BRILL Art & Perception (2014) DOI:10.1163/22134913-00002033 brill.com/artp

Edge-Based Shading as a Depth Cue in Paintings

Marianne E. Venderbosch [1,2,*], **Andrea J. van Doorn** [1,2], **Jan J. Koenderink** [1,3] **and Susan F. te Pas** [1]

[1] Experimental Psychology, Helmholtz Institute, Utrecht University, Heidelberglaan 1, 3584 CS Utrecht, The Netherlands
[2] Industrial Design, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands
[3] Laboratory of Experimental Psychology, University of Leuven (KU Leuven), Tiensestraat 102, 3000 Leuven, Belgium

Received 7 March 2014; accepted 6 October 2014

Abstract
We explored how an artist who uses a particular monochrome modern painting style generates the impression of relief in paintings. Three portraits, painted after model, were created especially for the experiment. Photographs of the paintings were presented on a computer screen. To investigate the perceived relief of observers we used a gauge figure task. We expected an effect of background contrast on perceived total depth range of the relief, because this is well known in the case of photography. We found that the contrast with the color of the canvas, white, gray or black, influences the perceived articulation of the relief but does not influence the perceived total depth range of the relief. The major difference between photographs and these paintings is that contrasts in the paintings are built up through edge-based shading, whereas photographs mostly contain tonal-area shading. The classical shape from shading cue does not apply to the impressions of depth evoked by the paintings. Perhaps surprisingly edge-based shading can be as effective as classical ways of creating pictorial relief.

Keywords
Depth perception, shading cue, perception of paintings, painting techniques, edge-based shading

* To whom correspondence should be addressed. E-mail: mariannevenderbosch@gmail.com

 DOI:10.1163/22134913-00002033

1. Introduction

1.1. Different Perspectives of the Artist and the Observer

The diversity of techniques in which they are created is characteristic to classical as well as modern paintings. The personal handwriting of the artist, connected to intelligence, intention and technique, might be the most important tool to display skills and bring out a message. Paintings and their creators are recognized through the ages by these specific differences in handwritings connected to technique (Gombrich, 1950). There are as many techniques as there are artists. Diversity in works of art is therefore limitless. The perspective of the artist who creates the painting is certainly different from the perspective of the one who is watching the piece of art, principally because the artist is involved in the process of making the painting. He has to build up the image in a given time and in a certain way or procedure, starting this process from a specific point on the canvas, evolving step by step to the eventual final result. The viewer, on the other hand, literally watches the painting the other way round, starting with the result, the image, as his point of beginning.

Being an artist and an art historian as well, I (Marianne Venderbosch) am fully aware of these different perspectives. Through practically creating a painting I study diverse aspects of building up an image. When finished I am interested in what effect a specific technique will evoke on human perception and I want to understand how these effects are achieved. In 2008 I made a series of paintings in black, white and gray tones of a person directly after a model (for an example, see Fig. 1). The images were painted on a canvas with a black, white or gray surface.

To me the paintings had an outspoken three-dimensional spatial effect on the viewer and I was curious about what caused this effect. How was the impression of depth in these paintings generated? Was the ground color, white, gray or black, important? And how important was the specific distribution of tonal touches, that is to say the painting technique? Inspired by the questions raised by these paintings I first turned to the fields of art history and photography.

1.2. Art Historical Background

For an artist there are various techniques to create depth in a picture, such as overlapping horizon, shading and shadow, relative size within the picture plane, color perspective or linear perspective (Bloomer, 1989). The most prominent in my paintings is the use of black, white and gray, so shading and shadows are probably most relevant.

The use of black, white and gray is mainly seen in sketches, as studies for paintings or underpaintings. An underpainting is a layer of paint applied to a ground, which serves as a base for subsequent layers of paint (Doerner, 1971;

Figure 1. Marianne Venderbosch, *Model on black canvas*, 2008, acrylic on canvas, 120 × 100 cm. Notice that the ground color is part of the image. Photograph by Marianne E. Venderbosch. © Marianne E. Venderbosch.

van Hout, 2005). A common objective is to create an effect of depth. Examples of (under)paintings in gray tones, black and white are the so-called Grisailles (from the French gris, gray). This is a technique to imitate bas-relief through monochrome painting in two or three shades of gray (Mayer, 1951). Grisailles were already used in Western Art in the 13th century. Examples are found in museums all over Europe. Grisaille was often used for the back panels of triptychs. A familiar example is the Ghent altarpiece by Jan van Eyck.

From the Renaissance on, we see the use of a painting technique called Clair Obscur (from the French, clair meaning light and obscur, dark) or Chiaroscuro (from Italian, chiaro meaning light and oscuro, dark). Leonardo da Vinci used this technique in the High Renaissance and after him many other painters like Caravaggio and Rembrandt made use of it. Since the Renaissance the manipulation of light–dark gradients has been one of the first techniques traditionally taught to Western drawing students. It has become widespread in Western drawing and painting (Bloomer, 1989). Apparently the use of black, white and gray tones or the manipulation of light and dark gradients is related to creating depth in a drawing or painting.

David Hockney has an interesting view on painting in his book *Secret Knowledge* (Hockney, 2006). Hockney concludes that two of the most fundamental principles of Western painting, linear perspective (the vanishing point) and chiaroscuro, come from studying optical projections of nature. Optical projections can occur naturally through a camera obscura (Hockney, 2006). Such a projected scene is seen from a fixed viewing point in space at a particular instant in time like in photography. If it is the case, like Hockney says, that painters made use of a camera obscura to study the dark and light parts for their paintings, it could be interesting for this research to know what photographers know about the use of light–dark contrasts.

1.3. Effect of Figure–Ground Tonal Contrast in Photographs

Photography captures the instantaneous effects of light and shade and among photographers the effect of contrast of the object with the ground tone is well understood. Strong contrasts with the ground tone (either white or black) decrease the plasticity of objects (Adams, 1952). For instance in a book on the art of sculpting the author remarks on the importance of the ground tone in documentary photographs: "...if the photographer wants to show the plastic qualities of the interior forms to the best advantage, he will usually avoid a strong silhouette because the contrast between the edges of the sculpture and the background tends to detract from the modeling of the forms within the contour and also obscures their relationships in depth by connecting all their outer edges in one continuous outline" (Rogers, 1969, p. 25).

1.4. Effect of Figure–Ground Tonal Contrast in Paintings

This 'photographical' or 'optical' way of shading is used by painters from the Renaissance on until the end of the nineteenth century. It was a major topic at classical art academies. In contemporary art it is still used as a classical technique in painting. Computer graphics has also implemented such optical shading (Foley and van Dam, 1983).

Other techniques than optical shading have been used, for instance so-called 'modeling' techniques, which are easily confused with optical shading because both are area-based tonal modulations. An example of such an alternative technique is the way sculptors often make their drawings, a technique that already existed in Byzantine art (Gombrich, 1950).

With the introduction of Modern Art, classical techniques of creating depth in paintings got liberated and next to already existing alternative ways of creating depth, still more alternative ways of creating depth and space emerged. In Modern Art, for example, we see that many artists do not use the traditional area-based tonal modulations, but apply line, edge and tonal areas in a free manner. Edge-based tonal modulation is ubiquitous in modern painting. Paul Cézanne and painters like Franz Marc famously pioneered it (Gleizes and Metzinger, 1912). By looking closely, one finds it equally in previous centuries though. Perhaps the first to remark on the importance of 'edge quality' in painting was Leonardo. His *sfumato* suggests a 'thick' time slice, hence a liveliness, quite distinct from a hard edge (Fehrenbach, 2002).

In art history I found theories about techniques of creating depth in paintings by using light–dark area-based or edge-based modulations. Do these theories apply to the paintings I created? To find an objective way to analyze the perceived effect of the painting technique I used, I collaborated with scientists (A. van Doorn, J. Koenderink, S. te Pas) specialized in visual perception. Together we tried to find answers using techniques from vision science.

1.5. Psychophysics on the Influence of Light–Dark Contrast on Perceived Relief

The effects of light–dark contrast are readily noticeable for the case of clear figure–ground segregation. In the case of uniform grounds, and strong tonal contrast between figure and ground, the pictorial relief of the figure tends to be flattened. In such cases the polarity of the contrast hardly matters (see Fig. 2). When the global contrast is minimized, such as in the left panel of Fig. 2, the contrast is bipolar, so the background is neither dark nor light with respect to the figure. The contour of the figure is necessarily 'lost' at various places. This configuration is well known to maximize the perceived relief of the figure, and is often sought for by photographers. It is applied in many photographed portraits. The above quote by Rogers (1969) in the context of documentary photographs of sculptures immediately applies to these cases.

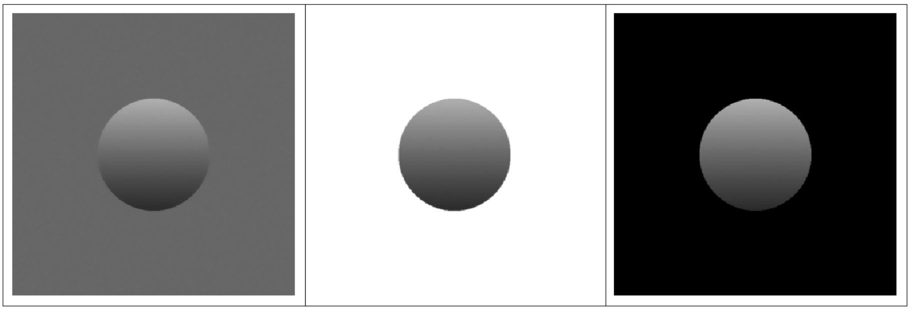

Figure 2. The object, a sphere, is identically shaded in all three images. In the middle image the ground color is much lighter than the object, in the image at right the ground color is much darker. In these cases the contrast polarity between the object and the ground color is fixed. In the left image the ground color is neither darker nor lighter than the object. At the top the object is lighter than the ground color, at the bottom it is darker. At middle and right the contrast switches polarity. Notice that the object in the left image has the highest perceived relief.

Two of the authors did an extensive study on this phenomenon for the case of a uniformly tinted torso in front of a uniform backdrop. In such a simple configuration the effect can be quantified in detail. Indeed, the strongest relief is obtained when the contrast with the background switches polarity along the length of the contour of an object (Koenderink *et al.*, 2002). These data fully confirm the phenomenological observation by Rogers (1969). Area-based tonal modulations are not the only way to generate an impression of surface relief. Indeed, pure shading is mostly confined to academic art. It is more common to see artists modulate the edges of a figure in a variety of ways. Such modulations are not necessarily tonal, they may as well be preliminary chromatic. Since pure outline tends to flatten relief, as can be seen in simple cartoon drawings, edge modulations necessarily involve a region about the suggested contour. This region usually involves both 'figure' and 'ground'. This is artistically advantageous, since a hard figure–ground segregation works against the unity of the painting. The edge modulation simultaneously divides and unites, which renders such methods categorically different from the clean renderings as in Fig. 2. The final effect can still be a strong relief articulation such as demonstrated in Fig. 3.

Such an articulation is not primarily based on classical 'shading', indeed it may, or may not, suggest such a shading. Even if it does so, the classical 'shape from shading' cue, in the sense of an inverse optics process, strictly fails to apply. We have found (Koenderink *et al.*, 2013; Koenderink *et al.*, in press) that such edge-based methods can be equally effective, or may even surpass, the well understood optical shading cues.

1.6. Research Questions

To investigate how the impression of depth in paintings such as in Fig. 1 is generated we address three major questions. Firstly is there an effect of the tonality or the painting technique on the total depth range of the relief? We would expect gray grounds to elicit most relief, and thus the largest depth range if area-based shading plays an important role in the perceived depth of the painting. Secondly, is there an effect of the tonality or the painting technique on the articulation of the relief, like we might expect when edge-based shading drives the percept? Finally, are such effects common to all observers or are there important individual differences?

2. Method

2.1. Creating a Set of Paintings as Stimuli

To find out how the impression of depth was generated in the paintings, we needed a new set of paintings created under controlled conditions. Based on

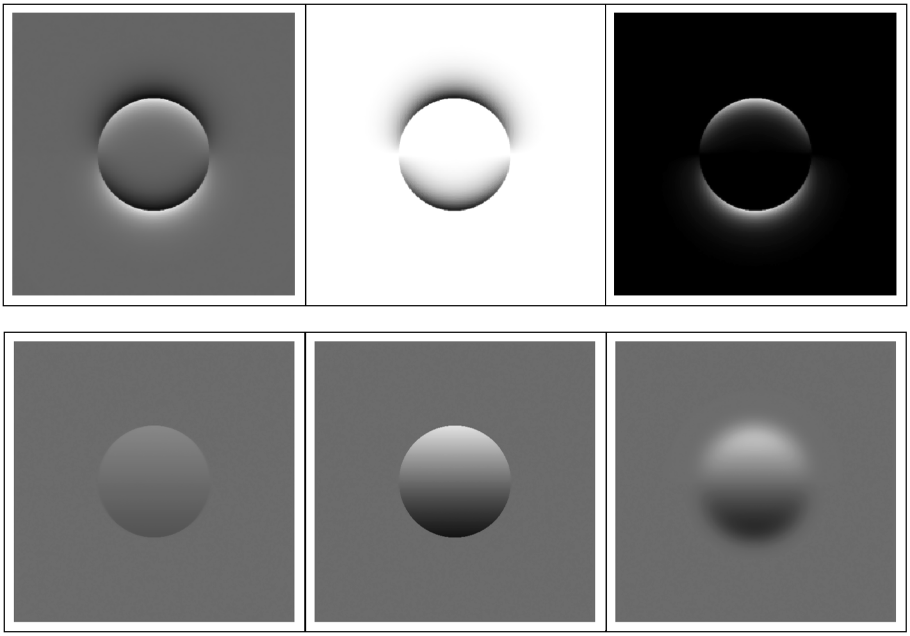

Figure 3. (Top) We compare a simple form of edge-based shading as articulated from gray, white, and black grounds. The articulation is similar in all three cases; apparently the tone of the ground is almost irrelevant. Notice that the 'ground' is not 'background' in the sense of 'backdrop'. Although there certainly is a sense of figure–ground segregation, especially in the center figure, the ground does not strongly appear to continue 'behind' the figure. In the middle and right figures it perhaps does so more. In all three cases there is no sense of a background of any specific shape — say surface like — or any specific depth. (Bottom) We compare the influence of shading contrast (left) and edge blur (right) on the articulation induced by the conventional shading stimulus (center; Ramachandran, 1988a, b). Apparently both shading contrast and edge blur have a strong flattening effect on the articulation. The blurred figure seems to grow out of the ground color without much of an apparent depth gap. The low contrast figure is definitely less 'in front of' the ground color than the high contrast one. In neither case is the ground color clearly defined as a 'surface', nor at any specific 'depth' with respect to the figure.

the experience of the artist that painting after direct observation should create the best three-dimensional results, she created the new set of paintings by working after model in a studio.

Working after model provides the artist with a lot more information about the model than working after photographs. The artist works differently than a camera, is able to form multiple perspectives, can zoom in on portions thereof and process this information into a single image. A camera operates not only from a fixed viewing point in space, but the result is an image of one single fixed moment in time, and is there and then translated into two dimensions (Hildebrand's 'Fernbild' versus 'Bewegungsbild'; Hildebrand, 1913). Painting after model means that the model is actually in the same physical space,

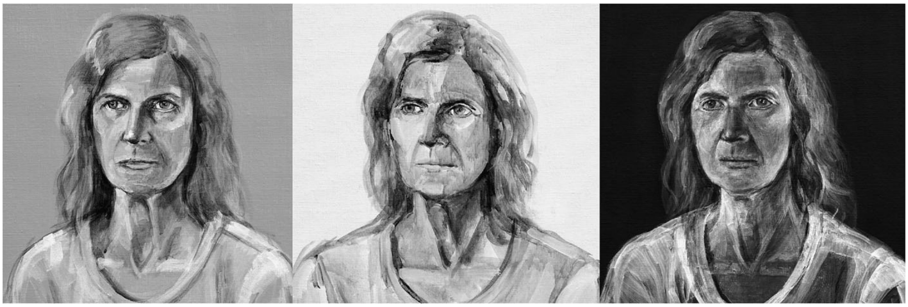

Figure 4. Paintings created by Marianne Venderbosch as stimuli for the experiment. Acrylic on canvas. In the left painting the face is modulated from the gray surface with white and black paint, in the middle the face is modulated from the white surface with nearly only black paint and at right the face is modulated from the black surface with mostly white and a little black paint. Photographs by Marianne E. Venderbosch. © Marianne E. Venderbosch.

talking, slightly moving and changing over time. In some way the painter can experience emotions or moods. To translate the physical space of the scene into pictorial space, the two-dimensional representation, the painter was switching back and forth between binocular and monocular vision, using monocular vision — and brushes as an instrument — to measure the proportions in the scene in front of her.

In three different sessions, each lasting two to three hours, three portrait paintings of the same person were produced in a studio with standardized light conditions. The model was sitting in front of a wall covered with textile alternatively in black, gray or white. The painter was sitting opposite the model at eye height. The distance between painter and model was 124 cm. The stimuli were painted in sessions of two to three hours, each one at different days.[1] The object was not to generate a likeness.

All stimuli were photographed under the same illumination conditions and rendered on a computer monitor in gray-scale. The monitor was a DELL U2410f monitor, 1920 × 1200 pixels liquid crystal display (LCD) screen. An impression of the stimuli is shown in Fig. 4.

2.2. *Psychophysical Method*

Measuring ‘depth’ in paintings is a difficult issue because paintings are two-dimensional flat objects. ‘Depth’ is an aspect of visual awareness; it is not a

[1] Lamps used: one directly on the model: Walimex vc 10000/fully open, height: 1.72 cm; one on the easel and painting: Walimex pro daylight 600, all on, 1.70 cm. Face height of the model: 21 cm. Paint used: acrylic paint; titanium white (Golden, #2380-4), zinc white (Golden, 2415-4) and ivory black (Winsor & Newton Galeria) for the portraits. The layers were painted in white gesso (Lefranc & Bourgeois, 224/0266335) and black gesso (Golden #3560-6). Gray was black gesso mixed with titanium white (Winsor & Newton Galeria, S1, 644 permanence A).

property of the physical object called painting. Depth cannot be measured with a yardstick. There is a difference between looking at a portrait of a person in a painting and looking at the face of that person situated in the scene in front of you. The depth dimension in the case of pictures is generally thought to be constructed by the brain on the basis of 'depth cues', prior information and the visual expertise due to an observer's experience (Palmer, 1999; Pirenne, 1970).

When you look into a painting you become aware of a 'pictorial space'. It contains pictorial objects that are bounded by surfaces usually known as reliefs or pictorial reliefs. A pictorial object is often seen as being 'in front of' a background. One says that the object is closer than the background, or that object and background are at different depths. Notice that the so-called 'background' is not necessarily surface-like, nor at any well-defined depth. Depth is a third dimension distinct from the two dimensions defined by the picture plane. Reliefs are smooth distributions of depth (Hildebrand, 1913), that is to say the surface may 'move into or out of depth'. This is known as shape or articulation. We prefer to use articulation because shape is often used for properties of two-dimensional figures. Throughout our experiments we will use two aspects of perceived relief of a face in a portrait. The first is the total depth range subtended by the face area (A in Fig. 5). The second is relief articulation defined as the amplitude of the deviation from the global shape (B in Fig. 5). Figure 5 serves to explain the various terms used in this paper.

For this experiment we used a method of measurement developed by Koenderink and coworkers (Koenderink *et al.*, 1992). It is a method where you insert a comparison object into the pictorial space. How is this possible? Superimposed on the photograph of the portrait (the pictorial space) is a 'gauge figure' (the comparison object) which is a computer rendering of an ellipse. The observer has to adjust the spatial attitude of the gauge figure to that of the painted face in such a way that it looks like a circle painted on the painted face. This is demonstrated in Fig. 6 where the white gauge figure fits the cheek of the woman and the black gauge figure is evidently off. The gauge figure in our experiment has a contrasting red color and therefore is very salient at all locations in all stimuli. The gauge figure has to be adjusted at about 255 places in a random order. This takes about 20 min for each painting. The paintings were measured in separate sessions over a period of one or two days with a variable break in between sessions and presented in a different random order for each observer. In this way we obtain a data structure that allows us to construct a three-dimensional rendering of the pictorial surface from the observations. The fit reflects an immediate visual judgment and is pre-cognitive.

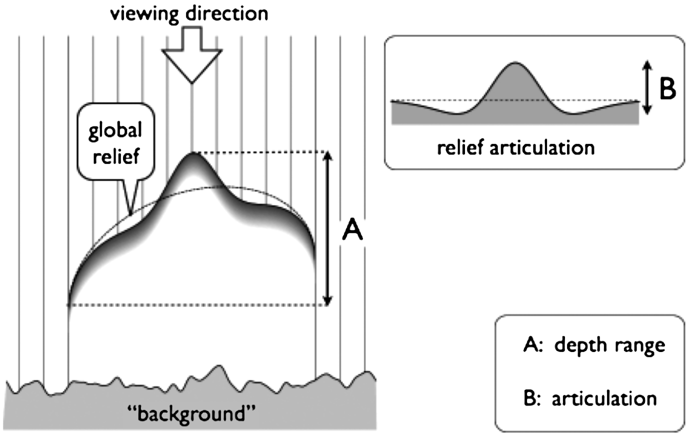

Figure 5. At left a schematic representation of *pictorial space*. The picture plane is not represented, since it is not in pictorial space. The 'background' is symbolically represented, but it is not necessarily surface-like, nor at some well defined depth with respect to the relief of the face. Everything is related to the direction of view. The 'relief' represents the 'pictorial face'. The 'pictorial head' has only a face (front), but not a backside. The background is often experienced as 'continuing behind the face', although the depth gap is fully ambiguous. The relief can be described in terms of a global egg-shape (technically a quadric), and a superimposed articulation. In the inset at right we show the articulation as the difference between the relief and a quadric approximation (dashed curve). The 'depth range' is defined as the total depth range subtended by the relief (A in the figure). A measure of the strength of the articulation is the amplitude of the deviation from the global egg shape (B in the figure). In the experiment we can only measure the relief, the 'depth' of the background is not accessible.

2.3. Set up

The stimuli with a size of 30 cm $\times$ 30 cm were presented on a computer monitor. The monitor was at 115 cm from the eye centered on eye height. The position of the observer's head was fixed with a chin-and-forehead rest. Observers wore an eye patch over their non-preferred eye. They did the task monocularly, because that is reported to generate the best depth results in two-dimensional presentations (Koenderink *et al.*, 1994). During the session the room was darkened. Observers controlled the attitude of the gauge figure through a mouse and keyboard.

2.4. Observers

The observers were familiar with the use of the task and had long experience with psychophysical experiments except for the painter MV. Age varied between 33 and 70 years. Except for the painter, there were no other artists among the observers. There were three females (AD, MV, SP) and three males (HR, JK, MW). All observers had normal or corrected-to-normal vision. Observers used their preferred eye. Three of the observers are also authors of this

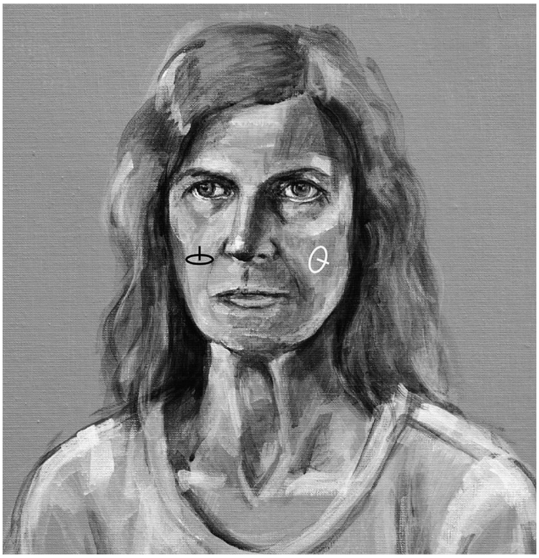

Figure 6. This figure illustrates the use of the gauge figure. We have superimposed two gauge figures over the face in a portrait. The one in white can be seen to 'fit' the relief of the cheek whereas the one in black does not fit at all and is not perceived as being 'on' the face. Notice that the 'fit' is not a physical fit but depends on the awareness of the observer. The axle, that is seen to stick out from the plane of the circle, is used to indicate the frontal side of the disk, and thus to disambiguate the foreshortening of the circle. Photograph by Marianne E. Venderbosch. © Marianne E. Venderbosch.

paper (AD, JK and the painter, MV) and were familiar with the aim of the current experiment. The other observers were not informed about the aims of the experiment. All observers were familiar with the painter and the model.

3. Results

3.1. Total Depth Range of the Relief

From the experiments we obtain about 255 slant and tilt observations for each stimulus and for each observer. From these observations we construct triangulated surfaces that represent the pictorial reliefs. Each triangulation contains about 255 faces and (for each stimulus) 150 vertices. The reliefs are parameterized by depth values at the vertices. Since the absolute depth is undefined, we used the convention that the average depth is zero.

In the first analyses we find the total depth range of the relief for each painting–observer combination. This is a very coarse way to characterize the relief with a single number. We consider the dependence of the total depth range of the relief on stimulus and observer.

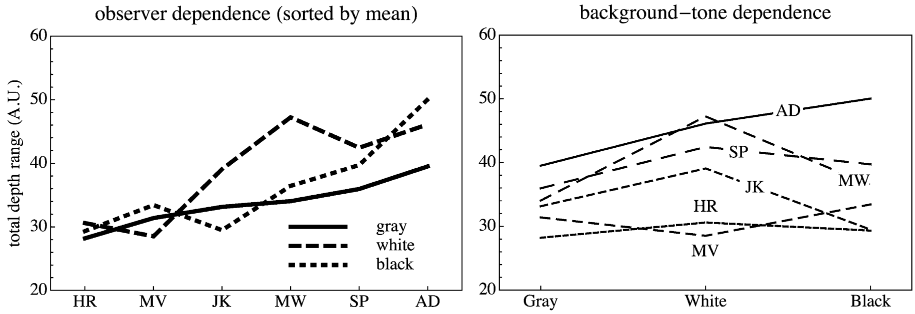

Figure 7. (Left) The perceived total depth ranges of the relief as a function of the observer, sorted with respect to the mean. The drawn line denotes the gray, the dashed line the white, and the dotted line the black tonal ground. (Right) The perceived total depth ranges of the relief as a function of the ground tonal value. For the gray stimulus the sequence from top to bottom is AD, SP, MW, JK, MV, HR. The numbers on the vertical scale represent the total depth range of the relief in arbitrary units (AU).

Figure 7 shows the perceived total depth range of the relief (the interquartile range of the depth values at the vertices[2]) as a function of the ground tonal value for the six observers and the three stimuli in two different ways. Figure 7 shows on the left the results of the perceived total depth ranges of the relief per stimulus and per observer as a function of the observer. In this figure the observers have been sorted such that the mean perceived total depth range increases monotonically. One notices that the curves for all three stimuli increase roughly monotonically (Kendall tau rank correlations are 1.0, 0.6 and 0.9).

The right panel of Fig. 7 shows the perceived total depth ranges of the relief for the observers as a function of the ground tonal color. Apparently the effect of the differences in ground tonal color on perceived total depth range is small and variable. An analysis of variance reveals that the observer is a significant factor (p-value: 0.005), whereas the ground tonal value is not (p-value: 0.11).

3.2. The Articulation of the Relief

The total depth range of the relief is a very coarse measure that reveals nothing about the local variations of depth within a surface. We call these local variations the ‘articulation’. For instance, a plane that is obliquely oriented with respect to the viewer would have a finite depth range, but no articulation at all. A convenient measure for the ‘articulation’ is the deviation from a tem-

[2] Given any set of values, we can find a ‘25% quartile’ value, such that one quarter of all values lies below it. Likewise we can find a ‘75% quartile’ value, such that one quarter of all values lies above it. The ‘interquartile range’ is the difference of the 75% and the 25% quartiles.

plate shape (the coarse relief) such as a plane, an egg-shape, and so forth (see Fig. 5). The articulation is then defined as the relief minus this coarse relief.

To determine the articulation in the perceived relief of our observers we first calculated a quadric approximation to the perceived relief. This quadric approximation defines our coarse relief. As a convenient measure of the amount of articulation we use the root-mean square deviation of the perceived relief from this coarse relief.

Figure 8 shows the articulation of the reliefs per observer for the three different tonal ground values. In Fig. 9 we plot the articulation as a function of the observer for all tonal ground values (left) and as a function of the ground

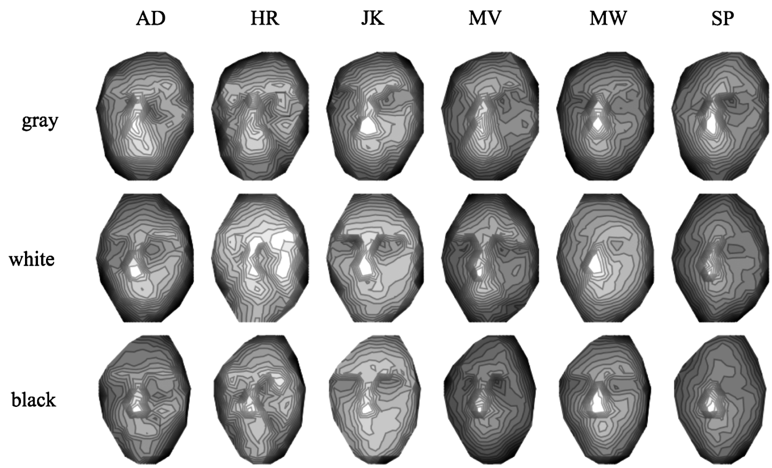

Figure 8. The articulation of the reliefs for all observers and for all ground tonal values. The dark-to-light scale signifies far-to-close in depth.

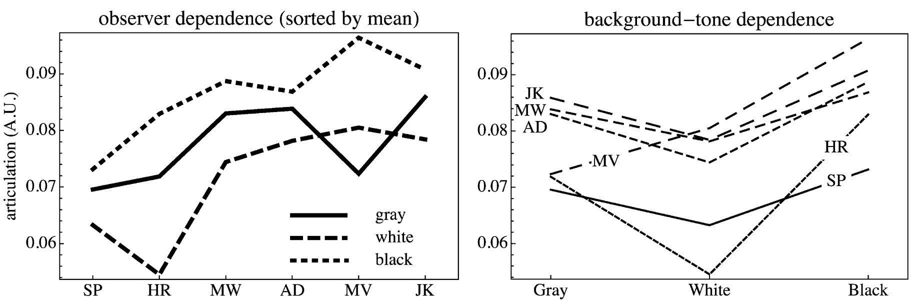

Figure 9. (Left) The articulation as a function of the observer, sorted with respect to the mean. The drawn line denotes the gray; the dashed line the white, and the dotted line the black ground tone. (Right) The articulation as a function of the ground tonal value. For the black stimulus the sequence from top to bottom is MV, JK, MW, AD, HR, SP. The numbers on the vertical scale represent the articulation in arbitrary units (AU).

tonal value for all observers (right). We see that the differences between observers are generally similar for all ground tonal values (Fig. 9, left). We notice a very similar dependence on ground tonal value for all observers (Fig. 9, right). These trends are indeed significant according to analysis of variance with two factors, stimulus and observer. The corresponding p-values are 0.003 and 0.012, respectively. Thus the articulation is significantly less for the white tonal ground than it is for either the gray or the black one.

3.3. Inter-Observer Differences

Although the trends discussed above indeed apply to the group of observers as a whole, there exist marked inter-observer differences. For instance, the total depth range and the articulation of the relief have quite different magnitudes for the various observers. Perhaps surprisingly we find no significant rank correlation between the total depth range and articulation of the relief (rank order correlation (absolute Kendall tau) less than 0.07).

4. Discussion

4.1. Discussion of the Results

This study addresses three major questions. Is there an effect of the ground tonality or the painting technique on the total depth range of the relief, is there an effect of the ground tonality or the painting technique on the articulation of the relief, and are such effects common to all? We discuss these questions in sequence.

4.1.1. Is There an Effect of the Ground Tonality or the Painting Technique on the Total Depth Range of the Relief?

Apparently not: although the p-value is rather low, we find no significant effect of the ground tonality on the total depth range of the relief. We would have expected such an effect in case the stimuli differed mainly with respect to the area-based contrast modulations (e.g., Fig. 2). However, this is not the case for the paintings, because they are mainly based on tonal edge modulations, which are different for the various canvas tones used (see Fig. 4).

4.1.2. Is There an Effect of Ground Tonality or the Painting Technique on the Perceived Articulation of the Relief?

Evidently this is the case. The perceived articulation is significantly lower for the case of the white tonal ground than either the gray or the black tonal ground (0.072 for white, 0.078 for gray and 0.086 for black, respectively, in arbitrary units). The effect that we found for the white ground is as expected: higher contrast (white ground) leads to lower perceived articulation of relief. However, we would have expected a lowering of the perceived articulation of the relief for the black ground too. The way edges are painted is very important (e.g., Fig. 1). It seems likely that the differences in perceived articulation of the relief are due to the difference in the way edges are painted. The third dimension in the portraits is achieved through painting contours as well as edges *within* the face. The quality of these edges can be soft as well as sharp and apparently this contributes to the perceived articulation of the relief.

4.1.3. Are the Effects Common to All Observers or Are There Important Individual Differences?

The general conclusions indeed apply to the observers as a group. However, we do see significant quantitative differences between the various observers. It is not possible to draw conclusions from a quantity like the total depth range of the relief alone, because there is no such a thing as a common depth scale. Some of the observers were also observers in previous studies. From this we know that the ratio of their total depth ranges of the relief appears to be invariant over the years. Apparently there exist real idiosyncratic properties (Gombrich, 1950; Koenderink *et al.*, 2001). This is also evident from the fact that we find very different observer-dependent ratios between the perceived articulation and the total depth range of the relief.

There is a small difference between the results of the painter and the other observers. In the results of the painter the gray tonal ground shows the least perceived articulation whereas for all other observers the perceived articulation is significantly lower for the white tonal ground.

4.2. Can we Generalize the Results to Other Paintings and Techniques?

The difficulty with using actual paintings in a psychophysical experiment is that they are unique. The artist created a set of paintings under controlled circumstances, and varied the canvas tone, using a technique with which it is impossible to create the exact same portrait on those different canvases. The reason for this is that figure and ground are connected and cannot be separated. Moreover, the artist is not trying to construct a physically correct likeness of the model, but rather a subjective percept that includes her own handwriting and technique, the exact things that we are trying to investigate. Given the fact that this means that paintings differ in other ways than just the canvas tones or even just the contrast of the edges makes it difficult to exclude that other differences between the stimuli have in some way influenced our results. This problem perseveres even if one would use a larger number of different paintings created in the same technique.

One could also argue that the effects we found are due to this particular model. We think that that is not the case, because the effects we found seem to be mainly due to painting technique, especially edge and contour treatment, and to observer idiosyncrasies.

Given the importance of the technique, however, one would expect to find effects of the artist. For this reason it could be interesting in future investigations to compare a number of different artists and their specific techniques of creating relief in a portrait (modern as well as traditional).

In conclusion, in our portrait study we find that canvas tone is not of primary importance for the perceived total depth range of the relief, but that it has a noticeable effect on the perceived articulation of pictorial relief. Apparently it is the way an image is created that is of remarkable influence. Non-classical techniques of painting, like edge-based modulation, can create very well a strong and beautiful impression of depth and space. Compared to traditional techniques where optical ways of shading are used (shape from shading), these alternative techniques are as effective as the traditional ones in the creation of pictorial relief.

Acknowledgements

We thank Huib de Ridder, Sylvia Pont and Maarten Wijntjes from the Department of Industrial Design Engineering of Delft University of Technology for their mental and physical support in this experiment and we thank Bertus Naagen in his support to create a perfect studio with all the necessary facilities. We thank the editor, Johan Wagemans, and two anonymous reviewers for their helpful comments on the first draft of this manuscript.

References

Adams, A. (1952). *Natural-Light Photography*. Morgan and Morgan, Hastings-on-Hudson, NY, USA.

Bloomer, C. M. (1989). *Principles of Visual Perception*. Design Press, NY, USA.

Doerner, M. (1971). *Malmaterial und Seine Verwendung in Bilde*. Ferdinand Enke Verlag, Stuttgart, Germany.

Fehrenbach, F. (2002). Der oszillierende Blick. Sfumato und die Optik des späten Leonardo, *Z. Kunstgesch.* **65**, 522–544.

Foley, J. D. and van Dam, A. (1983). *Fundamentals of Interactive Computer Graphics*. Addison-Wesley, Reading, MA, USA.

Gleizes, A. and Metzinger, J. (1912). Du “Cubisme”, Eugène Figuière Éditeurs, Collection “Tous les Arts”, Paris, France.

Gombrich, E. H. (1950). *The Story of Art*. Phaidon, London, UK.

Hockney, D. (2006). *Secret Knowledge, Rediscovering the Lost Techniques of the Old Masters*. Penguin Group, NY, USA.

Koenderink, J. J., van Doorn, A. J. and Kappers, A. M. L. (1992). Surface perception in pictures, *Percept. Psychophys.* **52**, 487–496.

Koenderink, J. J., van Doorn, A. J. and Kappers, A. M. L. (1994). On so-called paradoxical monocular stereoscopy, *Perception* **23**, 583–594.

Koenderink, J. J., van Doorn, A. J., Kappers, A. M. L. and Todd, J. T. (2001). Ambiguity and the ‘mental eye’ in pictorial relief, *Perception* **30**, 431–448.

Koenderink, J. J., van Doorn, A. J., Arend, L. and Hecht, H. (2002). Ecological optics and the creative eye, in: *Perception and the Physical World: Psychological and Philosophical Issues in Perception*, D. Heyer and R. Mausfeld (Eds), pp. 271–304. Wiley & Sons, Chichester, UK.

Koenderink, J. J., van Doorn, A. J. and Wagemans, J. (2013). SFS? Not likely!, *i-Perception* **4**, 299–302.

Koenderink, J. J., van Doorn, A. J., Albertazzi, L. and Wagemans, J. (in press). Relief articulation techniques, *Art Percept.* DOI:10.1163/22134913-00002032.

Mayer, R. (1951). *The Artist's Handbook of Materials & Techniques*. Faber and Faber, London, UK.

Palmer, S. (1999). *Vision Science: Photons to Phenomenology*. Bradford Books, MIT Press, Cambridge, MA, USA.

Pirenne, M. H. (1970). *Optics, Painting and Photography*. Cambridge University Press, Cambridge, UK.

Ramachandran, V. S. (1988a). Perception of shape from shading, *Nature* **331**, 163–166.

Ramachandran, V. S. (1988b). Perceiving shape from shading, *Sci. Am.* **259**, 76–83.

Rogers, L. R. (1969). *Sculpture, Series "The Appreciation of the Arts 2"*. Oxford University Press, London, UK.

van Hout, N. (2005). Functies van Doodverf met Bijzondere Aandacht voor de Onderschildering en Andere Onderliggende Stadia in het Werk van P. P. Rubens, *Thesis*, Katholieke Universiteit Leuven, Belgium.

von Hildebrand, A. (1913). *Das Problem der Form in der Bildenden Kunst*. Heitz, Strassburg, Germany.