color blending, the location of convex versus concave zones in the model was somewhat difficult to determine, causing the form to appear flat in the highly transparent zones. The only cues hinting the presence of a possible curvature change were the zones colored using the darker pigment, whose gradually fading color intensity suggested the presence of a slant.

4.2 | Effects in an analogous color surface 2: Depth blurring

This study model comprised of layers featuring cool and warm analogous colors, created from mixtures of green, blue, yellow and white pigments (Figure 15). The first layer was translucent, in a light cool cyan color made from a blend of green, blue and white pigments. The second layer was transparent, in dark cool cyan color obtained by mixing blue and green pigments. The third, transparent, light and warm colored layer was made from a mixture of yellow and green pigments.

In natural side illumination, the fact that the model consisted of translucent layers that differed in color temperature caused the boundaries of these layers to dissolve. During the creation of the model, before adding the final layer featuring the warm yellow-green tint, the boundary contrasts were better discernible. After adding the warm color layer, the zones appeared as dissolved, creating a gradient color blending effect that profoundly damped the perception of the surface's dynamic topography. The color brightness, progressing between bright, dark and moderate, when applied as translucent layers, also contributed to the flattening of the form. The specular highlights and the presence of curvilinear texturing helped to discern the boundaries of convex parts at the perimeter of the surface. On the middle areas, having less variance between convex and concave outlines, the specular reflections somewhat dampened the perception of depth. This was neutralized in some zones by the presence of a shadow that accentuated the areas further away from the viewer.

In the artificial backlighting situation, the boundaries of the color layers became clearly accentuated, with clear-cut edges where the brightness contrast was large, and softer, vibrating edges where that contrast was low. Interestingly, a strong glow effect occurred within the surface in areas allowing more light to pass through, which contributed to enhanced experiencing of surface spatiality and hinted the presence of dynamically alternating concave

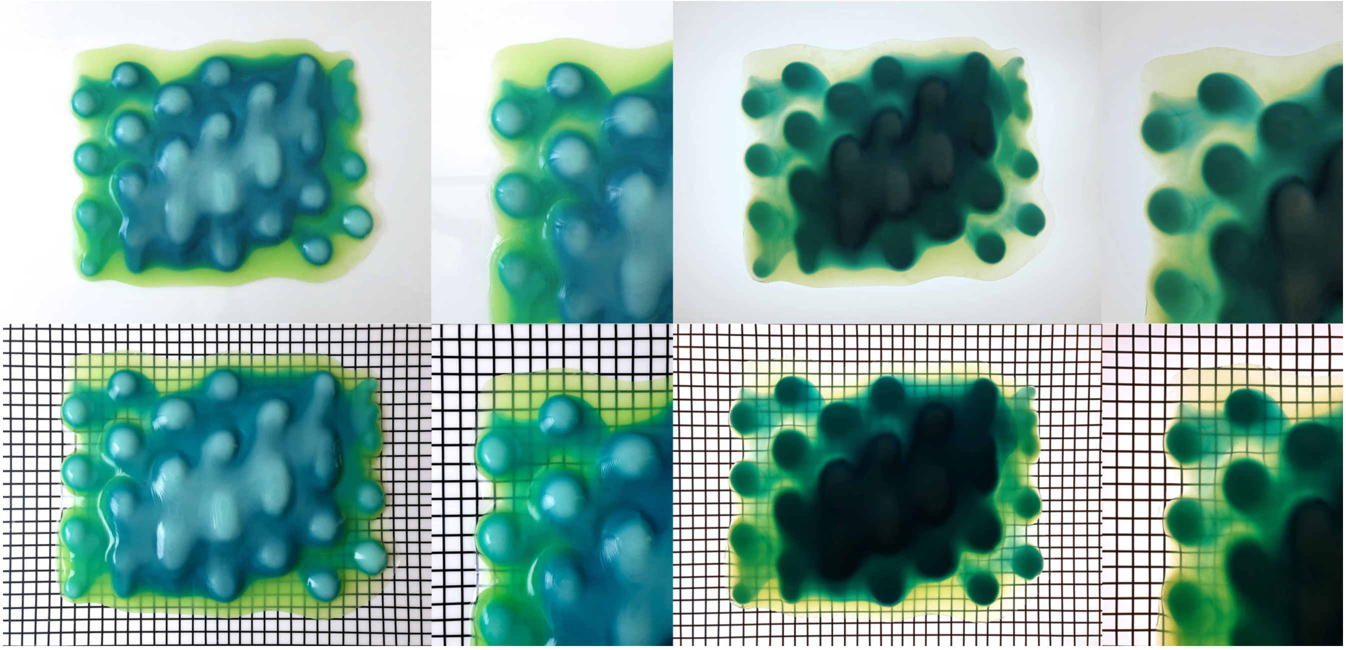


FIGURE 15 A thick, strongly undulant surface featuring the analogous color scheme and grades of transparency and translucency. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

and convex curvatures. The curvatures in the middle part of the surface, strongly flattened in the daylight-illuminated model, now became better visible due to the light reflected by the surroundings absorbed by the white-mint colored material. These zones were lit up and appeared matte, and became surrounded by visibly darkened underlay, which helped to correctly perceive their actual topography.

4.3 | Effects in an analogous color surface 3: Depth flattening and depth pronunciation

The fourth model also belonged to the analogous color harmony and featured three layers of color featuring transparency and opacity properties (Figure 16). The first opaque red layer was created by mixing red and white pigments. The second layer had a transparent orange hue, obtained by mixing red and yellow pigments. The third layer was opaque again, which was achieved by dyeing it with a large quantity of white pigment.

In natural side lighting, the strongest effects were related to the white layer. Its presence caused a cutoff effect, leading to a clear visual recognition of multiple inner forms embedded within the global material mass. Despite its neutrality, the white underlay was tinted by the colors of the neighboring zones and by the shadows arising from the side illumination. This made large portions of that white underlay to appear correctly as double-curved.

For the opaque red forms located directly on the white underlay, at the left and right sides of the surface, the opaqueness and the particular hue of color—red—resulted in the flattened appearance of these forms, despite their actual strong convexity and sphericity. Only the presence of local specular highlights and curvilinear surface texture accentuated by those highlights hinted that the opaque form could be undulant. On areas with no specular highlights, the round forms appeared as two-dimensional circles rather than as spherical entities. Such a flattening effect was diminished wherever the red figures lay on the translucent orange background. In that case, an effect of softening of the boundary of the solid color presented itself.

The artificial backlighting setup emphasized the actual topographical features of the surface as well as its depth. The white layer of the material, in the side illumination neutral, colorless and flat, now gained depth, hue and curvature. The light entering the white material from behind was refracted and absorbed differently in the different zones, depending on the material's thickness. This caused the material to appear yellow-grey tinted, with softly transforming gradients of bright yellow and darker grey tint alternating within the material mass and emphasizing the gradual transitions of surface slants. The red and orange layers underwent similar influences due to the light acting from behind. Because these layers had a tint, the effects were less pronounced but strong enough to emphasize the dynamic topography

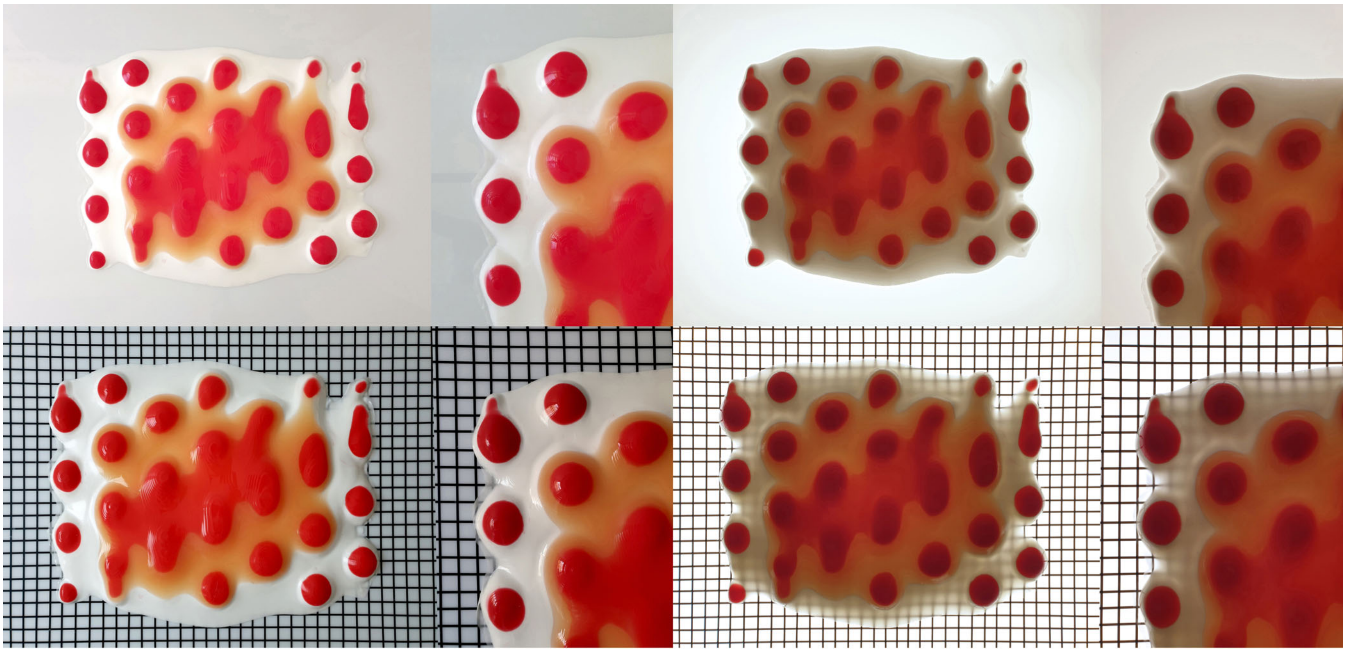


FIGURE 16 A thick, strongly undulant surface featuring the analogous color scheme and material translucency combined with opacity. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

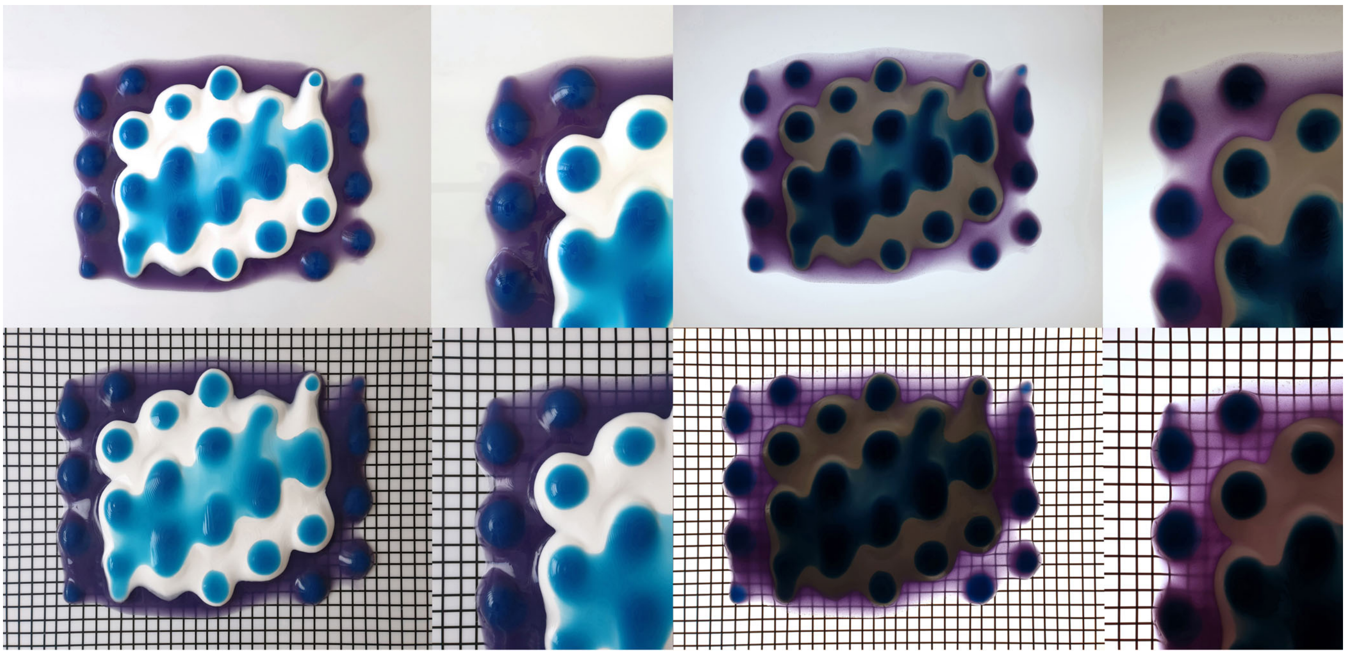


FIGURE 17 A thick, strongly undulant surface featuring the asymmetric color scheme and material translucency combined with opacity. The model colors at room temperature. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

of the surface. Wherever the translucent orange layer met the white one, an interesting effect of boundary darkening could be observed, accentuating the outline of that zone to a greater extent than in the daylight illumination setup.

4.4 | Effects in an asymmetric color surface: Depth extraction

This model featured an asymmetric color composition (Figure 17). One of its layers was dyed with a thermochromic

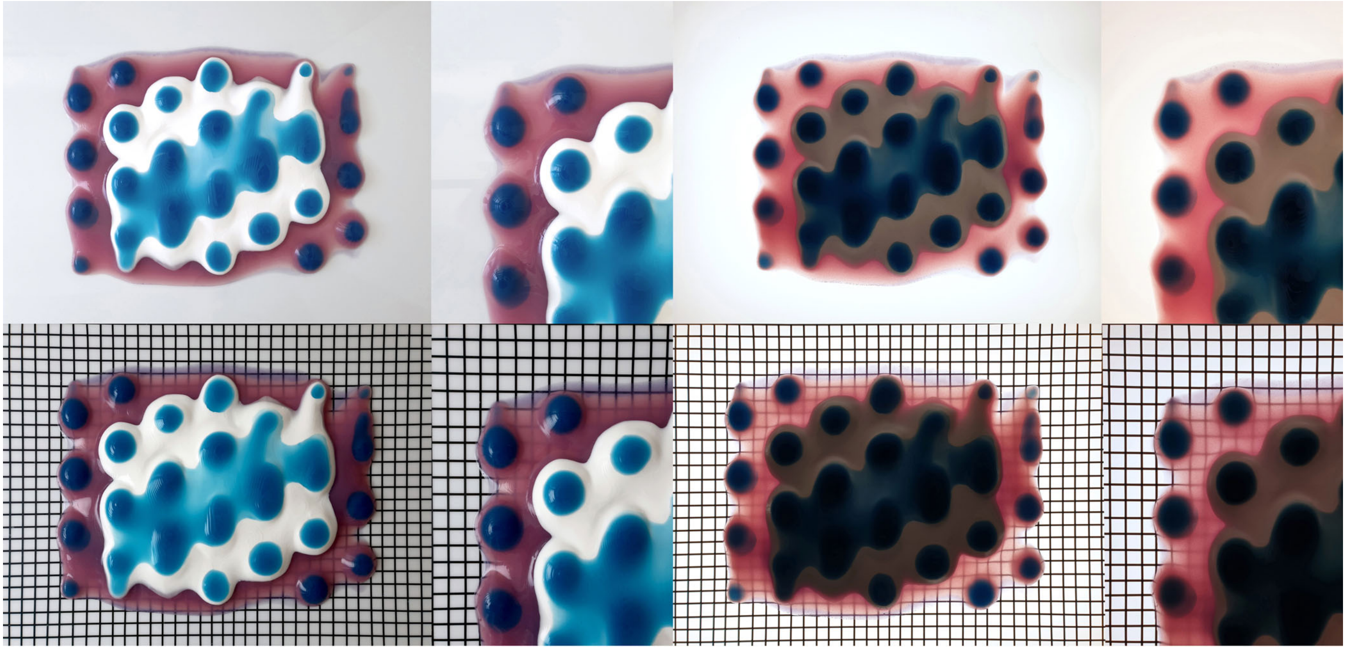


FIGURE 18 The same model as in Figure 16, here with colors when warmed up to a temperature above 30 degrees Celsius. Left and middle left: model in daylight illumination applied from the side. Middle right and right: model in artificial illumination from underneath

pigment. The first layer was translucent and colored using regular blue pigment. The second layer was entirely white and opaque. The third layer was translucent again, but this time colored using a regular red pigment as a base, complemented with a blue thermochromic pigment. Such a combination resulted in a dark violet layer, which, in warmed up state, turned the blue pigment component to a colorless one, revealing the regular red pigment added initially (Figure 18).

In natural side lighting, the color transition allowed for an increase in tension between the contrasting colors, and generated a transition in the perception depth, expressed by the shift of perceived distances of the respective zones of the surface in relation to the viewer. The opaque white layer created a buffer between the thermochromic underlay and the rest of the form. It appeared as an entity together with the blue layer on top, while the underlay appeared separated from it. In this way, the part of the surface containing the white and blue pigments seemed to float on top of the translucent one. I contrast to this, the translucent blue areas located on top of the translucent thermochromic underlay became assimilated within it, which was caused by the blending of hues and the resultant dissolution of boundaries between them. This effect was present also upon color transition of the underlay to red hue, despite the color contrast it made with the blue color. The topography of the middle zone was perceived correctly, due to the occurrence of specular reflections that emphasized the curvilinear texture of the surface and therewith enabled to visually discern and follow the actual curvature outlines.

In artificial illumination applied from the back of the model, the abovementioned effect of extraction and visual raise of the middle zone toward the viewer became even more pronounced. The topography of the middle zone, although that zone was not transmitting light, appeared close to the actual topography, which was facilitated by the presence of shadows in the convex areas of the surface as well as color gradients discernible in the blue layer. Regarding the interaction of forms with the thermochromic underlay, the effects differed for its two color variants. When in violet state, the underlay color mixed with the blue layer above it, creating a seamless blending effect that emphasized the convexity of these zones. When in red state, the colors of the underlay and the blue overlays did not blend strongly. Instead, they created tension and dissolving vibration at their meeting boundary, which, together with the effect of the white layer floating in the middle zone, made the red underlay appear to dissolve and glow from underneath. Overall, this created an impression of enhanced depth of the surface.

5 | ARCHITECTURAL SURFACE DESIGN STRATEGIES FOR ALTERNATING THE PERCEPTION OF DEPTH AND FORM IN DOUBLE-CURVED SURFACES

Based on the results of the visual observations in experiment series one and two, four strategies were developed that exemplify how architects and designers can manipulate the perceptions of depth and form in double-curved surfaces through informed use of color, light and varied transparency. The visual effects of each strategy were shown in physical models, which were placed in the same physical settings as in the earlier experiments.

5.1 | Strategy 1: Spatial color filtering with depth accentuation

This strategy harnesses the effects coined in the first observation series, concerning moderately undulant surfaces. More specifically, it employs transparent color blending, extended into three dimensions, combined with the effect of form, depth and thickness accentuation upon angular viewing. In this strategy, the transparent undulant surfaces are not overlaid directly on top of each other as strata. Rather, they are put together to form two sides of a 3D architectural surface element (Figure 19). Located centrally in an architectural space and viewed from multiple angles, in an actual application this could be a lightweight, screen-like, translucent architectural partition, or a hanging structure dividing an interior space into compartments. For this strategy, we recommend putting together two monochrome surfaces sharing the same hue as well as surfaces with varying colors that can blend to create additional hues.

As seen in the example models, this strategy counterbalances the dull appearance of the monochromatically colored surfaces, observed in the first experiment series. An optimal illumination situation for such surfaces is against a source of light. In this way, the backlighting will highlight the transparent surface's silhouette and accentuate the differences in material thickness through varying color brightness. These two effects will contribute to an enhanced perception of depth and form of an architectural surface. Because the surface will be viewed from multiple angles and in varying illumination, resulting from the cardinal orientation of the window placed behind, this perception can fluctuate throughout the day and as a person is moving through space, changing the viewing position. In this way, the monochromatic surface will offer both a uniform and non-obtrusive appearance in frontal viewing, as well as accents of more pronounced features, revealed through illumination changes and variable angular viewing.

5.2 | Strategy 2: Gradient screening of depth

This strategy utilizes the effects observed in the second series of observations. By combining variably transparent layers within the mass of an architectural surface, depth accents, in-mass shape cutoffs, and object boundary blurs can all be invoked and occur simultaneously within the surface. In this case, monochromatic and analogous colors can be combined to create moderate effects of depth emphasis. Alternatively, complementary and asymmetric color schemes can be used to generate more tensioned and dynamic effects. The latter option should be

FIGURE 19 A surface design strategy based on spatial color filtering with depth accentuation, achieved by assembling moderately undulant surfaces into double-sided volumes

applied carefully as it may create visual tension. To release from this tension, it may be advisable to employ smart material solutions, such as thermochromic or photochromic pigments, to periodically neutralize strong color contrasts. The optimal illumination setups for this surface design strategy involve both natural side illumination and artificial backlighting. These types of illumination can also be used in combination, to vary the visual effects at daytime and nighttime. A practical application resulting from this setup could take the form of façade paneling, interior wall cladding or a part of a suspended ceiling.

The model exemplifying the potentials of this strategy featured an analogous color scheme, with varying combinations of green, yellow and white pigments, and translucencies varying for each layer (Figure 20). The first, uppermost layer was a transparent combination of green and yellow pigment, resulting in a bright lime color. The second layer was made to be more translucent, with a pigment combination now altered by including a larger proportion of yellow, a smaller proportion of green and a small quantity of white. In the third layer, only white pigment was used, to achieve an opaque effect. The last, lowermost layer was colored using small quantities of white and yellow pigments, to form a translucent layer.

This particular combination of colors and transparency levels enabled to activate the perception of the surface as consisting of zones that form objects and grounds against each other. This effect was designed to be emphasized in the natural side lighting situation. The use of an opaque white layer in between the colored translucent layers was meant to create a visual illusion of this part being lifted slightly toward the viewer. The translucent background behind this part was designed to further accentuate the effect of a highly undulant form floating above its see-through background. Furthermore, the use of analogous hues and translucency of the colored layers created an effect of dilution of the differently colored boundaries. In the middle part of the form, where the colored zones had an irregular shape and were relatively thin, the outline of the form appeared dissolved and flat. In the parts toward the perimeter that were more curved, protruding and circular in form, the color translucency and large material thickness, complemented with the presence of shadows and accentuated surface texture, made them appear rounded and very deep. In the artificial backlighting setup, the most pronounced effect was that of a cutoff between the translucent lowermost layer and the almost opaque white one. This resulted in an accentuated two-dimensional inner outline, its fake flatness and illusion of inverted depth upon frontal viewing.

5.3 | Strategy 3: Vibrant massing

This strategy employs the effect of irregular in-mass pigment blending, as discussed in the first series of observations. The aim of the strategy is to create an effect of enhanced surface depth. In this case, concentrated pigments are stirred into the material mass. In general, for this strategy, the color of the stirred-in pigment can be uniform, monochromatic, or represent other color harmonies. However, the more distinct the color hues, the higher the risk of the surface depth becoming illegible and blurred, or flattened, resembling effects similar to the ones in the abstract impressionist drip paintings of Jean-Paul Riopelle and Jackson Pollock. Therefore, it is advisable to combine at most two to three monochromatic and analogous color hues to secure the depth enhancement effect, while complementary and asymmetric color schemes should be

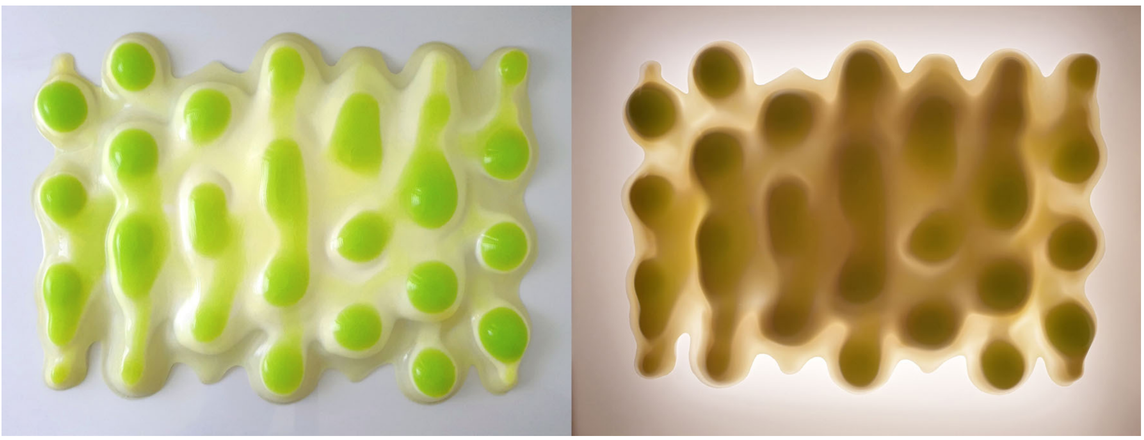


FIGURE 20 A surface design strategy based on gradient screening of depth, achieved in a strongly undulant surface featuring an analogous color harmony and varying grades of transparency and translucency. The model seen in daylight (left) and artificial backlighting (right)

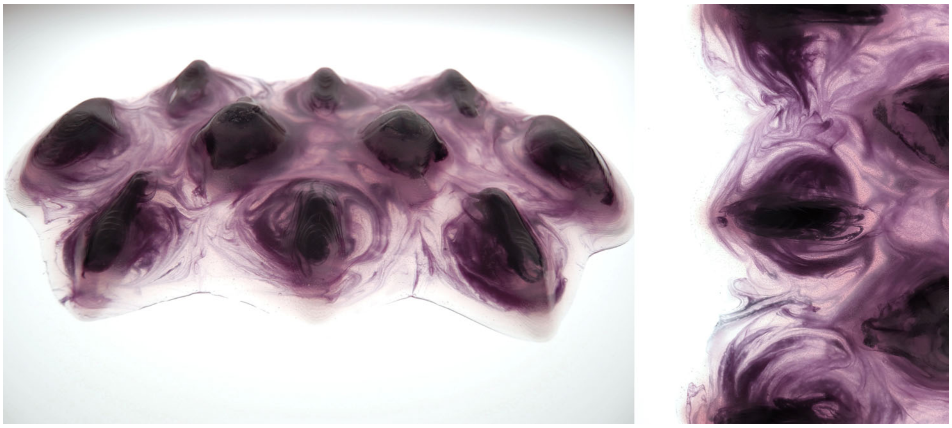


FIGURE 21 A surface design strategy based on vibrant massing, achieved in a strongly undulant surface featuring concentrated pigments stirred into a transparent material mass. The model seen in artificial backlighting

applied with caution. Regarding the hue of the silicone base to which the pigments are added, it should harmonize with the colors of the stirred-in parts.

The model exemplifying this surface design strategy featured pigments that were stirred into the material mass (Figure 21). That model was cast in two identical, transparent layers. For each layer, a violet mixture, created by pre-blending red and blue pigments, was manually stirred into the base material, forming irregular streaks of color within its mass. In the model, the stirred-in color hue was varied from a darker to a lighter hue of violet, achieved by pre-blending the blue and red pigments in two different proportions—one with the dominance of blue and the other with the dominance of red.

The strategy is robust as it offers similarity of enhanced depth perception in both backlighting and side illumination setups, and in frontal as well as side viewing. Therefore, surfaces of this kind could be used in numerous architectural settings—as single or double sided elements, as standalone components or parts of paneling systems, on ceilings, walls and facades, and even as skylight elements due to their translucency.

5.4 | Strategy 4: Animate reshaping

This strategy relies on the effect from observation series one. It employs reversible color transitions, achieved using photochromic and thermochromic pigments, to alter the perception of depth and topography of a double-curved architectural surface. This leads to an animate surface topography, reshaped by color transitions, alternating between a strongly undulant and a more flattened appearance. In this case, the 3D form erasure and emphasis effects arise from the carefully selected color compositions and transparency level contrasts.

The model illustrating this effect featured two layers of color representing the complementary harmony, one opaque and one transparent. The first layer was orange and opaque, achieved by mixing red and yellow thermochromic pigments with a regular white pigment (Figure 22). Accordingly, upon warming up, this layer turned toward a whitened appearance. The second layer was reddish inclining toward magenta, resulting from a blend of regular blue and red pigments, added in very small quantities in relation to the entire material mass.

When at room temperature, the orange form was designed to appear as a separate object placed on a translucent yet undulant background, with the boundaries between the two clearly delineated by a color darkening effect occurring along them. The orange part of the form was designed to create a dual effect of appearing opaque and monolithic while also having a discernible strongly undulant topography. This duality was possible to achieve due to the employment of shadows, textures and specular highlights, created on the surface through the side illumination. This type of illumination also enabled to emphasize the actual curvatures of the reddish underlay.

In warmed up state, the thermochromically pigmented zone was designed to undergo a partial geometric flat-out. In addition, the large surface thickness and thermal inertia of the material were harnessed to achieve a non-uniform color transition. As the higher temperature did not reach the deepest, thickest zones of the middle part, the change of color toward white could appear as a gradient color washout. The geometric surface features initially perceived as curved and dynamically alternating between concave and convex zones now appeared flat and less differentiated in their topography. Only the presence of curvilinear surface texture and ambient shadows cued that the surface is not completely flat. Moreover, the outline of that now very bright zone became well defined due to the presence of a powerful contrast with the much darker underlay. This effect of a white form against a dark ground caused the white form to visually protrude toward the viewer and the dark background to recede, contributing to the overall effect of difference in the location of the two colored zones, and therewith, difference in depth.

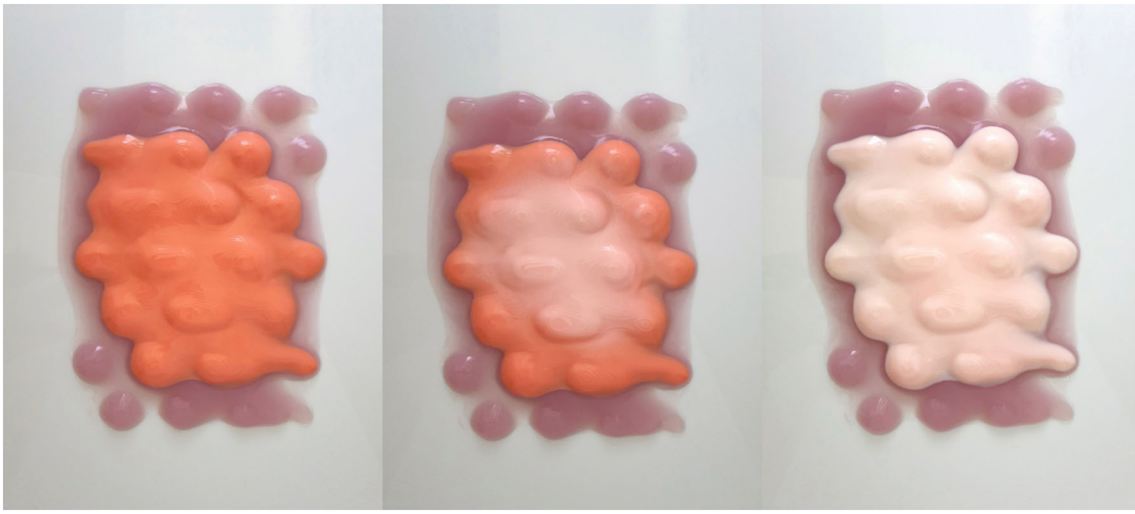


FIGURE 22 A surface design strategy based on animate reshaping, achieved with thermochromic pigments. The model seen in daylight, with gradual color transition induced by gradual surface temperature change

When backlit, the model was meant to exhibit further visual transition effects. The thermochromic zone gained a stronger definition of its outline and a darkening of its hue. When in the temperature-induced process of transition toward white, it exhibited a wider palette of colors, from light, washed out orange to dark intense orange (Figure 23). The zones where the thermochromic material was thinner could glow while the thicker ones presented themselves as whitish islands floating on top. Overall, dynamic effects of visual transitions and dynamic reshaping were activated, making the form truly vibrant and intensely deep in its visual appearance.

This surface coloring strategy is relevant to consider in the design of responsive building facades and interiors. For instance, the changes in color and appearance of a responsive façade could be triggered by sunlight hitting its surface or by a change in the outdoor or indoor temperature. This creates an opportunity to employ color in a more dynamic setting within the built environment. The presence of color transition offers the possibility of working with contrasting and bold color schemes, such as complementary and asymmetric color harmonies. In such a case, the possibility of altering the color to either colorless appearance or a monochromatic one creates a possibility of partial relief from the strong color scheme used. In this way, the experience of the environment can be dual, both invigorating and calming, depending on external factors and user preferences. As such, it could be relevant in the design of many architectural environments, for example, public buildings and residential areas that require visual enrichment and accentuation of esthetic and material features within the cityscape.

6 | RESULTS AND CONCLUSION: TOWARD COLORED SKINS AND VIBRANT, HYBRID ARCHITECTURAL SURFACES

This study has examined the problem of perception of depth and form in architectural surfaces with complex, double curved forms. The focus has been not only on the findings about depth and form perception of hybrid-color surfaces but also on the artistic aspects related to the esthetic appearance of handcrafted models. Although the latter issue cannot be easily evaluated from a scientific point of view, it is an important matter from an artistic standpoint, valuable for architects shaping contemporary buildings. By highlighting the importance of working not just with colored surfaces but also with mass pigmented elements and other surface design variables, the authors have sought to contribute knowledge that could be widely applied in architecture, design and arts.

What makes double-curved, in-mass colored surfaces appear deep or flat? Although a brief answer to this complex question is difficult to formulate, the main result of the study, that is, a compilation of the effects of various surface design parameters on the perception of depth and form, provides a roadmap with cues that can guide designers in their work with hybrid-colored surfaces (Figure 24). For instance, when it comes to the level of undulations, the results suggest that, in combination with color, texture and transparency levels, the undulations have equal potentials to appear both flattened as well as tectonically rich. In other words, with certain combinations of surface design parameters, a gently undulant surface can be made to appear very deep and tectonic, while

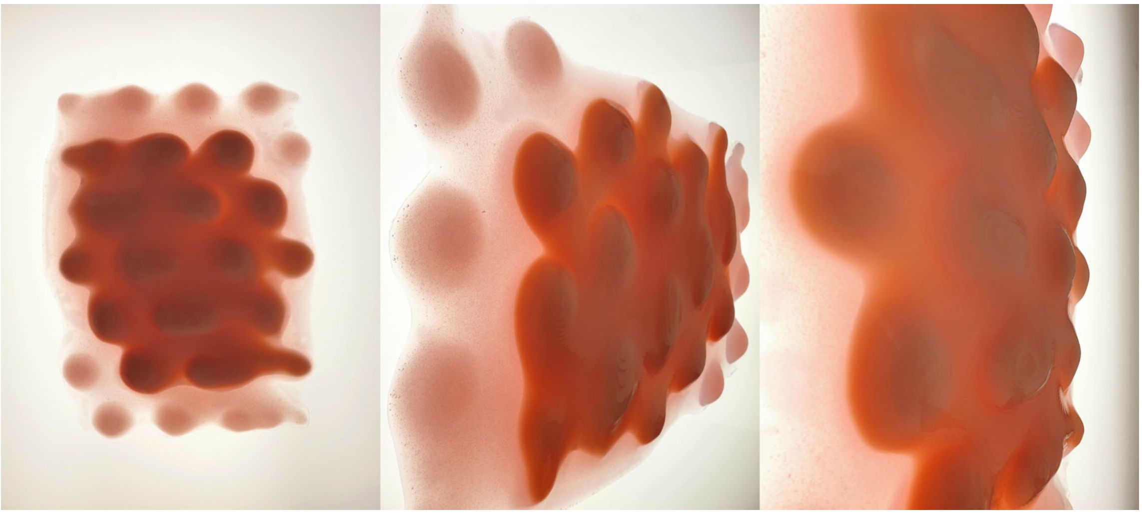
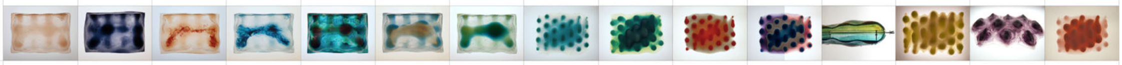


FIGURE 23 The same model as in Figure 21, seen in artificial backlighting, in the temperature-induced state of transition from orange toward white, exhibiting a widened palette of color hues, from light, washed out orange to dark intense orange



			Studied models											Models exemplifying resultant surface design strategies			
			Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Strategy 1 Spatial color filtering + depth accentuation	Strategy 2 Gradient screening of depth	Strategy 3 Vibrant massing	Strategy 4 Animate reshaping
Surface design features	Form undulations	Moderate	•	•	•	•	•	•	•					•			
		Strong								•	•	•	•		•	•	•
	Transparency level	Transparent	•	•	•	•	•	•	•	•	•	•		•	•	•	•
		Translucent		•			•	•	•	•	•		•		•	•	
		Opaque					•					•	•		•		•
	Color harmony	Monochromatic	•	•	•	•								•	•	•	
		Complementary					•	•									•
		Analogous							•	•	•	•					
		Asymmetric											•				
	Color saturation	Low	•		•	•		•	•	•	•	•	•	•	•		•
		High		•	•	•	•			•	•	•	•			•	
	Pigment	Traditional	•	•	•	•	•	•	•	•	•	•		•	•	•	
		Thermochromic											•				•
	In-mass coloring method	Uniform layering	•	•			•	•	•	•	•	•	•	•	•		•
		Pigment stirring			•	•										•	
Perceptual effects	Depth perception	Shallow/thin	•					•				•					
		Deep/thick		•	•	•	•	•	•	•	•		•	•	•	•	•
	Curvature perception	Flat	•		•	•	•	•		•		•					
		Concave/convex		•			•	•	•	•	•	•	•	•	•	•	•
	Figure bounds perception	Sharp		•	•	•	•	•			•	•	•				•
		Blurred	•						•	•	•			•	•	•	
		Glowing						•	•	•	•		•				
	Optimal viewing position	Frontal		•	•	•	•	•	•	•	•	•	•		•		•
		Lateral	•	•	•	•	•	•	•					•	•	•	•
	Optimal illumination	Daylight lateral	•	•			•	•	•	•	•	•	•		•		•
		Artificial backlight	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•

FIGURE 24 A summary of the main findings of the study, revealing complex interplays between surface design features and resultant perceptual effects

a strongly undulant one can be designed to have a flat appearance.

It can also be seen from the study that that color harmonies typically considered as favorable, such as the complementary one, may create a flattening effect if applied on curved surfaces that are translucent and opaque. On the other hand, color harmonies typically considered monotonous, such as the monochromatic one, when applied on curved surfaces that are transparent and translucent, gain a new dimension of varied depth and thickness that can enhance the perceptual experience of these surfaces, especially with carefully chosen illumination type and viewing location.

The results also show that further artistic interventions, such as casting a surface from layers of variably transparent color with intricate internal boundaries and forms, putting together colored surfaces into layered 3D constructs, manually applying colored pigment streaks into a uniformly treated transparent material mass, or working with smart pigments such as thermochromics, can truly make these surfaces come alive. This becomes very evident in spatial settings such as architectural interiors and exteriors, in which the illumination conditions and viewer positions dynamically change throughout the day, contributing to the vibrancy of perceptions.

The study concludes with a suggestion that the richness of visual effects offered by seamless, in-mass colored, double-curved architectural surfaces presents endless design possibilities, revealing a vast territory for playful, creative manipulation of color-related effects in architectural design of surfaces. The perceptual effects revealed in the analyzed models open a rich ground for further research on color, to probe more deeply the perceptual and physical phenomena, deepen knowledge on their emergence, and, ultimately, encourage new innovative applications in the built environment. With the current availability of sophisticated digital design and fabrication techniques, as well as novel sustainable material solutions, the realization of such colorful, hybrid, vibrant surfaces and building skins is within reach. Therefore, their promising potentials should not be overlooked in the design of architectural environments aiming to enhance the living conditions in the age of digitalization.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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