Articulation effects in lightness: Historical background and theoretical implications

Alan L Gilchrist
Department of Psychology, Rutgers University, Newark, NJ 07102, USA; e-mail: alan@psychology.rutgers.edu
Vidal Annan Jr
Rutgers Center for Cognitive Science, Rutgers University, New Brunswick, NJ 08854, USA
Commissioned for the Special issue on Articulation

Abstract. The concept of articulation was first introduced by Katz [1935 The World of Colour (London: Kegan Paul, Trench, Trubner & Co)] to refer to the degree of complexity within a field. Katz, who created the basic research methods for studying lightness constancy, found that the greater the degree of articulation within a field of illumination, the greater the degree of constancy. Even though this concept has been largely forgotten, there is much empirical evidence for Katz’s principle, and the effects on lightness are very strong. However, when articulation is increased within a framework that does not coincide with a region of illumination, constancy is weakened. Kardos (1934 Zeitschrift für Psychologie Ergänzungband 23) advanced the concept of co-determination, according to which the lightness of a surface is determined relative to more than one field of illumination. Gilchrist et al (1999 Psychological Review 106 795–834) argue that the fields concept should be replaced by the more operational frameworks concept and that a wide variety of lightness errors can be explained by a modification of the Katz principle: the greater the articulation within a perceptual framework, the stronger the anchoring of lightness values within that framework.

1 Introduction
The important role of articulation in lightness perception was first noted by David Katz (1935), whose work has been neglected for some time. Katz is generally remembered as a phenomenologist who described the various modes of color appearance, emphasizing primarily the distinction between surface color and film color. But, arguably, his most important contribution lies in the fact that he established the basic experimental methods used in the study of lightness constancy until today.

The most familiar of Katz’s methods has no name(1) but we will call it the light/shadow method. The observer sits facing a wall that is brightly illuminated by a window off to one side. A vertical screen, running roughly along the observer’s line of sight, casts a shadow on the left side, dividing the space into two adjacent regions of bright and dim illumination. A color wheel is mounted in each of these regions and the observer adjusts one of them to equate the two for lightness.

Two important findings emerged from the Katz experiments on constancy. First, the larger the area of a field of illumination, the greater the constancy within that field. Katz referred to this principle as the law of field size. Second, the greater the complexity, or degree of articulation within a field, the greater the constancy.

Although Katz created several formulae used to compute the degree of constancy found in such experiments, the most useful was created by Egon Brunswik (1929). The Brunswik ratio locates the observer’s match on a continuum between a match that represents the physical reflectance of the standard disk (100% constancy) and one that represents the luminance of the standard disk (0% constancy). Thouless (1931) improved on this measure by using a logarithmic scale for the distance between these poles.

(1) It is a type of asymmetric lightness matching.
1.1 *Experiments on field articulation*

Katz obtained Thouless ratios of 35% to 75% in his light/shadow arrangement, using a single disk in each field. But in one variation of the experiment he replaced the illuminated disk with a chart of 48 gray chips ranging from black to white. In this case, constancy jumped to 95%. Katz then urged his student Burzlaff to conduct a systematic investigation of the influence on constancy of the number of gray samples in each field.

Using Katz’s method of illumination perspective with a 20:1 illumination ratio, Burzlaff (1931) obtained relatively high degrees of constancy in all his conditions. But he confirmed the strong effect of articulation. With a single disk in each zone of illumination, he obtained Thouless ratios between 65% and 94%, but when he used the 48 patch chart in each zone, he consistently obtained ratios between 100% and 104%.

Katona (1929) projected a round spotlight onto a wall, covering a gray square and part of the wall surrounding it. Observers viewed the target square through one of three reduction screens that revealed either: (i) only a portion of the gray square, (ii) the gray square plus a portion of the spotlighted wall surrounding it, or (iii) the gray square plus the entire spotlight plus a portion of the non-spotlighted wall. In the first condition, Katona obtained almost zero constancy, but as more regions were seen constancy increased substantially.

Of course, the famous demonstration by Gelb (1929/1938) could be considered a matter of articulation. When a black paper suspended in midair is the only surface illuminated by a spotlight, it appears white. But it suddenly appears darker gray when a real white paper is brought into the spotlight next to it. But this is not a pure effect of articulation, because the white paper not only increases the articulation; it also raises the highest luminance in the display. Other work, however, has shown an effect of darkening the target by increasing articulation, even when the highest luminance is held constant. We and our colleagues (Gilchrist et al. 1999, figure 9) found Munsell values of 7.5 (light gray), 4.9 (middle gray), and 3.3 (almost black) for the black paper when groups of 2, 5, and 10 papers, respectively, are presented within the spotlight and each group contains a white paper. The percentages of constancy are shown in figure 1a.

Henneman (1935) varied the number of disks placed in each field in a Katz light/shadow constancy experiment. His results are shown in figure 1b. Using a single disk

---

**Figure 1.** Constancy (Thouless ratios) associated with different levels of articulation in (a) Gilchrist et al. (1999) and (b) Henneman (1935).
in each field of illumination, he obtained 29% constancy (Thouless ratio). When a single small gray disk was placed on the background near each target disk, constancy jumped to 42%. With three small black disks placed near the target disk, he obtained 50% constancy. Henneman noted (1935, page 52): “Apparently the more complicated the constitution of the field of observation in the sense of presenting a number of surfaces of different reflectivity, regions of different illumination, and objects set in different planes (tri-dimensionality), the more in accord with its actual albedo-color will a test object be perceived”.

2 Definition of the term
Sixty-five years ago Henneman (1935, page 23) wrote: “‘Articulation of the visual field’ has become recognized as an essential condition for the appearance of ‘constancy’ phenomena, though this rather vague term is badly in need of clearer definition and explanation”. In essence, articulation means complexity, either within the entire visual field or within a field of illumination. However, if one looks at the early experimental work on the topic (Gelb 1929/1938; Burzlaff 1931; Henneman 1935; Katz 1935), it becomes clear that, with few exceptions, articulation was operationally defined as the number of patches of different reflectance within a field of illumination. We use the term in this sense.

3 Articulation at work in modern research
For over 50 years, the concept of articulation was forgotten. This is remarkable considering the great attention, both in theory and research, paid to the concept in the first third of the past century. American theorists, who found themselves in a dominant position following World War II, were eager to distance themselves from what they considered to be vague European ideas. They sought to ground lightness theory in the newly discovered physiology of lateral inhibition. Contrast theories based on lateral inhibition (Jameson and Hurvich 1964; Cornsweet 1970; Heinemann 1972) had no place for concepts like articulation. But variations in articulation level can produce large changes in lightness, even when luminance factors on which lateral inhibition depends are held constant.

Lightness theories became much more realistic in the early 1970s, with the advent of the computer and machine vision. Articulation effects began to show up in empirical results even without their explicit recognition.

In 1977, Gilchrist reported several experiments that demonstrated a strong effect of depth perception on lightness. One of those experiments was later replicated by Schirillo et al (1990), with a stereoscopic display presented on a CRT screen. While Gilchrist had obtained a 65% level of constancy, Schirillo and his colleagues obtained only 30%. Was this weaker constancy associated with the CRT method? Schirillo and Arend became interested in these failures of constancy and in 1995 they reported an experiment testing the hypothesis that constancy failures occur when the target surface lies at the boundary of two depth planes, as in the earlier Gilchrist (1977) study. The hypothesis was confirmed. As can be seen in figure 2, they obtained 72% constancy when their target was located at the depth boundary, but 97% when it was not. But compare the two middle bars in figure 2. The 72% constancy obtained by Schirillo and Arend (1995) is much higher than the 30% obtained by Schirillo et al (1990), even though in both cases the target was located on the depth boundary. Although this comparison is not between two conditions of the same experiment, the results suggest a strong influence of articulation on constancy.

(2) There are several factors that could account for this difference in results, including the smaller visual field or the use of the mirror stereoscope in the Schirillo et al study, or the visibility of surface imperfections in the Gilchrist study.
Likewise, consider the data reported by Arend and Goldstein (1987), shown in figure 3, from a CRT experiment in constancy. Arend and Goldstein presented side-by-side displays under two levels of simulated illumination. Observers adjusted a target in one display to match a target in the other display for lightness. Marked failures of constancy resulted when each display consisted of a single target and surround, but constancy was almost perfect when highly articulated Mondrians were used instead.

Figure 2. Constancy (Thouless ratios) obtained in various experiments on depth and lightness.

Figure 3. Results from Arend and Goldstein (1987) constancy experiments with CRT displays. Perfect constancy is shown by solid horizontal lines.
4 Implications for lightness theory
The strong effects of articulation on lightness provide constraints for theories of lightness that cannot be ignored. Here is our interpretation of these constraints. Others may disagree with this analysis.

4.1 Contrast theories based on lateral inhibition
The role of articulation within perceptual frameworks presents the greatest challenge to structure-blind models, especially contrast theories based on lateral inhibition (Jameson and Hurvich 1964; Cornsweet 1970; Heinemann 1972). These models have an impoverished notion of context, limited to the average luminance of retinal regions immediately surrounding the target. Articulation can produce effects on lightness every bit as big as those produced by changes in surrounding luminance. A similar logic applies to other structure-blind theories, such as adaptation-level theory (Helson 1964).

4.2 Intrinsic image theories
Intrinsic image models seek the recovery of reflectance information through inverse optics. Analytic processes are held to decompose the retinal image into separate layers or components that represent reflectance and illuminance. For example, according to an earlier computational model by Gilchrist (Gilchrist 1979; Gilchrist et al 1983), reflectance and illuminance are disentangled by classifying edges within the retinal image and then integrating within classes the luminance changes at those edges. Neither edge classification nor edge integration is held to depend on articulation level, and it is difficult to imagine how articulation effects could be incorporated into such a model. Articulation effects seem inconsistent with the concept of inverse optics. For example, it has been shown that, if the illumination falling on a target of constant luminance appears to increase, the target will appear to become darker in lightness. This psychophysical fact nicely mirrors the laws of physics by which reflectance and illuminance are related to luminance. But the dependence of lightness on articulation level does not appear to mirror any laws of physics. In the physical world, the reflectance value of a surface does not depend on how many other neighboring surfaces are included in that region of illumination.

4.3 Bayesian theories
In view of the critical role of the highest luminance in anchoring lightness values (Li and Gilchrist 1999), there is an interesting point of contact between articulation level and probability. Lightness depends strongly on the ratio between the luminance of a target and the highest luminance within a field of illumination (Li and Gilchrist 1999). Thus, lightness will be more veridical when the highest luminance in a field is actually white, and this is most likely the greater the number of surfaces falling within a field of illumination.

4.4 Katz and Helmholtzian theory
Although Katz first uncovered the facts of articulation in his empirical work, his own theory could not accommodate these facts. According to Katz’s theory of lightness constancy, the stimulus value of a target seen in non-normal illumination is transformed, through a cognitive process similar to that of Helmholtz (1867/1924–1925), in a direction away from the stimulus value and toward its genuine or veridical value. But why the transformation should be more complete when the target lies within an articulated field of illumination is a question for which Katz could offer no explanation.

4.5 Gestalt theory
The Gestalt theorists, especially Koffka (1935) argued that lightness, just as size and motion perception, is determined in relation to a frame of reference. But frames of reference per se provide no role for articulation, as long as the lightness of a target is determined exclusively within its frame of reference.
5 Co-determination

Kardos (1934)(3) provided a crucial advance for the Gestalt theory of lightness. He recognized that lightness cannot be determined exclusively within a single framework. Exclusive determination is not logically tenable,(4) nor is it consistent with the empirical evidence.

Kardos proposed that the lightness of a target is co-determined, partly by its relevant field of illumination and partly in relation to what he called the foreign field of illumination. The Katz light/shadow arrangement can be used to illustrate the concepts of Kardos. For the target in bright illumination, the lighted region is the relevant field and the shadowed region is the foreign field. These roles are reversed for the target in shadow. It is an empirical fact that, except in special cases, the lightness value of a given target does lie somewhere between its lightness value when computed relative to the highest luminance in the relevant field and its lightness value when computed relative to the highest luminance in the foreign field.

Although Kardos was more explicit on the idea of co-determination, Koffka's thinking was closely related: "The more $x$ belongs to the field part $y$, the more will its whiteness be determined by the gradient $xy$, and the less it belongs to the part $z$, the less will its whiteness depend on the gradient $xz$" (Koffka 1935, page 246).(5) This implies that regions outside the frame of reference of a target influence its lightness, but not as much as regions within the frame.

The concept of co-determination provides a theoretical framework capable of accommodating the facts of articulation. Kardos argued that the degree to which lightness is determined relative to either the relevant field or the foreign field depends on the size of each of these fields and by the degree of articulation within each. Thus, Kardos produced the first coherent explanation for failures of lightness constancy. In general, lightness will be veridical to the extent that it is determined relative to the relevant field, but in error to the extent that it is determined relative to the foreign field.

Any theory that invokes the concept of fields of illumination must deal with the operational definition of such fields in proximal stimulus terms. How, for example, is the retinal image segmented into such fields? This problem has not received the attention it deserves. Helmholtz talked about taking the illumination into account. But whether the level of illumination is defined by the highest luminance in a field of illumination, or by the average luminance within the field, the key question is: where is the field of illumination? Over what domain of the image should one take an average value, or find the highest value? More than other Gestaltists, Kardos confronted the problem of how fields of illumination are perceptually segregated. He emphasized two factors: penumbras and depth boundaries. To these we can add many of the Gestalt grouping factors.

6 Pseudo-fields

However, once these segmentation factors are operationally defined, it becomes clear that these factors are bound to occur in the image even when actual fields of illumination are not present. Does this mean that such ‘pseudo-fields’ function as weak frameworks within which lightness is computed? And what happens when the articulation within

---

(3) English translation available on request.

(4) Frameworks that are small and/or poorly articulated cannot determine the lightness of the elements they contain. An example is the Gelb effect. A single black paper suspended in midair and illuminated by a spotlight appears white, showing that its lightness is determined by the larger environment, not by the illumination level in the spotlight. Kardos made the same point about the inverse case: a white paper located in a hidden shadow.

(5) Koffka’s term whiteness is the same as the current usage of lightness.
these pseudo-fields is increased? If increasing articulation strengthens the degree to which lightness is determined relative to these pseudo-fields, this should produce larger errors in perceived lightness. And this seems to be exactly what happens.\(^{(6)}\)

It has been shown (Adelson 2000; Gilchrist et al 1999) that the simultaneous-contrast illusion becomes stronger (that is, less constancy) when the black and white backgrounds are replaced by articulated Mondrian patterns, even when this reduces the difference in average luminance between the two backgrounds. Wishart et al (1997) have shown the same thing for another illusion: Adelson's corrugated Mondrian. Presumably articulation level is also responsible for the difference in magnitude between two illusions with a common topological structure: the Benary effect (Benary 1924), and White's illusion (White 1981). White's illusion is much stronger than Benary's illusion, but not when the articulation level in White's illusion is reduced to a minimal level, as can be seen in figure 4. Economou et al (1998) have demonstrated the role of articulation in another illusion they call reverse contrast. In this illusion, a gray target bar on the black background (and totally bordered by black) is surrounded by a set of white flanking bars. This makes it appear actually darker than an equiluminant bar on the white background that is surrounded by a set of black flanking bars. Figure 5 shows that the size of the illusion grows as the number of flanking bars in each group is increased.

Although Kardos did not recognize it, the existence of pseudo-fields shows that the concept of co-determination provides the basis, not only for an explanation of illumination-dependent errors, or what have been traditionally called failures of constancy, but also for an explanation of background-dependent errors, as found in the various mosaic illusions that have lately proliferated.

\(^{(6)}\) Ironically, this brings us back to something like Helmholtz's suggestion that the black and white backgrounds function, to some small degree, as different levels of illumination. This illustrates what we call pseudo-fields.
7 Importance of errors
Lightness errors provide an important theoretical tool. They are systematic, not random, and the pattern of errors can only reflect the nature of visual processing that produces lightness percepts. Just as there are two main classes of lightness constancy: constancy with respect to changes in illumination level, and constancy with respect to changes in surround, so there are two broad classes of lightness errors: illumination-dependent errors and background-dependent errors. The usefulness of the concept of co-determination in accounting for both classes of error suggests that it should be considered very carefully.

8 Modification of Katz's principle
We and our colleagues (Gilchrist et al 1999) have proposed a theory of lightness based on such ideas. From this perspective, Katz's principle of articulation must be modified. Katz claimed that increasing the degree of articulation increases constancy. But, as we have seen, when a framework does not coincide with a physical field of illumination, increasing the articulation level within that framework decreases constancy. We propose that increasing the degree of articulation within a framework strengthens the degree to which the lightness of a target is anchored within that framework.

9 Concept of the framework
The concept of the framework, or frame of reference, as we have used it, is derived from the concept of field of illumination, as used by Katz and the Gestaltists, but it is more operational. While field of illumination describes a structure that is present in phenomenal experience, a framework is the operational definition of this for use in computing lightness. A framework might be considered to be the surrogate in the visual software for a field of illumination.

Figure 5. Size of reverse-contrast effect as a function of the number of flanking bars (Annan et al 1998). The illusion may not be adequately conveyed by this illustration.
10 Conclusions

We conclude that articulation is a major factor in lightness perception, one that can produce effects on lightness just as strong as those produced by changing neighboring luminance values. David Katz deserves credit for discovering the fact that, in general, greater articulation within a field of illumination produces greater constancy. Developments in lightness theory have been hampered by neglect of Katz, and the vigorous industry of constancy research that took place in the first third of the 20th century.

Katz and the Gestalt theorists emphasized that lightness is computed relative to an illumination frame of reference, but it was Kardos who advanced the principle of co-determination by multiple frameworks of illumination. For a given surface, lightness is mainly determined by its relevant framework, but also by the foreign framework.

When the concept of framework is expanded to include pseudo-fields that do not coincide with fields of illumination, Kardos's principle can be expanded into a general theory of lightness errors. Articulation plays a key role in this theory. Within fields of illumination, optimal constancy requires anchoring within the relevant field. Thus greater articulation within local fields, by strengthening local anchoring, leads to greater constancy. Within pseudo-fields, local anchoring produces greater lightness errors. Thus greater articulation within pseudo-fields leads to weaker constancy.

Acknowledgements. This work was supported by grants from the National Science Foundation (SBR BCS-9906747) and the National Institute of Health (PHS-S06 GM08 223).

References

Benary W, 1924 “Beobachtungen zu einem Experiment über Helligkeitskontrast” [Observations concerning an experiment on brightness contrast] Psychologische Forschung 5 131 – 142
Gilchrist A L, 1977 “Perceived lightness depends on perceived spatial arrangement” Science 195 185 – 187
Gilchrist A, 1979 “The perception of surface blacks and whites” Scientific American 240 112 – 123
Helmholtz H von, 1867/1924–1925 Treatise on Physiological Optics English translation by J P C Southall for the Optical Society of America (volume 1, 1924; volumes 2 and 3, 1925) from the 3rd German edition of Handbuch der physiologischen Optik (first published in 1867, Leipzig: Voss)
Henneman R H, 1935 “A photometric study of the perception of object color” Archives of Psychology (No 179) 5 – 89
Kardos L, 1934 “Ding und Schatten” [Thing and shadow] Zeitschrift für Psychologie Ergänzungsbuch 23
Li X, Gilchrist A, 1999 “Relative area and relative luminance combine to anchor surface lightness values” Perception & Psychophysics 61 771 – 785
Schirillo J, Arend L, 1995 “Illumination change at a depth edge can reduce lightness constancy” Perception & Psychophysics 57 225 – 230
Schirillo J, Reeves A, Arend L, 1990 “Perceived lightness, but not brightness, of achromatic surfaces, depends on perceived depth” Perception & Psychophysics 48 82 – 90
Thouless R H, 1931 “Phenomenal regression to the ‘real’ object” British Journal of Psychology 22 1 – 30

© 2002 a Pion publication printed in Great Britain