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Susanne Liebmann in the critical zone

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Susanne Liebmann was not the first to experiment with equiluminous color stimuli—Alfred Lehmann has examined geometrical illusions in his Chromoscope 24 years earlier and Pleikart Stumpf (see *Perception* **25** 1231 – 1238), Wanda von Lempicka, Vittorio Benussi, and Wilhelmine von Liel (later Benussi-Liel) had all reported some measurements of resolution and illusions at equiluminance (see Liebmann's article for the references). However, Liebmann was the first to reveal the breadth of strange and curious phenomena that arise when colors are equated for luminance and she did so with astute observations and vivid writing.

She had set out to re-examine the claim that irradiation (the expansion of the apparent extent of the lighter areas of the figure) was the underlying cause of several geometrical illusions such as the Münsterberg and Zöllner figures. Lehmann had tested this claim in 1904 by presenting the illusions at equiluminance to eliminate the effects of irradiation. He reported that the illusions disappeared at equiluminance and argued that the irradiation theory was correct.

Liebmann's advisor, Wolfgang Köhler, suggested that she take another look at these earlier observations. She found that Lehmann had been right in reporting that the illusions disappeared at equiluminance but she found that they disappeared because, in fact, the stimuli no longer looked anything like the original figures—they were no longer appropriate for inducing the illusions. For example, the obliques of the Zöllner figure were blurred to invisibility. However, when the illusion figures were big enough to escape blurring at equiluminance, she reported that the illusion strengths remained undiminished.

She named the region near equiluminance the 'critical zone' and proceeded to evaluate the nature of the perception of form and space in that zone. She worked with 'primitive' materials (stimulus shapes cut out of colored papers and lights controlled by filters and rheostats) to obtain equiluminance but succeeded by using great care (amply described in her methods) and making individual settings for each subject.

One of the great pleasures of reading her article comes from the numerous, rich descriptions of her own and her subjects' reactions to the unusual distortions at equiluminance. The following excerpt gives an example.

> "When ... figures are perceived, then generally everything is soft, jellylike, colloidal. ... It often happens that parts which, in the normal figure, belong together now 'have nothing to do with each other' ... The character of the space suffers most; distances in depth lose their magnitude, become fully indeterminate, indeed vanish. The object character is affected, often becoming completely lost, and the figures appear incorporeal, 'ghostly' in a strange and, to our usual daily visual world, very foreign way. There are in psychology only a few phenomenal changes of so drastic a nature." (page 1460)

How did Liebmann's work fare over time? On one hand, her report of the melting of borders at equiluminance, particularly for blue/green borders, became known as the Liebmann effect and was re-examined and cited fairly often (Koffka and Harrower 1931; Hiltz and Cavonius 1970) albeit with credit for the discovery going to Koffka on a number of occasions (Kaiser et al 1971; Tansley and Boynton 1978). Tansley and Boynton (1978) linked the Liebmann effect to 'tritan' color pairs which differentially modulated only the S-cones. It was only for these pairs (probably approximated by Liebmann's blue and green papers) that they found complete disappearance of borders.

On the other hand, her work on illusions, form, and depth perception at equiluminance seems to have been forgotten. With Lu and Fender's (1972) report on the role of color in stereopsis and Gregory's development of a new 'Chromoscope' (Gregory 1977), interest in the field revived. Despite some misgivings (Mollon 1982), equiluminous stimuli became a tool for exploring the properties of the chromatic and, specifically, parvocellular pathways. Many of the subsequent discoveries had been reported in Liebmann's article. Lehmann's and Liebmann's original question of the fate of illusions at equiluminance was taken up in turn by Gregory (1977), Cavanagh (1987), and Livingstone and Hubel (1987). In the first two cases, with images large enough to avoid blurring, the strength of most illusions was unaffected at equiluminance; in the last case, with figures with finer lines, the same illusions were found to disappear—all as Liebmann would have predicted. The paper by Livingstone and Hubel (1987) was the first paper in six decades to reference Liebmann's work on illusions.

Figure 1. Susanne Liebmann, 1897 – 1990. This photograph has been kindly made available by a surviving relative of Dr Liebmann.

Here is a partial list of other phenomena originally described in Liebmann's paper: the loss of accommodation at equiluminance (Wolfe and Owens 1981), the fading, blurring, and filling in of images (Gregory 1977; Kelly 1981), and the loss of depth perception (Lu and Fender 1972; Gregory 1979).

Two phenomena reported by Liebmann have escaped rediscovery and certainly merit some follow-up. First, she reports that, as we would now expect, the resolution of a gap in a line is worse at equiluminance than when some luminance contrast is present. But, more interestingly, she claims that the resolution of the gap at equiluminance is 300% better if it falls between two objects than if it falls within one object, even though the gap and the adjoining lines are identical in both cases (see her figures 28 and 29). This large difference occurred only for the equiluminous color figures—the difference was minimal for the same figures presented in greys of low luminance contrast.

Second, she finds that she can produce the phenomena of equiluminance by dichoptically combining colored stimuli with the same colors in the two eyes but opposing monocular brightness differences. For example, a green square on a red background where the square is lighter than the background in the left eye but darker than the background in the right eye. "*In the combined picture* there resulted in the manner of the other experiments *a phenomenal critical zone in which the figure contours become indistinct and blurred* .... If one tested in this position monocularly, then the right picture as well as the left one was each in sharp focus and with brightness difference of figure and ground." (page 1492).

Liebmann did not follow up her original work in vision. There are only five subsequent entries in the *Psychological Register* for her and they deal mostly with developmental psychology. There are no entries after 1931.

With the rise of the Third Reich, she was expelled from the Berlin Psychological Institute and worked for a time as a speech therapist at a Jewish hospital in the city. In August 1939, through the agency of a British committee, she moved to England, working first as a nurse. She subsequently became a teacher at a hospital for subnormal children at Pewsey, Wiltshire, and was later appointed as an educational psychologist in the same institution, remaining there until her retirement. She was living in Pewsey in the late 1950s when she attended a lecture by her former advisor, Köhler. She politely turned down his invitation to visit Berlin while he was there, having vowed never to return. She wrote a short but moving letter to Köhler in 1958 to say that she had reconsidered her decision but we do not know if she ever followed it through. She died on the 21st of July 1990 at the age of 93.

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From the Psychological Institute of the Berlin University

Behavior of colored forms with equiluminance of figure and ground†

by Susanne Liebmann

Note: Where Liebmann used italics for emphasis these are preserved in the translation. Added comments and some obvious corrections to the original text are set off by brackets [...].

† Über das Verhalten farbiger Formen bei Helligkeitsgleichheit von Figur und Grund" *Psychologische Forschung* **9** 300 – 353 (1927).

Chapter I

§1. This work continues the experiment of Lehmann[1], which he considered a critical test of the hypothesis that a series of geometrical optical illusions are based upon irradiation (and only upon this).

It has often been remarked that certain geometrical-optical illusions may be explained by irradiation. For example, Münsterberg claimed that the illusion of the displaced checkerboard was due to irradiation[2]. Heymans[3] raised objections to this thesis, and Münsterberg[4] then attempted to invalidate these objections[5]. Pierce[6] attempted to decide between the opinions of Münsterberg and Heymans and brought to bear a number of qualitative and quantitative experiments; he used mainly an increase of brightness, of darkness, and several changes of color and of form. The results supported the assumption that irradiation is a valid explanation.

Lehmann presents evidence that the Münsterberg, Poggendorff, and Zöllner illusions are based exclusively on irradiation. He also claims that irradiation plays a role in the Müller-Lyer illusion, if a somewhat smaller one. After lengthy theoretical arguments in connection with his own work on "the distribution of light on the retina"[7] Lehmann talks of Münsterberg's displaced checkerboard pattern with respect to his figures 2B and 2E (our figure 1).

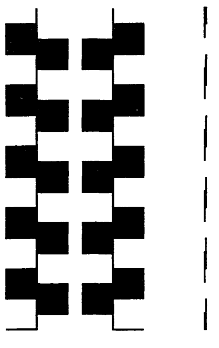

Figure 1.

Münsterberg, who first described this figure, asserts, in my opinion quite rightly, that irradiation is the cause of the illusion. The boundary lines between the white and black squares become displaced in the direction of the latter; the fine connecting line, however, does not change its position; it becomes at most a little broader if it is seen under a small visual angle. The vertical line changes thereby into a zig-zag line, as I have attempted to illustrate strongly exaggerated in figure 1E. In the checkerboard pattern, the displacements are, however, so small that they are not perceived as such; the vertical line is seen as a straight line inclined to the left or to the right. One senses a similar inclination already in figure 1E. So there can be no doubt that irradiation

[1] Lehmann, "Die Irradiation als Ursache geometrisch-optischer Täuschungen" *Pflügers Arch. f. d. ges. Physiol.* **103** 1904.

[2] Compare text in the explanation in the collection on Pseudooptics; quoted by Heymans, *Zeitschr. f. Psychol.* **14** 1897.

[3] ibid.

[4] *Zeitschrift f. Psychol.* **15** 1897.

[5] Compare chapt. IV, §2, point 4.

[6] Pierce, "The illusion of the kindergarten patterns". *Psych. Revue* 1898, p. 233.

[7] *Pflügers Arch. f. d. ges. Physiol.* **36**, 580, 1885.

can explain the illusion; but Münsterberg gave no evidence whether other factors apart from irradiation are at work (pp 88, 89).

Lehmann tests if the illusion is based solely on irradiation in different ways; he examines the effect of a mere contour figure and the effect of the thickness of the cross-stripes, etc. Of prime importance, however, is his method of using a special apparatus ('the chromoscope'), which—he claims—furnishes a simple and conclusive outcome.

This decisive experiment requires that one produce *ground and figure in two different colors of equal brightness.*

"Naturally diffusion circles are also formed in the eye in this case. However, just as much light is irradiated from the figure to the ground as from the latter to the figure. No brightness differences can develop and *thus also no displacement of the borders. Consequently, the illusion must disappear if irradiation is the cause.*" His apparatus[8] allowed the independent variation of color and brightness of the figure and ground areas.

In the case of the checkerboard pattern (see our figure 1) the figure was presented on a ground of the *same brightness*, for example green on red. "*The illusion disappeared completely*" reports Lehmann, "*the vertical lines now become straight and parallel ....* It is therefore demonstrated not only that irradiation can produce the illusion, but that it is the sole cause. If one eliminates the effect of irradiation there is nothing left of the illusion."

Using the same method, Lehmann also investigates the Poggendorff illusion, which he presents equally bright with the ground in the chromoscope. After a discussion of some other arguments he reports that "as soon as figure and ground have exactly the same brightness, the illusion disappears completely".

He finds the same results with the Zöllner pattern. "If figure and ground have the same brightness, *the main lines of the Zöllner pattern are completely parallel.*"

Lehmann then investigates the Müller-Lyer figure in the chromoscope. According to his explanation, irradiation must also work in the direction of the illusion, although acting alone it "cannot bring forth such enormous size ratios as are found here". In the chromoscope, the illusion remained almost unchanged with equal brightness of figure and ground. Lehmann comes to the conclusion that still other factors must be here at work.

§2. Benussi and Liel turn against the irradiation theory in a paper on the displaced checkerboard figure[9].

They explain in the introduction that "in contrast to other illusory figures, the displaced checkerboard figure has been little investigated. The reason for this is that the illusion is seen to be fully explained by irradiation". The paper sets out to prove that the illusion is in no way dependent on irradiation.

The pattern is studied with a special apparatus to quantify the strength of the illusion. The arrangement[10] allowed a variation of the brightness (and color) of the figure[11] which was cut out of a black[12] disk serving as the ground. Among other parameters, the colors and the brightness[13] were varied (mostly only of the figure).

[8] loc. cit., p. 90.

[9] In: Meinong *Untersuchungen zur Gegenstandstheorie und Psychologie* 1904.

[10] p. 451.

[11] Also separated for squares and main lines.

[12] In the experiments of table 3, violet.

[13] With table 2, p. 455, I do not learn with sufficient certainty from the text whether the variation of strong and weak lighting counts only for the figure or also for the black ground.

The figure consists merely of *one* vertical row (not as with Lehmann, who used two vertical rows). The strength of the illusion was measured through the adjustment of the position of a nearby white thread.

Here are the important results of the test series:
(a) If one compares the strength of the illusion as obtained in various experiments in which the figure is presented in various grades of grey of decreasing brightness, one finds that the illusion strength "*does not decrease with decreasing brightness difference between ground and figure*, as should the case be in the irradiation hypothesis, but increases".[14]

(b) In the authors' opinion, the irradiation hypothesis predicts that the illusion should fail to appear when one leaves out the main line, that is, more exactly, if one leaves a gap[15] between the left and right squares in the place of the continuous equally colored main line. This special case is therefore also investigated quantitatively and "here the illusion increases considerably, instead of, as predicted by the irradiation hypothesis, being reduced to nothing".

[(c)] Benussi – Liel also tested figures of different colors. Again the results show that "with a brightness decrease of the figure vis-à-vis the dark ground the illusion increases".[16]

Their tests reveal a lot of other evidence against the irradiation explanation that proves at least that irradiation alone cannot be the decisive factor controlling the illusion and its strength.

(d) Finally, as reported in the tabulated results, in experiments with different colors of the figure always on a constant violet ground, the strength of the illusion varies depending on whether the figure is *as bright as the ground* (the figure was either red or yellow), darker than the ground (black), or lighter than the ground (white).

In the last two cases (black and white) it is shown, contrary to the irradiation hypothesis, that the magnitude of the illusion is less than in the first case. When the figure, either red or yellow, is as bright as the ground, not only is the illusion seen, but it is stronger than in the other cases.

The authors come to the conclusion that the illusion with the checkerboard figure is not brought about through irradiation, and they try to explain it in the sense of a production hypothesis[17]. Variation of the expectation (the familiar S-, G-, and A-reactions[18]) shows a strong effect upon the subjective Gestalt conception.

For an explanation of the "increase of the illusion with the lessening of brightness difference between figure and ground[19]", the relationship of the displaced checkerboard figure with the Zöllner pattern is cited. "The smaller the brightness difference, the more the Z-Gestalt[20] obtrudes[21]." Owing to the decrease of brightness difference

[14] p. 453.

[15] p. 451.

[16] If one compares the curves of Benussi – Liel within row *a* (strong lighting) and within row *b* (weak lighting) it is clearly the case, but if one compares the respective, to each other related, experiments of *a* and *b*, then the case is not so definite: with a reduction of brightness the illusion increase does not happen everywhere, and there is often a weakening of the illusion.

[17] According to the authors the illusory moment lies "in the production of a presentation of a form given essentially through the crossing of lines", p. 465.

[18] In the G-reaction, the adjustment is made while the subject is asked to regard (for comparison) the contour of the presented figure as a Gestalt. In the A-reaction, the subject must attempt to see the contour of the figure as an independent and isolated object. For the S-reaction, the subject is not required to structure the understanding of the figure in any predetermined manner (p. 310).

[19] p. 464.

[20] Appearing like the Zöllner figure.

[21] p. 468.

between figure and ground, "the contours of the squares blur more and more, and the pure Gestalt of the Zöllner figure emerges more clearly by itself. These conditions are most completely filled with figures which are equally bright as the ground".[22,23]

Since the magnitude of the Zöllner illusion is markedly greater than that of the checkerboard figure, the strength of the illusion must increase with the decrease of brightness difference between figure and ground, and reach a maximum where this difference equals zero (p. 468).

§3. Thus the experimental results of Benussi – Liel stand in contradiction to those of Lehmann. Whereas Lehmann had found that with equal brightness of figure and ground the illusions (Münsterberg, Zöllner, Poggendorff) disappear, Benussi – Liel find that with the Münsterberg figure the illusion increases as one approaches and attains equal brightness.

Benussi – Liel themselves attribute the discrepancy between Lehmann's results and their own to the dependence of the illusion on various subjectively produced Gestalt concepts. The results of Lehmann which are in conflict with theirs may be explained from the Gestalt ambiguity of the more complicated figures he used.[24]

In his paper "Laws of inadequate Gestalt conception"[25] Benussi argues that "the assertion of Lehmann that the illusion of the displaced checkerboard figure is due to irradiation could draw its apparent justification only from the use of an *inadmissible experimental method*".[26] Essentially Benussi means here that whereas Lehmann had used two parallel vertical columns of the checkerboard figure, Benussi – Liel used only one, next to which was placed merely a white line. It is critical that with Lehmann's figure the space between the two rows is seen as a figure, in which case the illusion would be diminished in strength.

Doubtless Benussi – Liel and Benussi have shown that other factors than irradiation play an essential role—and those lie in the direction of Gestalt perception. Based on the Benussi – Liel[27] results, it is clear that the irradiation explanation is insufficient. But surely it is only Lehmann's assertion that the illusion rests *exclusively* on irradiation which is rejected. The outcome is not so straightforward if one allows that irradiation is a strong contributing factor next to which other factors may play a role.

Benussi – Liel are of the opinion that on the basis of their results the irradiation explanation can be rejected as incorrect.[28] However, in our opinion, the experiments of Benussi – Liel which speak against the chromoscope results of Lehmann have not conclusively refuted the power of proof of his experiments.

Recently, Hoffman[29] reported the irradiation proof of Lehmann without mentioning the contradictory results of Benussi – Liel. Evidently, the work of Benussi – Liel has not had much impact in the face of the chromoscope results of Lehmann.

Granted, Tables 1 and 2 of Benussi – Liel deal with the *decrease* of brightness difference between figure and ground, *but not with the decisive case (Lehmann's) of equal brightness.*

[22] p. 465.

[23] Parallel statements from Benussi are found in his work "Zur Psychologie des Gestalterfassens" (in Meinong, loc. cit., 1904, p. 303ff) about experiments with the Müller-Lyer arrangement. Also here (p. 318) the strength of the illusion changes among other things "inversely to the brightness difference between figure and ground" (we disregard here experiments with figures of different brightnesses); the same applies also to the relation of the main lines to the ground.

[24] Benussi – Liel, loc. cit., p. 457.

[25] *Arch. f. d. ges. Psych.* **32** issues 3 and 4, p. 415.

[26] Compare also statement by Benussi in his report on Lehmann's work (*Zeitschr. f. Psych.* **41** 201 – 203).

[27] p. 457.

[28] p. 455.

[29] F. B. Hofmann, in: *Tigerstedts Handbuch der physiol. Arbeitsmethoden, Raumsinn des Auges,* Leipzig, 1910, p. 132.

Benussi – Liel's results deal only with the increase of the strength of the illusion with *decreasing brightness of the figure* (on a black ground). It could well be that a brightness decrease of the figure enhances the illusion, whereas with both figure and ground of equal, medium brightness, which Lehmann examined in his chromoscope, the illusion became virtually nil. Also the individual comparison of strong and weak lighting (their table 2) yields no definite result of a decrease of the strength of the illusion. In their table 3, where they report illusion strengths for *equal brightness* of figure and ground, the ground is a constantly dark violet. There is no investigation of medium brightnesses. Moreover, the critical zone is not examined by varying the brightness of one of the two colors, as in Lehmann's experiment, nor is a comparison made of the strength of the illusion with the same color at equal and different brightnesses. They only report on the effect of red and yellow figures, set to equal brightness with the ground, compared with the effect for white and black figures.

Although the results of Benussi – Liel lie in direct contradiction to those of Lehmann, they are not really directly comparable. One could attribute the conflicting results of Benussi – Liel to additional special factors. The direct, simpler and conclusive test with respect to the question of illusion strength at equal brightness still seems to be provided by the Lehmann experiment.

Chapter II

§1. We re-examined the Lehmann experiment—a test of illusion figures with different colors of figure and ground under conditions of equiluminance—in a number of ways.

(a) For example, we cut illusion figures (Zöllner, Poggendorff, checkerboard, etc.) out of a large piece of green cardboard. The cardboard was placed vertically some distance in front of a large piece of red cardboard so that one saw the illusion figure as red on a green field. Each of the cardboards was lit by a lamp whose light was occluded for the other cardboard (diagram in figure 2). The intensity of the light could be varied for either cardboard in a simple way. In some experiments the variation was accomplished by moving the lamp (varying the distance from the illuminated cardboard), in others through changing the resistance of a rheostat, in others through grey filters, and in the rest by tilting the rear cardboard at an angle to its light source. We also varied color and brightness by using uncolored cardboards (white or grey) illuminated through color filters as needed.[30] Color, brightness, and figures were varied in many different ways.

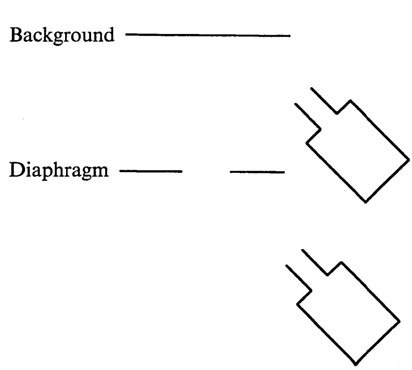

Figure 2.

[30] In some experimental trials we used a fine-adjustment device (from Hering – Rupp) with which the illumination intensity can be varied by turning a reflecting screen.

(b) In other experiments, full figures were hung from the ceiling on thin (and for the observer invisible) hairs, parallel to a wall and, for example, 30 cm in front of it. One projection lamp lit the wall, while another lit the figure (so that one lamp illuminated only the wall, the other only the figure). Again we used sometimes colored paper for the figure and the ground, and sometimes colored filters in the optical path of the lamps. The light intensity was varied through grey filters or through resistance.

In each of these arrangements we produced equal brightness for different colors and compared the phenomena with those at different brightnesses. Especially important to us was observing the entire time course of the change, for example when one slowly and continuously lightens the initially darker ground for a figure of constant and medium brightness until the region of equal brightness is reached, and then one goes further until the ground is clearly brighter than the figure. And, correspondingly, keeping a constant ground brightness and observing the effect of a variation of figure brightness.

If the experiment is to be pure, it is understandably necessary to ensure that no brightness differences should appear on the cut edges of the cardboard. Otherwise, with variations of the brightness of the surface, the contours or parts thereof would stand out with a differing brightness. This is easily achieved in practice with the use of thin (opaque) cardboard. Also any visible grain of the paper could corrupt the experiment.

§2. What was there to expect?

According to Lehmann's description, it was to be expected that the illusion would disappear with equal brightness. For example, that with the staggered checkerboard (figure 1) the vertical lines would become straight and parallel, and that corresponding effects would be seen with the other illusion figures.

However, according to Benussi–Liel, the checkerboard illusion increases at equal brightness. That is, the apparent inclination of the verticals becomes stronger (whereby the figure somewhat blurs and becomes similar to the Zöllner figure). On the other hand, to the extent that a different Gestalt percept is subjectively realized, for example, say, the area between the two rows of the checkerboard pattern stands out as a figure, the illusion might become weaker.

In almost all cases[31] the results of our experiments confirmed Lehmann's findings: the illusion disappeared at equal brightness. But how did the figures appear in the critical zone?!

§3. According to the descriptions by Lehmann and Benussi–Liel, one can generally assume that eliminating the brightness difference only affects the illusion strength, that is the vertical is seen more or less tilted. In short, one largely expects a figure of the same kind as one sees it in a normal experiment with brightness difference, only with the position of the verticals somewhat changed (and somewhat diffuse). However, our experiment shows in an exaggerated and surprising way that the situation is in no way sufficiently characterized in this manner and that in the critical zone it is what is optically given that changes most strongly. It is not the case that the illusion merely disappears, that one sees the figure approximately as it is with a brightness difference (and only in the sense of another figure–ground organization according to Benussi–Liel) with or without the geometrical-optical illusion. In fact, more extensive phenomenal changes take place, different in type and strength.

1. (a) In the critical zone it often happens that everything generally becomes diffuse—there is no figure on the ground, but everything flows into each other. There is only ground present, in a very strange, flowing and also somewhat flickering way.

(b) Alternatively, the figure is there only as a diffuse region in the ground, without a figural form being recognizable.

[31] See, however, §10.

2. When (under slightly different circumstances) figures are perceived, then generally everything is soft, jellylike, colloidal. The figure does not stand out from the ground. It is not only there with blurred contours, but the whole of it is diffuse and ill-defined. *Drastic figural changes occur.* The figure is often totally unrecognizable. Under many circumstances, certain parts are absent (wholly submerged); very often the figure changes its shape in a very characteristic way or follows another course in its contour. It often happens that parts which, in the normal figure, belong together now 'have nothing to do with each other', etc.

3. Still other phenomenal changes come into consideration. The 'manner of appearance' changes itself. The character of the space (as in 1b above) suffers most; distances in depth lose their magnitude, become fully indeterminate, indeed vanish. The object character is affected, often becoming completely lost, and the figures appear incorporeal, 'ghostly' in a strange and, to our usual daily visual world, very foreign way. (Also in respect to the character of the 'personal experience of objects' the situation changes frequently; the 'world' is here often no longer characterized through the experience of distal objects—what is seen is less separated from the observer.)

There are in psychology only a few phenomenal changes of so drastic a nature. Through the above hints, the reader does not receive a clear picture of how astonishing they look; but everyone can obtain a vivid image in a technically very simple way if one cuts out from a strongly colored (for example red) thin opaque cardboard a plane figure (for example, a star), and some distance behind it erects a differently colored (for example, green) cardboard.[32] Each of the two cardboards is lit separately by a lamp from one side. One views this from a certain distance while an assistant varies the distance of one of the lamps from the screen so as to vary the brightness difference between the two papers through equal brightness and then to the opposite brightness difference.

The phenomenal change happens in a relatively broad zone, and it is naturally instructive to follow the *transition* which occurs in the critical zone.

Whether the phenomenal change is stronger or weaker depends on the circumstances. But, ignoring the most extreme distortions, *there remains the question whether, in the presence of strong phenomenal change, there is more or less illusion, that is tilt, at equiluminance.* Against these effects of an entirely different magnitude this necessarily appears as a secondary problem; the primary problem is in the foreground: How do figures appear when they are different in color but equal in brightness to the ground? In which way do colors without a brightness difference contribute to the perceived existence of figures, bodies, things, and the structure of the visual environment?

§4. For impartial psychological analysis, it is at first glance highly paradoxical that with strong (and strongest) color differences figures are seen so poorly.

One thinks thus: a figure will, of course, stand out less clearly from its ground the less the optical qualities of coloring and brightness of figure and ground are different; if both, for example, are in slightly different grey or narrowly different red, then the figure will stand out less and unclearly. It will become diffuse more easily. But here we deal often with the strongest red and green, or red and blue—colors that are most noticeably different from each other—and still the blurring is extreme.

With equally bright saturated colors, for example contrast colors, a flickering, glowing, blurring takes place, indeed kind of a glare. Visual acuity or resolution is poorer for equiluminous colors than it is when there are brightness differences. But one is indeed most strongly surprised when one sees what a blurring, what figural changes, what changes in character of the visual environment occur in the 'critical zone'.

[32] Of course, care is necessary: the arrangement must be pure in the sense of the remarks at the end of §2.

These changes are quite different in magnitude from what one would expect with 'merely poor visual acuity' (compare Chapter IV, §1).

[Considering acuity,] the following point is important: If a figure appears blurred under some circumstances (uncorrected eye, fog, smoked glass, distance, etc.), then two types of effects can be distinguished. There are cases where—even though blurred, uncertain, or 'veiled'—the figure is, however, there. With normal clearer appearance, it would be seen only more sharply contoured and more clearly seen. But there are also cases where the blurred figure is also figurally different, as if it were another figure than what is normally seen. Many such examples are known from visual acuity experiments. Such a 'change in character' is often present in great strength in our figures at equiluminance.

Moreover, if one can extrapolate from a vividly experienced percept in the critical zone to imagine our visual world without any brightness differences, if one imagines how it would be in our world if there were strong color differences but no brightness differences, so one would feel that our world would differ in its basic character. Aside from very few special circumstances (observation from a close distance, where visual integration suffers), it would be a *world without firm objects, without solidity, without figures clearly separated from their ground, from each other*, even from us. (This is similar to how it looks when one dives under water and gazes in a flowing, ghostly, close medium in which one is immersed.) It would be tempting, if it were easier to accomplish technically, to live exclusively in such a world for some hours, even days. Such an experiment would probably be very tiring and trying; already such viewing for only a few minutes of a wall with figures in front of it is extremely trying, and not just visually.

§5. So far, we have spoken briefly of equiluminance; in fact it is the case that the 'critical zone'—the zone in which the described phenomenal effect exists—lies in the vicinity of equiluminance and this could usually be established by various methods; this zone has a certain width (see Chapter III, §5) and emerges abruptly when one varies the brightness of one of the two colors gradually or in steps; the phenomenal change does not grow slowly and constantly with a reduction of the brightness difference: one can vary the *brightness difference* within a wide range *without any noticeable change* for the observer; then suddenly—close to equiluminance—the change happens, growing at a high rate.

(This is not without bearing, for example, in respect to the experiments by Benussi – Liel, tables 1 – 3, as these authors assumed that the changes in the strength of the illusion would be evident when comparing cases deviating by different amounts from equiluminance.)

§6. The degree of phenomenal change depends on various circumstances: the size and the form of the figures, the intensity, saturation, and type of color composition, the distance, and the manner of viewing (in Chapters III and IV we report on special pertinent findings). In summary, one can say that the phenomenal changes in the critical zone[33] are stronger with small, narrow figures than with large, broad figures; stronger with complicated figures than with simple ones having smooth running contours; stronger with extreme than with medium light intensities; stronger with low than with high saturation of colors. We report in Chapter III, §3 on the role of the composition of colors. Tiring of the eyes, staring, and so forth strengthens the effect; decreasing of the distance of the observer from the object lessens it. Observation from closer distances yields sharp contours while at the same time strongly affecting the ability to perceive an object at one glance.

[33] Which for the most part is to be expected from the analogy to the usual visual acuity findings.

§7. If one notices the changes in the critical zone, then there is the question why Lehmann and Benussi – Liel reported none of this in their descriptions (apart from a remark by Benussi about a blurred appearance and thus a tendency to a Z[öllner] figure).

The answer seems for us to be that Lehmann focused on the question of the magnitude of the illusion, the inclination of the vertical, and was not interested in other phenomenal changes in connection with his work, and that he worked under special circumstances which did not produce a strong blurring, etc. Lehmann's and Benussi – Liel's observations do not let us know clearly enough under what circumstances (distance of observer, etc.) they experimented. Benussi – Liel furthermore reported few observations within the critical zone; they predominately examined various large brightness differences. However, with small brightness difference one is, as we found out, easily put outside of the critical zone, because of the abruptness of the transition to the critical zone.

§8. With the aforementioned situation, we did not restrict ourselves to just observing the illusion figures of Lehmann and Benussi – Liel, but we also investigated many others. Next we want to report on experiments with *simple disk figures.* As an example we give the report of a subject who participated in experiments in which a specially lit red disk (of about 8 cm diameter) hung on an invisible thread approximately 30 cm in front of a green-lit wall (or also several different figures, some larger and hung at rather great distances from each other). The subject observed from a distance of 4 or 5 meters. The brightness was varied, first with regard to the disk, which for example was at the outset darker than the ground and was made lighter in steps until it was brighter than the ground or the other way round; or, second, keeping the disk brightness constant and varying the illumination of the ground.

Subject W: "In contrast to how the disk usually appears in front of the wall, when it is lighter or darker than the ground, there exists a zone, approximately in the region of subjective equal brightness of both, with a very different percept: With the transition into this zone from a noticeable brightness difference, suddenly everything appears to flow softly into each other; sometimes the ground flows completely over the small disk. The circle is not there! (even *without* eye movements). If one sees it anyhow—which happens sometimes in alternation—nevertheless one is not at all, aside from this strange flowing together and blurring, viewing something structurally stable. In a strange glowing and swimming of the entire field, everything flows together. It is not at all that a 'figure', much less a 'thing', emerges from the ground. If one sees the disk better, then the contours are unclear, but also somewhat different than when one has a white disk on a black ground, whose periphery changes objectively and gradually by increasing darker shades towards the ground, but *all* is so strangely soft and flowing into each other. The depth differences have almost entirely disappeared. In one region of the ground—that of the circle—there is a flooding or diffusion suggestive of something red and green flowing together spatially and really everything in the region is colloidal with a soft halo, and it is a broad zone until something emerges from the ground with greater changes (produced with brightness differences of a stronger type), forms itself, separates itself out, and becomes the 'thing' and then gets again sharp contours, becomes hard and fast and stands out clearly in depth in front of the ground."

About the 'blurring' with simple black-and-white coloring of figure and ground[34] the subject says: "Here there is also a blurring in the critical region, in a narrower zone, where there is with equal brightness a complete homogeneity; phenomenally

[34] In these experiments the figure was, for example, a dark grey in a medium-grey field; the figure was then brightened in steps or gradually until it was equally bright as the field, so that a homogeneous field was there, then brightened further until it became much brighter than the field.

there is something different here: the figure 'disappears' here in that it fully merges into ground (often with a jerk); but everything is quieter, firmer, there is less there of the unusual in the other sense; in a very small range, quite close to equal brightness, ie near homogeneity, it is similar as with color experiments. There is also *some* diffusion, a 'softening of the contours' and a vague flooding, swimming in the contour region, changes of form, etc."

From the report of subject K (grey crescent with a hole, background red): "It closes in the critical region over the disk, like stretched rubber membranes. The disk drowns".

Wall with a circular disk in front of it, as above red on green, circle ($r = 2$ cm): "When I move further away from the circle (7 m) it appears extremely unreal. The wall collapses over it; often there is no trace of the circle."

Circle ($r = 4$ cm), distance 2 m: "The entire thing is already strangely unreal. The circle is rather poor, cloudy, often as if there were a cloud around the circle which hangs in space ... when I get further back it appears extremely unreal."

Subject L especially notes: "The circle becomes very restless, it moves to and fro in space ... the entire view has something tormented." Subjects often reported a characteristic 'dazzle' in the critical zone (but that disappeared when one introduced a brightness difference at higher levels of illumination).

These examples taken from records are typical also for the reports of the other subjects.

§9. We now describe some typical *figural changes with less simple figures* (in which we ignore complete or almost complete diffusion and the manifold changes of 'appearance' which often occur).

Some of the experiments were conducted so that the subjects would be able to describe the changes of what is seen as the brightness *difference*[35] moved into the critical zone (and then away from it); this also allowed a *comparison* of the presentation in the critical zone with presentations having a brightness difference. However, we also performed some of the experiments using a *completely objective* procedure. That is, the subject was first presented with the object within the critical stage and described it without knowing what was objectively presented or how the figure looked with a normal presentation. If one then subsequently changes the brightness of figure or ground, so that now a brightness difference exists—or one permits the subject to approach the figure—then the subject is often greatly surprised at how *different* the figure becomes.

Let us mention that we *also* frequently performed these experiments *with psychologically naive* subjects.

With reference to the remarks in §6 above, the experimental results to be reported now have been obtained at the mean optimal conditions; the colors were as saturated as possible, the light intensity strong. In the experiments in which brightness was varied, the distance between the subject and the object was 2 or 5 m. In the experiments in which the distance was varied, the subject approached the object from a great distance (about 20 m) in steps up to about 30 cm.

From experiments on a great number of different figures with many variations, the following are chosen as typically characteristic:

1. A disk with a toothed edge (figure 3, for example 3 cm wide) (gear contour) appears in the critical zone as a blurred *round disk*; the teeth have almost disappeared. If the object has slightly bigger teeth (figure 4, for example 3 cm wide), the points of the teeth appear rounded off. There are no 'tips' to the points; often this figure also appears as just a blurred *round disk*. If the object has very large teeth, these often do not disappear all together. They come and go and the whole is very restless and flickering.

[35] Similar to the change in distance from which the subject observed.

2. Correspondingly, in the critical zone a rectangle with a jagged bottom edge often appears not only with an indistinct, rounded-off, wavy bottom edge (as depicted in figure 5) but also as an *oblong area* whose lower part is very restless and blurred without any sense of the jaggedness.

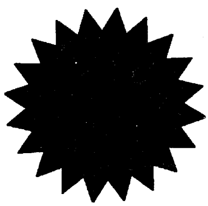

Figure 3.

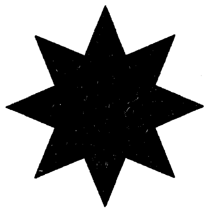

Figure 4.

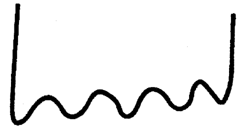

Figure 5.

3. A rectangle with a steep, jagged line cutting up and down across its surface yielded in the critical stage either a rounding off of the teeth in the sense of figure 5[36] or even a vertically striped surface (indicated in figure 6) of great uncertainty (if the entire surface did not blur to a restless filled oblong).

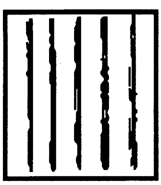

Figure 6.

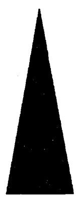

Figure 7.

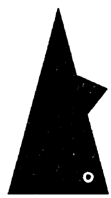

Figure 8.

Figure 9.

Figure 10.

4. A pointed triangle, figure 7, appeared with a rounded off point (and very restless; the vertical position of the figure seemed to sway to some subjects); if a very small triangle was exposed, it often appeared as a blurred oblong *line.*

5. With figure 8[37] in the critical zone there was a triangle (quite blurred), without a trace of the 'nose' on the right. Under some circumstances, but only with great uncertainty, subjects had the impression that "something was going on", but even then no clear formulation could be given. Only when one presented a strong brightness difference or allowed the subject to move closer did he/she see to his/her astonishment that on the right of the triangle there was a point.

And it was the same if one viewed a circle or a square that was somewhat irregularly formed, or to which such figural disturbances were added.

6. Small circles in the arrangement shown in figure 9 gave a picture in which the pairs of neighboring circles figurally blurred; in the extreme they were seen as represented in figure 10 as blurred oblique ovals (often even 'lines'). At intermediate stages, the oval area more or less resembled a dual distribution with regard to its shape about its midpoint.

We have tested whether in the critical zone there is (with the complete blurring of the pair of small points into an oval, but also with partial blurring) a subjective change of the Gestalt percept (compare Wertheimer, "Untersuchungen zur Lehre von der Gestalt. II", *Psychol. Forschung* 4). We find that for the most part a subjective production of the alternative Gestalt versions (longer oblique pairs from upper left above to lower

[36] For all such shapes the remarks in §6 concerning size and width relations are highly important; a very flat oblong with flat teeth dissolves into a *horizontal* bar.

[37] Compare Chapter IV, §1, 5a.

right below as in the experiment of Wertheimer, a/bc/dc, p. 304) was *not possible.* There are compelling circumstances for the short oblique form; the subject saw them without any possibility of another percept in the form of long obliques. Also when the small circles did not fuse completely into the total composite figure, no effort helped to produce subjectively the required alternative. If one tried, under circumstances where the individual circles fused *only slightly* with each other, with all effort to see group bc and 'clamp' it onto a point (for example b), the other point disappeared—dissolved into the ground—and appeared again only when one permitted a small variation from the 'natural' version (or when the natural figure returned against the will of the subject).

7. In a similar way, figure 11 resulted in a percept of a more or less blurred or even isolated emerging *diagonal* from the lower left towards the upper right in the group, often with the disappearance of one or both of the remaining adjacent rectangles (often also with a separation in depth).

8. Arrangements like figures 12, 13, and 14 were often seen as continuous stripes, frequently with only a washed-out region or an uncertainty in the middle. The stripe was thus 'completed', with the upper and lower portions flowing into each other. And only when the subject came closer to the object, up to a short distance, which brought what was seen out of the critical zone, did the subject see that something was 'wrong' in the middle, and only with yet closer approach (for example 50 cm) or after producing a noticeable brightness difference did the subjects see to their astonishment how different the middle of the figural arrangement was 'objectively' than they had supposed.

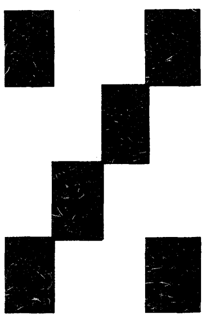

Figure 11.

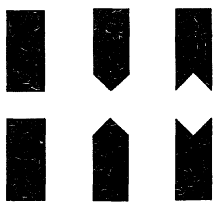

Figure 12. **13.** **14.**

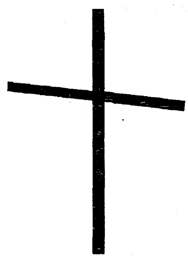

Figure 15.

The same was true when one displayed a cross sign, etc. with gaps (see Chapter IV, §1, point 5e, for example figure 28).

9. When one displayed a standing cross on which the horizontal line was somewhat obliquely inclined, see figure 15, the figure often appeared first as a somewhat washed-out regular cross with a horizontal left – right line.

All of these figural changes occurred not only with short exposure times, but were similarly observed with steady, longer observation—and it is the same, in principle, with fixed gaze or free viewing. Indeed, very long observation (more than 15 s), especially combined with staring, *amplified* the effect yielding complete blurring in the specified directions.

§10. We do not want to discuss here yet the extent to which these figural changes can be explained by *diminished 'visual acuity'* (compare Chapter IV). We want to see next which figural changes occur in *illusion figures*, as Lehmann used them: the Zöllner figure, the displaced checkerboard figure, and the Müller-Lyer figures.

We avoid again the cases of complete diffusion blurring and complete figural uncertainty, and describe experimental conditions where, in spite of the blurring of contours, etc., distinct 'figures' are to be seen and we give typical cases.

1. The collateral lines of the Zöllner figure (the short obliques[38]) are totally blurred and *disappear* into a restless ground. There are edge-blurred verticals present. Slightly indefinite irregularities to the left and right of the verticals are suggested, sometimes in the form of 'lumps' of flowing indefinite form[39] ("it looks quite indistinct", like a "pipe cleaner"). Sometimes the collateral lines are next to the verticals as transverse areas[40] (as in figure 16), but often in indefinite positions, more often lying horizontal to each other than to some extent oblique.[41] And *corresponding to these figural changes* there is no 'illusion', that is one sees the verticals extending vertically.

2.(a) Similar things were observed also with the *checkerboard* figure: aside from the blurred, slightly lumpy, irregular shape of the vertical, the pairs of squares merged into a sort of indistinct rectangles which were oriented more horizontally than obliquely; and this often with separation of the form from the vertical (for example "besides the rectangles there is a pole; the rectangle extends smoothly over the vertical") (as in figure 17). Also here consistent with the figural change, *no* 'illusion' was seen in the sense of obliqueness, the verticals appearing vertical and parallel.

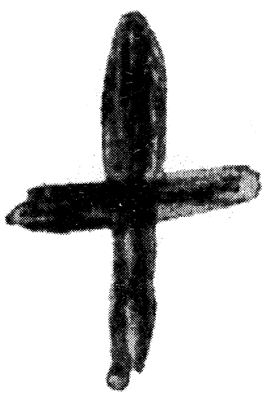

Figure 16.

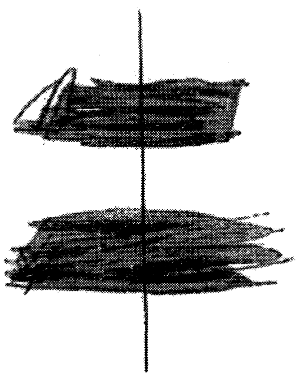

Figure 17.

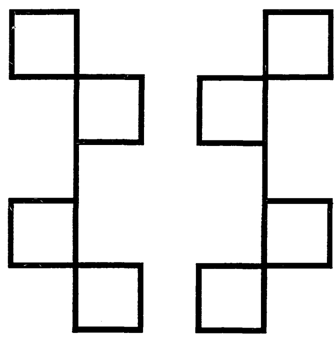

Figure 18.

(b) These findings relate to the usual checkerboard figures, in which the vertical position of the pairs of squares differs only little; we also experimented with arrangements in which the squares were vertically *more* displaced (in extreme form in the diagram in figure 18)—this resulted in little (or no) illusion under normal conditions. Here, in the critical zone, the pairs of squares fused in the *oblique direction*, and the 'illusion', the oblique appearance of the vertical, *became much more pronounced*, corresponding to the figural changes.

3. The (half) Müller-Lyer figure in the form of figure 19 blurred in the critical zone in that the angle became bulky and figurally uncertain (figure 20) even to the extent of appearing approximately with tips normal to the horizontal figure (figure 21).

[38] Short, *narrow* obliques.

[39] Especially with larger stronger obliques.

[40] Separated in Gestalt form and often in space from the vertical.

[41] (From a typical report:) "When the illumination of the figure is lowered the collateral lines disappear first. One sees for awhile the collateral lines which one fixated, but the collateral lines no longer belong together. The main lines are in front; at the back, somewhat lost in space, floats a dim thin stripe. It has nothing to do with the main lines."

Correspondingly, we observed a *weakening* of the illusion; the line ceased to be perceived longer in the sense of the Müller-Lyer illusion.

The other half of the Müller-Lyer figure (figure 22) blurred in the critical zone into something like a rhombus (figure 23). Here there was no weakening of the illusion, but under certain circumstances a marked increase of the illusion: the horizontal appeared even *shorter* than with normal viewing.[42]

There is also a zone of blurring with figural changes of the described type when one operates in a neutral or monochrome field with very small brightness differences. If one uses the same paper with grey screen for figure and ground, so that with completely identical brightness there is a homogeneous field, and very small brightness differences are produced through a somewhat stronger or weaker illumination of the figure or the ground, then one finds in a small range an analogous 'critical zone' as in the tests with heterochromatic stimuli. We tested some of the illusion patterns using such an arrangement, and found that also here the strength of the 'illusion' is affected in a similar manner and in special cases the 'illusion' disappears.

Figure 19.

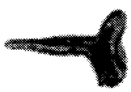

Figure 20.

Figure 21.

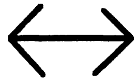

Figure 22.

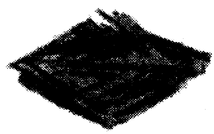

Figure 23.

§11. We see therefore that *whether an existing illusion appears stronger or weaker or is reduced to nothing in the critical zone largely depends on which figural changes occur in the critical zone.*

The type of the figural changes depends very much on the *chosen* form of the illusion figure. If, for example, with the Müller-Lyer figure in figure 22, we use more pointed angles, and longer arrowheads there is a stronger tendency to see the figure as a rhombus. However, with a greater angle for the arrowheads, a longer horizontal, and short arrowheads, the figure appears as a bar with 2 vertical stripes, similar to figure 21.

The same is the case, as mentioned above, when one changes the position of the pairs of squares in the checkerboard pattern (in which it also depends on their size): if the lower square is displaced just a little downwards, this will lead more easily to a blurring yielding approximately horizontal bars; if it is displaced downwards more, this will lead more easily to a figural change producing an oblique bar (in the sense of the Zöllner illusion).

Besides such objective conditions, subjective ones also come into question: with different subjects such a figural change appears in different strength, and it thus happens that with an identical experimental arrangement—especially when additional, arbitrary, subjective percepts are added, here and there different values for the strength of illusion will result.

Given the range of figural change of the object, it is to be expected that the 'illusion' has varying strengths; the outcome as regards the strength of the illusion agrees in the described cases with what *would be expected with a corresponding objective variation of the figure.*

[42] Compare the correspondence of these experimental results with those of Benussi in *Zur Psychologie des Gestalterfassens*, p. 318 ff. For the b figure [figure 22 here]: "the strength of the illusion changed inversely to the brightness difference between figure and ground." For the a figure [figure 19 here], Benussi reports the following: "With a decreasing brightness difference between figure and ground the strength of the illusion of the a figure decreases."

The statement of Lehmann, that the experiment with heterochromatic equal brightness proves that the illusion itself is based on unilateral irradiation, is according to our results no longer conclusive.

If it were so that in the critical zone the figure *as a whole was seen figurally* as under normal conditions, only differing in that the illusion (the apparent *oblique* position of the verticals) disappeared, specifically, because the one-sided *reduction in size of the dark* squares brought on by irradiation no longer occurs, then Lehmann's proposition would be conclusive. But we see that in the critical zone figures are seen to a large degree *as changed* and it is no wonder that with figures so different, the strength of the illusion is also different. Indeed, under certain circumstances an illusion of an apparent inclination etc. is no longer present. As well, we have seen that under certain conditions the illusion can also *increase* through the figural changes occurring in the critical zone.

The figural change is therefore decisive for the fate of the strength of the illusion. If one compares the figure in the critical zone with that perceived in normal conditions, then the difference *is not* mainly in the sense Lehmann suggested. He claimed that the normal figure shows a one-sided shrinking of the dark squares caused by irradiation whereas the critical figure at equiluminance does not; the critical figure thus being more *veridical.* We find that the figure changes—and does so to a considerable degree—with respect to the object.

Again there is the question why Lehmann and Benussi–Liel did not report the strong phenomenal changes of the figure (aside from Benussi–Liel who spoke of a "tendency toward a Zöllner figure" with the somewhat blurred checkerboard figure. We refer to the remarks in §6).

In all cases of a distinct change of the strength of the illusion in the critical zone we found phenomenal changes of the figure which explained the change. Only in the cases where the figure was viewed very close up did it remain phenomenally unchanged and yet lose the illusion. But this is such a poor condition for *viewing* that, even with a large brightness difference, a weakening of the illusion is to be expected. If one views, for example, a large Zöllner figure from a close range so that only one part is clear, say two neighboring collateral lines with the attached verticals, then the illusion here is also weaker and often absent.

So it was in all the cases which we investigated; we found a similar result (that the strength of the illusion was [never] considerably changed *without* a figural change, apart from the circumstances of close observation), so far with no variation of the stimulus conditions.

Chapter III

One can seek an explanation of the described phenomenal changes in the critical zone by using different approaches. We performed pilot studies of different types; in the following paragraphs we report on parametric experiments, which refer first of all to the visual acuity measurements known in the literature.

§1. It is known that the visual acuity for the border between two colored fields decreases when one equates the brightnesses (although from the available descriptions one could not have expected the dramatic accompanying phenomenal changes which we reported in the previous chapter).

In color photometry, one has used for a long time the fact that with equiluminous colors the contour between the colored surface easily blurs. In order to establish equiluminance in the photometers of Frauenhofer and Dove, for example, one color is varied until the border between both color surfaces is least distinct. Frauenhofer, Dove, Lummer, and Brodhun consider two differently colored surfaces as equally bright when the borders are hardest to recognize. We consider here only the existing investigations[43] where *the color surfaces bordered on each other*, not where a specially inserted, e.g. black, border line was present.[44]

Also here we are not—for the time being—concerned with the problems of the determination of exact *equiluminance* of colors; we are interested in the phenomenal changes in the critical *zone*. This lies, as all our experiments have shown, in the *region* of equiluminance, and we are satisfied with this approximate location.

From older experiments we single out here:

Brücke[45] in his essay "About some consequences of the Young–Helmholtz theory" asked the question "up to which degree of *spatial differentiation*, up to which degree of *visual acuity* can we be led by colors alone, *without the help of light and dark*?"

Brücke selected among color papers those which seemed to him subjectively equally bright and which remained equally bright even on viewing from various distances. From such equiluminous color pairs, for example red–green, he used the one color as ground and from the other he cut out small squares (each 1 cm^2) and glued them in two rows onto the first such that the diagonals of the squares were oriented quite randomly, sometimes vertical, sometimes horizontal, sometimes oblique. In the same manner, for comparison purposes, black squares of the same size were glued on a white ground. In this way he determined the *distance* at which the orientation *of the squares* on both adjacent figures was still *recognizable.*

He found that a difference in brightness facilitated the discrimination of details more than a difference in color. The distance from which the subject could just recognize the orientation of the black squares on a white ground was in each case greater than the distance from which the details of, say, red squares upon an equiluminous green ground could still be recognized. With colors one must come *closer.*[46] (Brücke attributes his result to the geometrical distribution of the cones on the retina; compare with Chapter IV, §1.)

W. von Lempicka[47] worked with glued striped disks of equal and different brightness; we report on the relevant experiments in §4 in comparison with our experimental results.

§2. Next we made the following *grating* experiments: Two squares were cut out in a thin, but opaque dark-grey sheet of cardboard, which was set vertically. The side of each of the squares was 1.5 cm and the horizontal distance between the squares was 5.5 cm. Parallel strips, 2 mm wide, were glued in place across the cut-out squares, spaced 2 mm apart. In the first experiments, the strips in the left square were red, those in the right square were dark grey like the cardboard. At a distance of about 20 cm behind the first cardboard, two surfaces were fixed in turning devices which by turning relative to the light source made the surface lighter or darker. A green surface was placed behind the left-hand striped cut-out and a white surface behind the right-hand dark-striped grating. If the subject stood a short distance in front of the diaphragm, then he saw the grating squares as vertically striped, in alternating stripes of the diaphragm and the color of the rear surface.

[43] Compare literature of R. Pauli "Die Sehschärfemethoden" *Zeitschr. f. Biol.* **58** 29—A. Kohlrausch "Über den Helligkeitsvergleich verschiedener Farben" and "Theoretisches und Praktisches zur heterochromen Photometrie" *Pflügers Arch. f. d. ges. Physiol.* **200** 210 and 216.

[44] Compare for example Pauli "Untersuchungen über die Helligkeit und den Beleuchtungswert farbiger und farbloser Lichter" *Zeitschr. f. Biol.* **60** 319. The frosted (ground) glass disk was "cut in two half-circle shaped pieces and cemented together again with darkened Canadian balsam. Through the separation line ..."

[45] *Sitzungsber. d. Akad. d. Wiss., Wien, Mathem.-naturw. Kl., III. Abt.,* **80** No 1–2, pp 18–73; **84** 425.

[46] Compare also the observations of Exner "Studien auf dem Gebiet des lokalisierten Sehens" *Pflügers Arch. f. d. ges. Physiol.* **73** 155.

[47] "Räumliche Farbenmischung auf der Netzhaut" *Zeitschr. f. Sinnesphysiol.* **50** 217 ff.

The room was lit with a bright lamp, which illuminated the grating diaphragm obliquely from above.

The green and the red of the colored grating were then set to equiluminance[48] by each subject viewing it from a *close* distance.

In the other grating, we adjusted the rear surface to a light grey so that the colorless square was filled with alternating dark and light grey stripes.

a) Observed from a distance of 8 m both squares appeared 'not resolvable'; one had to come closer to see the stripes, the brightness and color difference, or the sharp contours of the stripes respectively. As in the experiments of Brücke and W. von Lempicka, we first measured the critical distance, that is how close—starting from a distance of 8 m—the subject had to approach in order to clearly recognize the stripes of one or the other grating.

Among the various possibilities of instruction we chose that "of clear appearance, of clear distinction of color or brightness differences of the stripes"; the subject thus approached from a distance of 8 m in steps toward the test arrangement. We determined how close he had to advance so that he saw either the one grating clearly resolved as bright–dark striped, or the other as red–green striped. After some preliminary experiments, we chose here a less objective method: The subject was shown the color arrangement from close up before the start of measurements because this reduced the scatter of the results.

We compared first the 'resolution' for a grating of (narrow) red and green stripes with that for a similar grating of light and dark grey stripes. In this case, the pure phenomenal difference of red and green did not appear to be smaller than that of the selected light and dark grey.

Table 1 gives the results for the 6 subjects. The columns contain the mean values for about 5 measurements each (the scatter was very small); the first column shows the values for the red–green grating.

Table 1.

Subject	Red–green grating m	Light grey–dark grey grating m
Ar	2.6	4.6
De	2.0	5.0
Ja	2.7	4.0
Ka	2.9	5.1
Li	2.5	4.8
Wa	1.1	4.0

The simultaneous measurement we used proceeded so that the subject first saw both squares as unresolved from a great distance. When he/she approached nearer, *first the neutral light–dark grey grating was resolved and then on coming still closer, also the colored grating.*

The result corresponds on the whole to that of the aforementioned authors: The values obtained for the red–green grating are generally less than those for the neutral light–dark grey grating.

b) The light grey–dark grey brightness difference used here thus yielded better visual acuity ratios than the colored grating. We now asked ourselves what brightness

[48] Through rotation of the green rear surface.

difference must the two grey shades have in order for the visual acuity to be *the same* as for the equiluminous colored pair? To start with we confined ourselves to a qualitative judgement with regard to the phenomenal stripe difference.

For this purpose we added to the above-described experiments the following procedure: The subject approached the gratings from a distance of 8 m until he/she saw the red–green striping clearly in the colored grating (the grating could be *resolved*). The subject remained standing at this distance and we looked for that brightness difference of the neutral stripes in the other grating (through changing the brightness of the rear surface) at which also they could just be resolved. (First the neutral square was made equiluminous, homogeneous, by darkening the rear surface; then the rear surface was brightened until the subject saw[49] the light–dark striation with the same suprathreshold clarity as the colored pair next to it.)

The described procedure has many shortcomings; nonetheless it provides a direct comparison, and here we were only interested in establishing once the order of magnitude of an equivalent brightness difference.

Next we needed to establish the magnitude of the equivalent brightness difference. This was determined through the amount of the rotation, in number of degrees, from the position giving homogeneous brightness for the neutral grating; with our arrangement we obtained for the subjects in table 1 values of about 10° rotation. The *apparent brightness difference*, which with our illumination corresponded to a rotation of the order of 10° was *very small*, in any case *much* smaller than the *phenomenal* color difference for the other square. Two *greys differing very little* produced at a given distance the same resolution as two strongly differing but equiluminous colors.

A more exact objective determination of the difference was adjourned for later experiments, which must be properly carried out with spectral colors.

c) In special experiments we also tested the effect of gratings with equal colors and different brightnesses against neutral ones with the same brightness difference. We started from a brightness difference in a neutral grating (grey in the back, somewhat darker in front) and adjusted the colored grating (through change of the illumination) to equiluminance, on the one hand for the bars of the colored grating in front and the bars of the neutral grating, and then likewise equiluminance of the background of the colored grating and the background of the neutral grating.

Then we measured again how close the subject must come so that the neutral or the (now monochrome) colored grating could be resolved.

We used for the monochrome grating different colors (red, orange, green, blue) and measured in the medium brightness range. The critical distances in our series showed *no pronounced difference*.

An example is given in a table referring to an orange colored monochrome grating (the numbers here are the results of single tests of these subjects and give the critical distance in meters).

The table shows that the distances for the neutral and for the monochrome grating of equal brightness are the same. This result is, of course, tentative and valid only for the medium brightness levels we used. It could be that, with systematic variation of the brightness level, differences between the neutral and the monochrome gratings would come to light. In this case, differences would also be likely to arise between monochrome gratings of different colors, given that we keep the brightness differences equal within each grating and the overall brightness level the same (compare Chapter IV, §4).

[49] This was tested in experiments with special approaches: the adjustment was varied until both gratings were resolved at the same distance.

We operated here with a small brightness difference. If one compares the results for subjects De and Ja presented in tables 1 and 2, one finds that the subject must move somewhat closer to resolve the monochrome grating (table 2) than to resolve the equiluminous red–green (table 1). The very small brightness difference of the monochrome grating thus resulted in a slightly poorer resolution than did the differently colored equiluminous grating (table 1). The brightness difference was, in fact, here (table 2) considerably smaller than with the light grey–dark grey grating in table 1, as is shown by the substantially closer distances required to resolve the neutral gratings of table 2 vis-à-vis those of table 1.

Table 2.

Subject	Monochrome grating m	Neutral grating m
De	1.45	1.50
	1.50	1.52
	1.50	1.44
Fu	2.90	2.95
	2.95	2.90
	2.87	2.85
Ja	2.30	2.40
	2.40	2.45
	2.50	2.35

§3. The color pairs which we tentatively used in the experiments described above were in the first place contrast colors (red/green, blue/yellow). How is it with other color pairs? Is the contrast ratio crucial for the existence of the 'critical zone'?

We did in fact often use other color pairs besides the contrast colors and always found the critical zone with its characteristic qualities.

For a closer comparison we set up a grating experiment of the following type: The arrangement and instructions were the same as in the experiments in the preceding paragraph (except that in this experiment only *one* grating square was displayed at a time).[50] We produced four diaphragm gratings of the same form in the colors red, yellow, green, blue—in each case the most saturated of the Ostwald papers. Out of the same paper we produced background surfaces, so that we could use each of the diaphragm gratings with three differently colored rear surfaces. We obtained the following colored gratings:[51]

[50] Also the surround was not black, but over an area of 65 cm × 48 cm it was colored in one of the two grating colors.

[51] Unfortunately, for technical reasons we could not systematically measure for most subjects the gratings of all color pairs. If one compares the values for the same subject (A, D, Wa) obtained with the red–green grating of table 1 with the values obtained with the red–green and green–red gratings of table 3, one can see that the latter values are overall higher than the former; the grating in table 1 was shown against a black field, whereas the field of table 3 was in each case in one of the two grating colors; the difference thus suggests that the corresponding grating presented against a black field is somewhat harder to resolve than when the field is in one of the grating colors. This fact corresponds to the new findings about color thresholds with different surrounds. Compare Koffka *Die Grundlagen der psychischen Entwicklung* 1921, pp 162 and 266, pp 170 and 222 in the second edition (which also gives further literature).

Diaphragm grating	Background	Diaphragm grating	Background
red	yellow	green	red
red	green	green	yellow
red	blue	green	blue
yellow	red	blue	red
yellow	green	blue	yellow
yellow	blue	blue	green

All experiments were made with a constant (medium) brightness level. Starting from an equiluminous red–green grating, the illumination of the other gratings was adjusted until the subject perceived each time one color of the next grating as equiluminous with the red of the red–green etc., so that in the experiment all gratings were displayed at approximately the same brightness level.

For a more thorough study of the question, the experiments must, of course, be made much more detailed. For theoretical purposes, one would have to work with pure spectral colors; still, something can be inferred from our preliminary experiments despite the often very large scatter of results.

In table 3 we give the results; the values (in meters) show how close the subject had to approach in order to resolve the grating of a given color combination and to recognize the colors.

Table 3.

Subj.	B,g	G,b	B,y	Y,b	G,y	Y,g	Y,r	R,y	G,r	R,g	B,r	R,b
A		2.7		3.0	3.0	4.3	3.7	3.7	2.7	3.0		3.9
D		1.0		1.7	2.7	1.8	1.3		2.7			
G		2.0		3.0	2.2	2.6	2.5		2.8			
H		4.0		4.0	4.2	2.8	3.2	3.8	4.5	4.6	3.3	4.5
M	1.0	2.4	1.8	2.6	2.1	2.5	2.5	3.2	3.5	3.6	1.75	2.6
deS	1.9		1.95	2.7		2.3	6.0	5.4		7.0		5.6
V		2.7		4.0	3.9	4.0	3.7	4.0	4.0	3.6		3.6
W				2.4		1.4	2.0	2.8		2.8		3.8
R	5.0		5.0					5.2		5.0	5.8	7.0

The sequence of the experiments was random; but we have arranged the table in a *particular sequence* suggested by the analysis of the results.

With each color pair the color listed first is that of the grating bars (and the field) and the second is that of the grating interspaces.

The resolution distances for the individual subjects are quite different. For the purpose of comparison, we have used several different arithmetic procedures. Even if the results cannot be seen as definitive because of excessively large scatter, it is interesting that the different procedures agree largely in their outcomes.

a) We determined, for example, the median of each subject's values from all the color pairs and then subtracted that median from each value; the results are in table 4 with the median shown in the first column.

In spite of the considerable scatter, a sequence is observed in the deviations from the median. We have compiled in the last row of the table, sub 1, how much the minuses outweigh the plusses for each pair. The result is the rank order 1, 2, 3, 4, 5.5, 5.5.

Similarly, when one determines the medians of the deviations within each pair (table 4, sub 3) the rank order is 1, 2.5, 2.5, 4, 5, 6.

Table 4. Deviation from each subject's median in decimeters.

A	30		−3		0	0	+13	+7	+7	−3	0		+9
D	17.5		−7.5		−0.5	+9.5	+0.5	−4.5		+9.5			
G	22.5		−5.5		+4.5	−3.5	+0.5	−0.5		+2.5			
H	40		0		0	+2	−12	−8	−2	+5	+6		+5
M	25.5	−15.5	−1.5	−7.5	+0.5	−4.5	−0.5	−0.5	+6.5	+9.5	+10.5	+7.5	+0.5
deS	27	−8		−7.5	0		−4	+33	+27		+43	−9.5	+33
V	39		−12		+1	0	+1	−2	+1	+1	−3		−3
W	26				−2		−12	−6	+2		+2		+12
R	51	−1		−1					+1		−1	+7	+19
1) Number of													
−		8−		5−		6−		7−		3−		2−	
=		1=		3=		2=		0=		1=		0=	
+		0+		3+		6+		8+		9+		8+	
		8−		2−		0		1+		6+		6+	
2) (Median)		(−8)	−4¼	(−7½)	0	0	0	−1¼	+2	+3¾	+2	(+7)	+9
3) Median		−5.5		0		0		+1		+2.5		+7.25	
4) Middle between upper and lower medians		(−)4¾		(−)⅝		(−)1½		(+)2⅛		(+)4¾		(+)6¼	

The mean between the 'higher part-median' and the 'lower-part median' (table 4, sub 4) gives the sequence 1, 3, 2, 4, 5, 6.

If one determines the medians of all single columns (table 4, sub 2) the order is (1), 3; (2), 6; 6, 6; 4, 8.5; 10, 8.5; (11), 12, which is again quite similar with respect to the order of the color pairs.

b) In another arithmetic procedure, we rank ordered the values for each subject (with the difference of the numbers equivalent to a row of 36 ranks) and used the rank values to find medians across subjects.

Table 5.

	B, g	G, b	B, y	Y, b	G, y	Y, g	Y, r	R, y	G, r	R, g	B, r	R, b
Rank	(7⅓)	8½	(10)	22⅓	19	19½	17⅓	25	27	25⅓	(21)	28
	(1)	2	(3)	8	5	6	4	9	11	10	(7)	12
Combined	8⅓		19		19		20.8		26		26	
rank	1		2½		2½		4		5½		5½	

Therefore a sequence of the *pairs* [presented in table 6] is indicated (starting from the pair that is resolved on average only at the greatest proximity and ascending to those which can be resolved on average at the greatest distance).

Moreover, if one confronts the results of the different calculations, the sequence of the second and third color pair (*one beneath the other*) is less certain, as is that of the fifth and sixth; we summarize this in the diagrams shown below [tables 7 and 8].[52]

In table 7, the degree of blurring decreases from I to IV; in table 8, the pairing of the colors is indicated by brackets; the first pair on the left (I) shows the least blurring etc.

[52] These conclusions apply naturally only to the [colored] papers used by us.

Table 6. Combination of tables 4 and 5.

	table 4, 1)	4, 3)	4, 4)	table 5
B, G	−8	−5.5	$-4\frac{3}{4}$	$8\frac{1}{3}$
B, Y	−2	0	$-\frac{5}{8}$	19
G, Y	0	0	$-1\frac{1}{2}$	19
Y, R	+1	+1.0	$+2\frac{1}{8}$	20.8
G, R	+6	+2.5	$+4\frac{3}{4}$	26
R, B	+6	+7.25	$+6\frac{1}{4}$	26

Table 7.

B, G	I
B, Y; G, Y	II
Y, R	III
G, R; R, B	IV

Table 8.

B				
G				
Y				
R				
	I	II	III	IV

We see the following:

1. In our experiments, the *contrast pairs* [B, Y; G, R] are not simply those that produce the strongest (or weakest) blurring. They fall in II and IV, being separated from one another by the other pairs.

2. Correspondingly, qualitatively 'adjacent' colors do not always result in stronger blurring.

Within the scope of our investigations, it is enough to say that under our experimental conditions the color pairs all showed strong blurring (the corresponding white–black gratings were resolved generally at around twice the viewing distance of the colored gratings), *and that the contrast colors did not show the strongest blurring—nor the weakest. They lie in our table between the other color pairs.*

A further discussion of the results of the above grating experiments would seem to us premature, as our experiments still show great scatter. Replication of the measurements would therefore be necessary and, for theoretically general purposes, should also be done with pure spectral colors. Finally, we experimented merely at *one* brightness level; certain points suggest the idea that a complete understanding of the problem would only be possible if the experiments were conducted systematically at different brightness levels.

For a more detailed discussion, various factors necessarily come into question and these could be evaluated only in a separate investigation. With a differently colored equiluminous pair, the degree of saturation of a single color must be considered, as well as the ratio of the strengths of saturation of the two colors and their specific brightnesses among others.

Because we operated with a constant brightness level, our colors were *necessarily* presented at different saturations. But as we did not vary the saturation systematically, no general conclusion is possible from the results with regard to a slighter blurring of less saturated colors or of colors of equal or different degrees of saturation.

And so conclusions about the 'prevalence' of single colors seem premature to us. In his visual acuity studies Pauli[53] states "Blue and green yield the least acuity, red a better one, and yellow and white the best with equiluminance of all colours". With our results the first was true, but in our experiments red was better than yellow in the

[53] loc. cit., p. 328.

various combinations; certainly one must consider that with the brightness level of our experiments the yellow was 'too dark' but this again clearly indicates that such conclusions cannot be definitive before a systematic variation of brightness level is carried out.

§4. From the literature we select for comparison the results of Wanda von Lempicka.[54]

The author worked with disks with stripes glued on them. Directly comparable with our experiments are her experiments in table 9 (p. 243) No. 1 (red–green stripes, equiluminous) in comparison with No. 4 (black–white stripes, brightness difference 339°).[55]

Table 9.

	Subj. 1	Subj. 2	Subj. 3	Subj. 4	Subj. 5
Red–green	4.3	4.1	5.7	4.5	3.4
Black–white	6.7	7.1	8.3	7.6	4.4

As in our case, the distance for resolution here is overall noticeably lower with the equiluminous red–green stripes than with the neutral striping of different brightness. The subject must come considerably closer in order to resolve the red–green striping.

W. von Lempicka investigated 8 other combinations next to those above, four pairs of stripes of each color next to equiluminous grey, 2 pairs of a color next to different-brightness grey, and 2 pairs of colors of different brightness.

Table 10 gives her experimental results; we give the experimental results from the perspective of the important question of the comparison of equiluminance with brightness difference in an easy to survey sequence, that of the brightness differences of the striping.

Table 10.

No.[56]	Brightness difference	Colors	Subj. 1	2	3	4	5
1 (5)	0	blue–grey	2.6	2.8	2.5	2.5	2.2
2 (6)	0	green–grey	2.9	2.9	2.7	2.9	2.7
3 (7)	0	yellow–grey	3.4	3.4	3.1	3.5	2.8
4 (8)	0	red–grey	3.4	3.6	4.0	3.9	3.2
5 (1)	0	red–green	4.3	4.1	5.7	4.5	3.4
6 (10)	36°	red–grey	3.4	3.8	4.4	4.1	3.2
7 (2)	36°	red–blue	4.0	3.9	5.1	4.4	3.4
8 (9)	271°	yellow–grey	6.1	7.1	7.1	7.7	4.5
9 (3)	271°	yellow–blue	6.3	7.1	8.6	7.7	4.6
10 (4)	339°	black–white	6.7	7.1	8.3	7.6	4.4

[54] "Räumliche Farbenmischung auf der Netzhaut" *Zeitschr. f. Sinnesphysiol.* **50** 217 ff.

[55] The numbers in the table represent the distance at which the stripes were resolved, in meters. For more detailed experimental conditions, see loc. cit., p. 242 ff.

[56] In the brackets we give the sequential number given by the author. We have rounded off the values for clarity to [the nearest] decimeter; the brightness differences are degrees of white added beyond equiluminance.

With each subject one sees that there are clearly two groups of values: the group of lower values (range shown in table 11, row A, values now given in decimeters) includes the equiluminous combinations (1 – 5) and the combinations with small brightness differences (6, 7); and the group of higher values (table 11, row B), where the results are clearly apart from the others, includes the combinations with considerable brightness differences.

Table 11.

	Subj. 1	Subj. 2	Subj. 3	Subj. 4	Subj. 5
A	26 – 43	28 – 41	25 – 57	25 – 45	22 – 34
B	61 – 67	71	71 – 83	76 – 77	44 – 46

From the additional results available in the table (we refer to the conclusion of Lempicka p. 243 ff) we note[57] that, in general, the values increase with brightness difference. However, this does not capture all the facts.[58]

The pairs with one neutral color each gave respectively smaller values than the pairs with two chromatic colors of equal brightness difference: the values can be arranged in the following rows:
a) No. 2 green – grey, smaller value than No. 5 green – red (brightness difference 0)
b) No. 4 red – grey, smaller value than No. 5 red – green (brightness difference 0)
c) No. 6 red – grey, smaller value than No. 7 red – blue (brightness difference 36°)
d) No. 8 yellow – grey, smaller value than No. 9 yellow – blue (brightness difference 271°)

The same—the slightly easier fusion of the pairs with one neutral member—also appears to play a role in distinguishing combinations which do not have an identical brightness difference. Thus: e) No. 6 red – grey yields a lower value than No. 5 red – green, although No. 6 has a brightness difference of 36°, while No. 5 is equiluminous. And perhaps this is also involved in row 10 (black – white) showing very often, but not generally, a lower value than row 9 (yellow – blue), although in row 10 the brightness difference is greater than in row 9.[59]

When measuring the critical distance of the approach of the subject, which we used in §2 and §3 following earlier authors, one must take into account that colors do not appear equal or equally bright from various distances.[60] W von Lempicka found[61] that in her experiments red and blue appeared darker from a distance than from close up whereas yellow and green appeared brighter. This explains[62] the finding that her red – blue (see table 7), which produced a whiteness difference of 36° at a normal brightness level, yielded lower values than her red – green (see table 5), which yielded equiluminance when brightness was measured. With the last disk, the red is probably seen darker in the distance and the green brighter, whereas with the first disk both sides

[57] In a somewhat different way than the author.

[58] Compare loc. cit., p. 245.

[59] Comparing her results to ours, one notes that with her combinations of a chromatic color with equiluminant grey she gets the sequence grey, green, yellow, red; moreover her equiluminous pair red – green (table 5) gives somewhat higher values than the red – blue pair (table 7), which was, however, displayed with a 36° brightness difference.

[60] Compare Brücke, Pauli, loc. cit.

[61] loc. cit., p. 239.

[62] "One is led to the statement that for spatial fusion of the chromatic colors the brightness relationships that were found for the colors by one of the usual methods are not critical, but what plays a decisive role are the apparent brightness relationships obtained at a greater distance." (p. 245)

are likely to be seen as being darker. This should also be taken into consideration in a discussion of our results with colored grating; this source of error would be radically remedied through the use of the method which we describe in §5; this method does not involve changes in the [viewing] distance.

§5. Measurements comparing the effect of a color difference on the one hand and a neutral brightness difference on the other, can be made *without the use of changing the distance* as a measurement basis. We used a procedure in testing various figures that consists in directly determining the range of the critical zone.

The principle of our experiment was as follows:

A flat figure was cut out of a large (about 50 cm wide) thin opaque white cardboard (like the hole mentioned in Chapter II, §9). This card with a hole was mounted vertically and another white cardboard was placed about 30 cm behind it as a rear surface. Each of the two surfaces was lit separately with a projection apparatus in whose optical path (good) color filters were inserted. The intensity of the illuminating light was independently varied by resistance changes in each illumination circuit.

So, for example, the front surface could be lit dark green and the rear bright red. Observing from a distance in front, one then saw the cut-out figure as bright red on a dark green field.

If one removed the colored filters, the illumination was neutral and one saw in this example the figure seen in the hole as bright grey against a dark grey ground.

If one exposes a medium-bright red cut-out figure against a dark green ground and increases the illumination of the green by a gradual decrease of the resistance of the front lamp, one arrives at the critical zone of blurring (in the region of equiluminance of red and green). With a continuing decrease of the resistance one goes past this zone and the figure appears again clearly in a bright green field. *How big is the range* of the critical zone can then be determined in terms of the values of the resistance.

In comparison to such measurements one could proceed in the same way without colored filters; the cut-out figure appears at first light grey against a dark field; with a decrease of the resistance of the front lamp, as above, one also arrives in a zone of blurring—here with complete homogeneity of the cut-out figure and field—and from there one proceeds to a grey figure against a light-grey field.

The two procedures are qualitatively different. In the first, the surface colors remain different despite the brightness variations of the front surface; with the second procedure with neutral colors there is complete homogeneity in the critical zone.

We asked ourselves:

How does the size of the critical zone compare in the color and neutral-tint experiments? How do the different figure sizes and figures vary in effectiveness?

The subjects were instructed to report the onset of 'blurring' on entry into the critical zone and likewise the return of sharp focus on leaving the critical zone.

Naturally, the procedure was also varied so that the change of appearance was not observed just with increasing brightness of the various surfaces but also, conversely, with falling brightness.

Practice for the subjects is necessary for these experiments.[63] But soon a rather good constancy in the reported values was established (constancy of the criteria employed). The viewing was generally steady (but without staring). For future experiments, a better definition and a more systematic variation of the conditions will be necessary. But as the following tables of our preliminary experiments show, the constancy of the results was satisfactory with our procedure as a result of training of

[63] These experiments are not easy: with less practice of the subjects and with less care in experimentation and in instruction the scatter is very considerable.

the subjects. The resistance was changed gradually at approximately constant rate so that an entire experiment (for example, observation of a dark field through the critical zone and beyond into a bright field—brighter than the figure) took no more than 5 seconds.[64, 65]

In order to obtain a more direct comparison of the experiments with and without colors, we used the lamps with provision for filters in the experiment without colors, but inserted a grey filter instead of a colored filter. Here we chose filters that with the same resistance gave neutral surfaces of equal brightness to that of the constant rear color surface. (For this purpose, the red rear surface was made equiluminous with the front neutral one through change of filter; thereafter the rear, now neutral, surface was made to have equal brightness as the one in front. Only then was the front changed from dark to light and the other way round in the experiment.)

Systematic experiments of this type were set up with two cut-out figures: a small vertical stripe (figure 1 of table 12) (length 12 cm, width 0.9 cm) and a cut-out of the shape in figure 24 (figure 2 of table 12) (width 3.3 cm, height 4 cm, tooth height 3.8 cm).

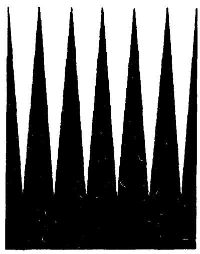

Figure 24.

The subject viewed from a distance of 2 m from the front cardboard; the room was lit medium bright.

For each figure, we made 10 measurements (5 in descending and 5 in ascending order). This happened with the neutral and with the color conditions for each figure. With 3 of the 6 subjects we repeated all experiments again on another day.

The slider of the rheostat was calibrated in centimeters proportionally to the resistance. We measured the position in centimeters, at which in the ascending mode—increasing the brightness of the front surface—the onset of blurring was reported. Similarly, we measured the end of the blurring, and repeated the procedure in descending mode. (The sequence was varied randomly in the experiments.) The scatter in these experiments was very small. The relative brightness values corresponding to the resistances were determined photometrically.[66]

We are interested in the *extent of the critical zones* and this is best characterized by the *quotient of the two brightnesses*, the upper boundary and the lower boundary of the critical zone in our experiment.

Individual values are different for each subject, but within an experimental series they are constant for each subject, so that we can characterize the series through their median values, with the ratios of the upper and lower boundary values defining the range of the critical zone in the experiments.

[64] For future experiments a mechanized change of the resistance and variation of the rate is for many reasons necessary.

[65] The experiments are quite possible also without continuous observation, by using single exposures with brightness steps; we refrained from doing this because of the very cumbersome procedure.

[66] The photometry was performed by Willy Engel, PhD. We thank him here.

Table 12. Ascending and descending critical ranges expressed as quotients of boundary brightness values.

	w/b figure 1		r/g		w/b figure 2		r/g	
	desc.	ascen.	desc.	ascen.	desc.	ascen.	desc.	ascen.
La	2.17	1.35	2.9	1.8	2.5	1.6	3.7	2.8
Li	1.2	1.32	1.9	2.01	1.75	1.7	2.1	2.1
v. A	1.48	1.5	1.3	1.7	1.8	1.6	1.9	2.42
Ja I	1.6	1.5	2	2.06	1.85	1.7	2.1	2.3
Ja II	1.5	1.5	2.3	1.8	1.8	1.7	2.0	1.9
Kau I	1.6	1.35	1.9	1.55	1.75	1.56	2.2	2.1
Kau II	1.6	1.56	1.8	1.7	1.75	1.6	1.9	1.85
Pe I	1.47	1.57	1.6	1.7	2.05	1.74	2.3	1.875
Pe II	1.75	1.4	1.9	1.56	1.95	1.82	3.0	1.8

The resulting ranges, expressed as quotients, are given in table 12.

We used various types of calculations to summarize the results.

a) If one determines first for all subjects for each vertical column the median (together with upper and lower median values), we find that:

	w/b figure 1		r/g		w/b figure 2		r/g	
	desc.	ascen.	desc.	ascen.	desc.	ascen.	desc.	ascen.
Upper median	1.48	1.35	1.7	1.63	1.75	1.6	1.95	1.87
Median	1.6	1.5	1.9	1.7	1.8	1.7	2.1	2.1
Lower median	1.7	1.53	2.15	1.9	2.0	1.72	2.65	2.36

1. *The red–green values are everywhere larger than the* corresponding *white–black values*; specifically [the values shown are r/g—w/b for descending and ascending critical ranges for figure 1 (the first two columns) and figure 2 (the last two columns)]:

Upper median	+0.22	+0.28	+0.2	+0.27
Median	+0.3	+0.2	+0.3	+0.4
Lower median	+0.45	+0.37	+0.65	+0.64

2. The *two figures* differ clearly with regard to their ranges: the values for *figure 2* are everywhere greater than the corresponding values for figure 1. This means the 'critical zone' is larger for figure 2, not only with colors (red–green), but also with regard to the range of blurring with a pure brightness difference (black–white). The difference in the ranges between the two figures is of the same order of magnitude as the difference between black–white and red–green values discussed in point 1.

Differences [67]	w/b		r/g	
	desc.	ascen.	desc.	ascen.
Lower median	+0.27	+0.25	+0.25	+0.24
Median	+0.2	+0.2	+0.2	+0.4
Upper median	+0.3	+0.19	+0.5	+0.46

[67] We present here the differences between the values for figure 2 and the corresponding values for figure 1.

b) These results apply not only to the overall median values, but also, with only occasional exceptions, to *each experimental series.* In table 13 the differences between the ranges have been determined with respect to each experimental series in the same manner as previously for the medians for all subjects combined.

Table 13. Differences from median values.

	r/g−w/b figure 1		r/g−w/b figure 2		fig. 2−fig. 1 w/b		fig. 2−fig. 1 r/g	
	ascen.	desc.	ascen.	desc.	ascen.	desc.	ascen.	desc.
	+0.73	+0.45	+1.2	+1.2	+0.33	+0.25	+0.8	+1.0
	+0.7	+0.69	+0.35	+0.4	+0.55	+0.28	+0.2	+0.09
	−0.18	+0.2	+0.1	+0.82	+0.32	+0.1	+0.6	+0.72
	+0.4	+0.56	+0.25	+0.6	+0.25	+0.2	+0.1	+0.24
	+0.8	+0.3	+0.2	+0.2	+0.3	+0.2	−0.3	+0.1
	+0.3	+0.2	+0.45	+0.54	+0.15	+0.21	+0.3	+0.55
	+0.2	+0.14	+0.15	+0.25	+0.15	+0.04	+0.1	+0.15
	+0.13	+0.13	+0.25	+0.135	+0.58	+0.17	+0.07	+0.175
	+0.15	+0.16	+1.05	−0.02	+0.2	+0.42	+1.1	+0.24
Upper median	+0.14	+0.15	+0.175	+0.17	+0.175	+0.135	+0.1	+0.125
Median	+0.3	+0.2	+0.25	+0.4	+0.3	+0.2	+0.3	+0.24
Lower median	+0.72	+0.51	+0.75	+0.71	+0.44	+0.27	+0.75	+0.635

Also here the above results are confirmed:

The median range of the critical zone in these experiments was generally *greater* in the experiments with colors *than in the corresponding experiments* with neutral colors. And everywhere figure 2 showed larger critical zones than figure 1.

c) We enclose here [in table 14] yet another calculation wherein the value for the ascending and descending procedures are averaged for each of the four conditions (figure 1 w/b, r/g; figure 2 w/b, r/g).

Table 14. Averages and differences of averages.

	figure 1		figure 2		figure 1	figure 2	w/b	r/g
	w/b	r/g	w/b	r/g	r/g−w/b	r/g−w/b	fig. 2−fig. 1	fig. 2−fig. 1
	1.76	2.35	2.05	3.25	+0.6	+1.2	+0.3	+0.9
	1.26	1.955	1.725	2.1	+0.7	+0.4	+0.5	+0.1
	1.49	1.5	1.7	2.16	+0.01	+0.5	+0.2	+0.7
	1.55	2.03	1.775	2.2	+0.5	+0.4	+0.2	+0.2
	1.5	2.05	1.75	1.95	+0.6	+0.2	+0.25	−0.1
	1.475	1.725	1.655	2.15	+0.25	+0.5	+0.2	+0.4
	1.58	1.75	1.625	1.875	+0.2	+0.25	+0.05	+0.1
	1.52	1.65	1.895	2.0875	+0.1	+0.2	+0.4	+0.4
	1.575	1.73	1.885	2.4	+0.2	+0.5	+0.3	+0.7
Upper median	1.5	1.7	1.7	2.0	+0.15	+0.225	+0.2	+0.1
Median	1.52	1.75	1.75	2.15	+0.25	+0.4	+0.25	+0.4

§6. With one subject (Pe) we repeated the measurement of §5 at a distance of 5 m, in order to see in a preliminary test how the results change compared to those gathered at 2 m distance. The result was generally shifted towards somewhat higher brightnesses.

The 'ranges' (brightness quotients) for figure 1 are just about the same as with 2 m, with *no clear difference* from the measurements for 2 m distance. For figure 1 with the 5 m distance, the ranges are in general *greater* with the w/b test and with the r/g test there is also an increase, albeit not so pronounced. Also at the 5 m distance we found throughout that within each measurement group *the corresponding ranges are in general greater with r/g than with w/b and that figure 2 gives larger ranges than figure 1.*

Table 15. Quotients of ranges ($n = 5$).

	figure 1				figure 2			
	w/b		r/g		w/b		r/g	
2 m	1.47	1.57	1.6	1.7	2.05	1.74	2.3	1.875
	1.75	1.4	1.9	1.56	1.95	1.82	3.0	1.803
5 m	1.5	1.53	1.6	1.7	2.04	2.1	2.4	2.41
	1.58	1.41	1.63	1.6	2.3	2.1	2.49	2.3

Table 16. Summary of ranges.

2 m	1.52	1.65	1.9	2.09
	1.575	1.73	1.89	2.4
5 m	1.52	1.65	2.07	2.4
	1.5	1.62	2.2	2.4

Chapter IV

The fact that color differences are much less effective than brightness differences for achieving clear, well-defined figures and objects in space is of considerable interest for the theory of perception. Especially so because with the phenomenal problems here one taps an area that offers an entirely different environment than our accustomed world of visual objects.

For an *explanation* of the phenomenal changes in the critical zone many more additional arguments must be considered. We briefly present these in the following paragraphs and, for some points, we bring additional experimental clarification.

§1. Much of what is reported can be understood (in the sense of §§1, 2, 3, of the previous chapter) as a change with regard to *visual acuity ratios in the usual retinal meaning* of this word. We are less able to distinguish neighboring stimulus differences with equiluminous heterochromatic lights than with chromatic or neutral lights of different brightnesses. The reason can be sought in the *anatomical relationships of the retina*, in the geometric distribution of the color sensitive elements (an example is provided by the postulate of von Brücke:[68]

"If one makes the discrimination ability directly dependent on the spacing of the axes of the cones from each other, and if one assumes that for each of the three primary colors just as many cones are present, and that all these cones are evenly distributed, so that [any] two of the same color mediating cones in the center of the retina are at the same distance from each other, one can say that, according to geometric principles, the spatial color discrimination ability relates to the spatial discrimination ability for bright – dark ... in the ratio ... 1 : 1.7."

This Brücke thesis is not the only form in which one can think of the retinal distribution of the color sensitive elements underlying the observed phenomena.

[68] loc. cit., Vol. **80**, p. 68.

Many of the observations can be explained starting from this without further ado,[69] including the blurring of border contours and the slight blurring of narrow small figures, of the tips of figures, gap completions, all of which become sharp in close observation.

However, one cannot say that what happens in the critical zone is only the effect of visual acuity in the above sense of the word; what happens here is not explained by such visual acuity processes; indeed it seems that the concept of acuity misses the essential element. We raise a few points:

1. One is dealing here often *with matters of quite different orders of magnitude.* 'Acuity' refers to the smallest size, in the sense of the minimum resolvable separation, etc. For example, if one determines (compare tables 1 and 3) the critical distance for resolving gratings with 2 mm narrow stripes (similar results are found with individual stripes in a field), one can then be asked to predict the change in the critical zone with a circular disk of 2 cm or more in diameter. One would then expect that the essential effect would be that the border would cease to be sharp, that blurring would take place in a narrow (2 mm) region along the circumference and otherwise nothing else would happen. In reality, however, there is with these objects typically a process of an entirely different spatial order of magnitude (2 cm or more compared with 2 mm), as described in Chapter II, §3. The *entire area* is in flux and uncertain. One deals not only, and even not primarily, with the blurring of the border, but the entire figure becomes so strangely unstable, undulating, and flowing. And here and there it happens that a 2 cm disk completely fades away as a figure, indeed 'it disappears into the ground'.

If one is here not dealing with a processes of mere 'acuity' loss in the sense of a minimum separation, then something else should be invoked such as the impairment of accommodation, staring phenomena, and afterimage effects with fixed and moving eyes.

Here we can report:

a) Without doubt *accommodation processes* in the critical zone are strongly impaired. Already subjectively one feels exceptionally uncertain with regard to accommodation—"how far is the object?"—and phenomenally it typically happened that with an objective distance of the target from the ground of 30 cm in depth, this depth difference completely disappeared, often so that it was in no way possible for the subject to reproduce this depth difference in any manner.

Poor accommodation is certainly an important factor for the lack of sharpness of what is seen.

We were able to make here a simple decisive experiment: In the experimental arrangement with the rhombus-shaped cut-out (figure 25), we attached on a thin thread hanging in the hole a small *fixation point* of a different brightness than the figure and ground (for example a small white square of about $\frac{1}{2}$ cm^2). With such an arrangement, normal, good, stable, and secure accommodation was possible, even in the critical zone (critical with regard to the cut-out figure and ground). However, even when this was done, the blurring and the figural change were *in no way eliminated.*

b) Phenomenally there exists a rather close relationship of the processes in the critical zone with those which occur with prolonged direct staring at an object in a homogeneous field; without question, objective relations are here also pertinent. But such staring phenomena require, as is known, a considerable period of steady fixation before they reach this stage. But here, on transition into the critical zone, the changes come about quite differently and quickly; indeed, they are *present from the outset.*

[69] Several of the general phenomenal changes could be regarded as secondary consequences of changes in relative acuity.

(And it should also be mentioned that, with staring phenomena, typically a sudden and even small eye movement—voluntary or involuntary—suffices to destroy the effect, to restore focus, whereas in the case considered here such changes do not occur when one moves the gaze, voluntarily or involuntarily.)

c) With regard to an explanation in terms of *afterimages*, it is enough to remark here that, as mentioned above, our phenomena are typically present from the outset if the display is initiated in the critical zone.

d) We would like to mention incidentally another point: visual acuity measurements in chromatic fields depend very much on the retinal location (purely foveal or in the periphery at different degrees of eccentricity). However, our phenomenal changes in the critical zone are little affected by the changes of the fixation point, as long as they are not extreme. It makes scant difference to the coarseness of the appearance whether one fixates here or there, looking with free or firm view (as long as one avoids prolonged staring, which only enhances the overall effect). If the experienced observer finds only small differences in the overall character of the phenomenon, then the naive observer (as long as extreme peripheral fixation is avoided) viewing with changing fixation still perceives the *same* strange, fluctuating event. Voluntary fixation is in this situation actually rather unnatural and difficult.

2. Further one would expect that with, say, red – green colors in an approximately regular geometric distribution, a grey would be seen at the border (correspondingly violet would occur with red – blue colors, etc.). Thus, at the border of a red disk in a green field, a washed-out grey stripe should appear at the border, with the grey fading away in the space of a few millimeters in either direction from the border. But we could find such borders only partly there and only in exceptionally few cases. The typical display did not give such simple color mixing at the periphery, but rather the red and green flowed in the previously mentioned strange manner, softly and without delineation into each other. The geometry of the effect was perceived either as a wide halo or a variation from the center outwards or—and this only in one special case—a variation from the periphery inwards.

3. Visual acuity as defined above is governed by the visual angle. It is to be expected that when tests are carried out at *varying distances and object sizes*, then for the most part a constant visual angle will be critical for the various patterns. (If visual acuity is a simple function of the size of the retinal image, then overall[70] the resolution will be the same for small objects seen from close up as for larger ones observed from far away.)

If one varies the object size in our experiments, the critical distances do *not* simply follow a constant visual angle throughout.

We followed up this result with some pilot experiments. We used for this purpose red disks, each hanging about 30 cm in front of a large grey-green wall, each illuminated to achieve equiluminance. The subject moved away from the disks starting out at 1 m distance; the critical distance was that where the described phenomena of fuzziness etc. ensued. (For this the circle should be observed without prolonged staring.) The diameters of the individual disks were $2\frac{1}{2}$, 3, $3\frac{1}{2}$, 4, $4\frac{1}{2}$, 5, and 6 cm. The critical distances were determined individually for each disk in a random series of presentations.

The following table gives the results for the values of the critical distances. Three measurements were taken for each [disk] size (in random sequence) for the subjects Sch, F, Ov; two for subjects Vp, L; and for subject J only a few, single measurements of the different critical distances were possible.

With the restriction of measurement steps to quarter-meters and with the practice of our subjects, the scatter here was so small that we were satisfied with these few

[70] Apart from added factors like accommodation conditions.

measurements. Repeated measurements resulted in the same value in most cases; deviations over $\frac{1}{2}$ meter[71] occurred only in isolated cases.

Table 17a. [Critical distance in meters.]

Subject	Diameter [of disk, cm]							
	2	2.5	3	3.5	4	4.5	5	6
Sch	2.50	2.50	2.75	2.75	2.75	3.50	3.50	3.75
Fr [F]	4	3.75	3.75	4.00	4.25	4.50	4.75	5
Ov	3	3.25	3.50	3.75	3.75	3.75	4.75	4.50
L	2	2	2.50	2.50	2.50	3	2.75	3.25
J	3.25	3.25	3.50	—	3.50	—	—	3.75

The table shows that the critical distance generally increases as the size of the object is increased but *by no means as strongly* as would follow from the geometry. The distances in meters are much less different from each other than they should be if a constant visual angle were the determining factor. And here it is not a question of a *small* deviation, but of a quite *noticeably different curve shape*. The following consideration serves as illustration. We start from the values obtained with the 4 cm disk as a reference. If we take a distance value with the 4 cm disk as characteristic for the critical visual angle (a), then arithmetically one would expect with a 2 cm disk the value $0.5a$ (to produce an equally large retinal image), and with a 6 cm disk the value should be $1.5a$. We see, however, that the value with a 2 cm disk is much higher than $0.5a$. In all cases, it amounts to $0.8a$ to $0.9a$. Similarly, the value with a 6 cm circle is lower than $1.5a$ in all experiments, ranging from $1.1a$ to maximally $1.36a$. One sees that the values *change much less* than they ought to if the visual angle were to be constant.

Table 17b (based on calculations of the critical distance at 4 cm as 'a').

	2 cm		6 cm	
Sch	(expected $0.5a$)	$0.9a$	(expected $1.5a$)	$1.36a$
F	"	$0.9a$	"	$1.2a$
Ov	"	$0.8a$	"	$1.2a$
L	"	$0.8a$	"	$1.3a$
J	"	$0.9a$	"	$1.1a$

The various states of accommodation need to be considered as a possible source of the deviations and that, as we mentioned in Chapter III, §4, equiluminance itself is not constant for different distances. Nevertheless, it does not seem possible to completely explain these deviations by these factors alone.

4. When considering the sharpness of the perceived *contours*, contrast conditions should obviously also be taken into account. In visual acuity experiments, one would correspondingly expect that if adjacent parts have maximal color contrast, the situation would be definite and unequivocal. But this is not the case (compare Chapter III, §3).

5. In contrast to an attempt to explain the result solely by the visual acuities in individual retinal areas, by far the most important factor seems to us to be *the type of figural changes* which typically occur in the critical zone (compare Chapter II, §9 f).

[71] The values for Fr at 2 and 2.5 cm, Ov at 5 and 6 cm, and L at 4.5 and 5 cm do not fit the curve; this is due to the effects of bias and contrast caused by the order of presentation of the experiments, but the deviation is again only $\frac{1}{4}$ m.

Also, with the usual visual acuity experiments, the rules of form perception at threshold (of the 'sense of form') cannot be derived simply from the values of the minimum separable distances for the resolution of points and single lines, etc. This is known, and we refer as example to the studies of Guillery[72], Lohner[73] and Hofmann[74].

Frequently one is urged to state that the process of seeing forms lies "only in a small part in the area of physiological optics, but essentially in the psychological one". Whether it is most adequate to consider that the essential phenomena depend on retinal, microscopic relations to which by pure summation are added 'psychological factors' or, rather, the other way round, that one must start from aspects of form perception is not discussed here (compare §3).

We repeatedly mentioned in Chapter II §9ff that the facts of figural change in the critical zone cannot be derived from the visual acuities obtained for the smallest areas. We now report in the following on more detailed experiments with the figure in Chapter II §9 (the triangle with a nose):

a) In the initial experiments, subjects were not told which patterns will be presented: a plane figure shape, figure 8[75], was displayed as a cut-out figure; figure and ground were red and green, in equiluminance. Starting from a distance of 7.5 m (whence the figure was not yet recognizable), the subject approached the object until he/she recognized a distinct sharp figure (the instruction was principally to state while slowly going forward *what* the subject saw). Typically the course was that, while approaching, the subject first saw a plane triangle, somewhat blurred, but clearly a plane *triangle* (without a nose); on coming closer there appeared in the region of the nose a diffuse, formless haze, and only on approaching much closer did the subject recognize the correct figure (a triangle with a nose), mostly with great surprise: "But there is another point, which wasn't seen before!" The tip of the triangle requires, angle-wise, smaller visual angles than the nose, and is seen *earlier* (at a greater distance) sharply at the same time.

The process was repeated with figures of other sizes, where the approach started from a distance of 23 m.

b) We tested the same in experiments where the subject, instead of coming in from a distance, started from a small distance where the figure was clearly perceived and moved back while describing the change in what was seen. Or, starting out from a *brightness difference* between figure and ground at a constant distance at which the figure was clearly present, we changed the brightness of the figure (or the ground) to produce the critical zone. Also here it was typical that in one stage a plane triangle was seen, often "of poor quality, washed out and unsharp", but nothing was seen of the "nose".

I also performed the experiment in its simplest form (compare Chapter II, §3) with a subject who knew nothing of psychological things. I held a plane green figure (triangle with nose) in front of a red surface whose brightness I changed to equiluminance—she suddenly called out, astounded "Where is the appendage? You conjured it away!"

The process was similar with many other figural arrangements, where a piece appeared as an 'appendage', a 'bad adjunct', or a 'disturbance' of the figure.

c) With the cut-out shape of figure 25 (height 11.7 [cm]; width 4.4 [cm])[76] we made some qualitative determinations with regard to these facts in distant viewing experiments where the subject was familiar with the tests.

[72] For example "Einiges über den Formensinn" *Arch f. Augenheilk.* **28** 274, 1894.

[73] *Die 'Sehschärfe' des Menschen und ihre Prüfung*, 1912.

[74] 7th Congress for Experimental Psychology, Marburg 1922, p. 128.

[75] Base 1.9 cm, side 3.8 [cm]; base of nose 0.8 [cm]; the nose sat on the right side, 1.4 cm away from its bottom end and 1.6 cm from the top end.

[76] Rhombus side 6.3 [cm]; side length of the nose 0.85 [cm]; base length of nose 0.6 [cm]; the nose was 2.2 cm from the bottom tip of the rhombus and 3.5 cm from the right tip.

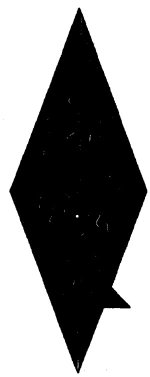

Figure 25.

It must be noted again that with such experiments everything depends to an exceptional extent upon *cleanliness* in carrying out the tests; for example that the *edges* of the cut-out figure do not produce differences of brightness through shadow and light effects at the edges; this sort of implementation in the setup can substantially change the result, indeed even conceal the phenomenon.

With this figure the nose is geometrically identical to the bottom end of the rhombus when it comes to a point.

For comparison purposes this experiment was also done with a brightness difference. With the subjects approaching from a distance, the following spontaneous reports resulted at the reported metric distances [table 18]:

Table 18. Distances in meters.

	Equiluminance	Figure darker than ground	Figure lighter than ground
Subject W			
A flat rhombus is there	3.5		
Rhombus is clearly there without a nose	2.6	7.7	8.0
Something is happening in the region of the nose		4.7	5.3
Nose is present but not clear	2.0		
Everything, including the nose, is clear and sharp	1.6	3.0	3.0
Subject G			
Unsure, doubtful, blurry, rhombus?	6.4	9.3	
Clear, regular rhombus	3.3–3.5	6.5	5.0
Something round and blurred in the region of the nose		4.5	
The nose is clear	1.3–1.2	4.0	4.0

In separate experiments at equiluminance, subjects attended to *the lower point of the rhombus and to the nose* simultaneously, making a comparative judgment. A zone was clearly established on repeated coming forward and moving back in which the lower tip of the rhombus was clearly there but the nose was not. With subject W, both were clearly there until a maximal distance of 1.20 and 1.80 m, including the nose; the lower tip of the rhombus, however, was seen sharply even at about 2.20, 2.50, and 3 m. Subject G saw the nose sharply until about 1.40 m, or at most 1.90 m; the lower tip of the rhombus until about 3.30 or 3.50 m.

With two subjects (W and L), we also performed control experiments by suspending a fixation mark of a different brightness (compare Chapter IV, §1): it was a white sharp-edged square piece of paper hanging on a thin thread in the middle of the cut-out figure. In an experiment these values resulted with the subject approaching [table 19]:

Table 19. [Distances in meters.]

	Subject W		Subject L	
	without fixation mark	with fixation mark	without fixation mark	with fixation mark
Rhombus tip sharp	3.30	2.20	4.0	3.0
Nose sharp	1.80	1.60	1.60	1.30

Even when a fixation mark was present, there was a difference in the distance at which the two tips became sharp, thus a zone in which the rhombus tip was quite sharp, but the nose was not. (The values obtained in experiments with a fixation mark are overall somewhat smaller than those observed in experiments without a fixation mark; this could mean an improvement of visibility through the well-defined fixation, but a simultaneous contrast effect could also play a role, in that the equiluminance of figure and ground is disturbed through the contrast effect of the bright white mark.)

d) With a number of the subjects we performed further experiments with the objects being approached at equiluminance, comparing the presentation of a triangle with a nose to a smooth somewhat *small triangle*[77] *without a nose.* The subjects knew both objects, but did not know which of the two had just been presented. As a critical distance, we defined the spot at which the object was clearly recognized, so that on coming still closer it did not figurally change.

The results (table 20) showed that the distance values for the triangle without a nose were always substantially greater than those for the triangle with a nose. The difference amounts to 10 to 100%.

Table 20. [Critical distances in meters.]

	Subj. A	Subj. E	Subj. D	Subj. V	Subj. L[78]
Triangle without nose	3.80	2.00	4.10	4.30	4.10[78]
Triangle with nose	2.90	1.00	3.20	3.80	2.40
Ratio of the distances	1.3	2.0	1.3	1.1	1.5 [1.7?]

Similar experiments[79] were performed with 3 more subjects with, in addition to the red – green equiluminous presentations, the same objects were presented *in greys of different brightnesses* (light grey figure on a dark ground).[80]

The table shows that in all experiments the distances found for the triangle without a nose are considerably *larger* than those for the triangle with a nose. The red – green values are in all cases *smaller* than the light – dark [l/d] values, that is, the subject must come substantially closer with equiluminance and color difference than with neutral brightness difference. The ratio of distances for the two figures is *considerably*

[77] Whereas the triangle with the nose had a base length of 1.9 cm and a side length of 3.8 cm, the values for the triangle without a nose were: base length 1.7 [cm], side length 3.4 cm.

[78] With subject L the experiment was performed with the target known to the subject.

[79] With the other triangle with a nose and a triangle of equal size without a nose.

[80] The experiments were performed with naive subjects; the objects in question were randomly interspersed in a test series among displays of other figures.

Table 21 [first part].

	Subj. J		Subj. D		Subj. Ls	
	l/d	r/g	l/d	r/g	l/d	r/g
Triangle without nose	14 m	10 m	13 m	9 m	7 m	3 m
Triangle with nose	6 m	3 m	12 m	4 m	4 m	1 m
Ratio of distances	2.3	3.3	1.1	2.25	1.75	3.0

greater for each subject for the red–green presentations than for the neutral ones, that is the *figural difference* matters much more with heterochromatic equiluminance than with brightness difference.

e) In other experiments we examined the familiar *'gap completion'* from the usual visual acuity experiments. However, here we presented the *same gap under different figural Gestalt conditions*: in one instance as *a gap within a figure*, in the other as *an interval between two figures.*

Figure 26 shows a cross with a gap in the vertical lower branch.

In figure 27 a full cross is shown and the gap objectively of the same size as in figure 26, is here placed between the cross and an eight-arm star.

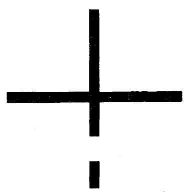

Figure 26.

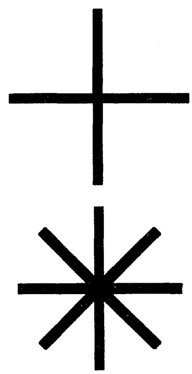

Figure 27.

The figures were presented in an umbrella-spoke array[81] provided with an aperture, at equiluminance (green on a red ground) and the critical distance was sought for the recognition of the actual figure (clear perception of the gaps). Typically on approaching from a distance the subject saw the double figure straight away as 'two images', the 'non-coherence' of the two figures was quickly appreciated; with the gap figure, however, it was harder to see the gap (which here was embedded 'in the Gestalt'). The results are given below [table 21 (second part)].

Table 21 [second part].

	Subj. J	Subj. E	Subj. Ls
Cross with gap	3.2 m	3.0 m	3.0 m
Cross and star	3.8 m	3.2 m	3.5 m

[81] For the measurements we used the following special dimensions: the total height of the cross with the gap was 12 cm, the width of the bars 0.3 cm, the gap was 0.8 cm long, the distance of the gap from the bottom end was 2.4 cm. The full cross, aside from the fact that the gap was filled in, was identical to the cross with the gap. The distance from the cross to the star was 0.8 cm. The star (we used here a small star) had a total height of 4.5 cm, its rays were again 0.3 cm wide.

To resolve the gap in the cross, the subject always had to come a little bit closer to the object than was necessary for recognizing the gap as a separation between the two complete figures.[82] (The gaps in the two configurations are geometrically identical and it is not likely that the resulting difference could be ascribed to the somewhat different, form-specific color distribution in the region of the gap.)

Correspondingly we investigated the visibility of the gap in a somewhat different figure (figure 28)—a smaller Maltese cross with a gap—in comparison to a double cross star (figure 29).[83] We also tested this same configuration in three subjects in a light–dark version, a neutral configuration with a strong brightness difference. The results of this experiment are given in parentheses [in table 22].

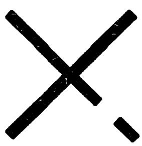

Figure 28.

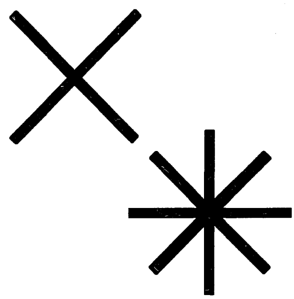

Figure 29.

Table 22 shows greater scatter and considerably greater differences in the results than with the long, large vertical cross. The subject always had to come much closer to the object in order to resolve the gap in the figure than to resolve the gap between the two complete figures (the difference is also present, although much reduced, in neutral patterns with a brightness difference; with one exception, the neutral values are greater than the values in the color experiment at equiluminance).

Table 22 [Maltese cross experiments].

	Subj. J	Subj. Li	Subj. Ls	Subj. De	Subj. E	Subj. W[84]	Subj. G[84]
Cross with gap	1.4 (6.0)	2.8 (7.0)	1.8 (4.0)	1.0	1.1	1.4	1.0
Cross and star	7.6 (6.5)	5.6 (7.6)	2.9 (4.3)	5.0	5.0	3.2	2.7

[82] In preliminary experiments it was found that if first the cross with a gap was presented and then, after it was resolved, the double figure, this resulted regularly in an increased recognition distance; if the order of presentation was reversed—first the double figure and after its resolution the cross with a gap—then we got for the cross with a gap a value which was greater than in the first sequence, but still a little smaller than the value for the double figure. With the measurements in the above table we proceeded so that we began with a display of a full cross exposure and then between each presentation of the cross with a gap and the double figure (to naive subjects) we displayed a full cross once or many times.

[83] The Maltese cross had a bar length of 2.9 cm and bar width of 0.3 cm. The gap was 0.3 [cm] × 0.3 cm and was located in the cross, 0.6 cm from the edge. The star had a total height of 2.7 cm vertically; its other bars were 2.5 cm long.

[84] With subjects W and G the dimensions of the figures were somewhat different: the Maltese cross length = 3.2 cm, bar width = 0.4 cm, the gap 0.4 [cm] × 0.4 cm, length of the remaining piece of the cross with the gap 0.6 cm; star length 3.2 cm; the vertical bars of the star were 0.5 cm wide, the other bars 0.4 cm wide.

6. One can ask if the fuzziness, the blurring of the contours is based entirely on peripheral factors in accordance with Brücke's theory. An experimental answer seems difficult. We tried to address the point with the following question. Are the phenomenal changes in the critical zone also present when approximate equiluminance is produced in the visual field but not necessarily in each eye itself? A possibility to create such experimental conditions presented itself in the following way.

If one presents to each eye in a haploscope a plane figure and a ground field as figurally identical, it may be possible to find a condition where a brightness difference of figure and ground is produced for each eye individually but at the same time equiluminance of figure and ground is produced in the *combined* picture.

The figure seen by each eye is green, and the ground red. The diagram represents the case where the brightness difference is in one direction for the left eye, and in the opposite direction for the right eye. On fusion of the intensities, the brightnesses of the combined picture appear equiluminous, as shown in the following diagram:

	figure	ground	
b_4		———	l. eye
b_3	———		
b_{mean}	———	———	
b_2	———		r. eye
b_1		———	

or

	figure	ground	
b_4		———	l. eye
b_3	——— r. eye		
b_m	———	———	
b_2	——— l. eye		
b_1		———	r. eye

Figure 30.

In the experiment we sought to produce this with three given constant illumination intensities and changing the fourth (in the manner of the experiments described in Chapter II, §1) continually (from quite bright to quite dark and the reverse) in search for the potentially present 'critical zone'.

Haploscope experiments of this type are quite delicate[85]; we were concerned not only with exact figural fusion but also that the brightnesses, when combined, really gave the mean brightness (not that a brighter one simply 'won').

In the picture frames of the haploscope, good thin glass sheets were vertically arranged; in the middle of each sheet a narrow curved edge of a postage stamp was carefully glued; behind each glass sheet (about 20 cm in depth) a green or a red screen was vertically mounted; each of the glass sheets and each of the screens was provided with special illumination, approximately as in the above diagram. Then the illumination of *one* screen was slowly and gradually changed (through adjusting a rheostat) from extremely dark to very light and vice versa. *In the combined picture* there resulted in the manner of the other experiments *a phenomenal critical zone in which the figure contours became indistinct and blurred* (the wavy curve was indistinct or was not present). If one tested in this position monocularly, then the right picture as well as the left one were each in sharp focus and with brightness difference of figure and ground. As in the experiments described in Chapter III, §4 the critical zone extended on the rheostat to several centimeters. If one used the same intensity variation with purely monocular viewing of the respective image, then a critical zone was again found. Whereas the zone with haploscopic combination lay between 20 cm to 17 cm on the rheostat, with monocular viewing it lay between 14 cm and 10 cm.

The result of the experiments indicates that the blurring is not necessarily a peripheral effect. The experiments must, however, be continued systematically in a much more extended way; the combination of different intensities holds some very interesting possibilities.

[85] Haploscope experiments in relation to the 'illusion' problems have been performed by various authors (not as applied to question considered here); the results concerning the existence of an illusion or the strength of an illusion, have been quite controversial. Lehmann has already explained (loc. cit., p. 101) that extraordinary care is necessary.

Let us summarize: As points 1 – 6 show, it does not seem possible to conceive of the phenomenal changes in the critical zone simply as impairments of visual acuity (in the sense of the sum of the retinal conditions of small areas); but this does not mean that because of the decisive counterarguments such a visual acuity explanation is completely eliminated. What is certain is that it is not sufficient and it is likely that, despite the seemingly well-founded explanation based on visual acuity, the phenomena of the critical zone must be differently derived.

§2. One can also think of a principal explanation in terms of *irradiation.*

This could at first seem paradoxical. The thesis that the geometrical optical illusions in question are derived from irradiation was discussed in Chapter I and the decisive experiment of Lehmann rests on exactly the point that with equiluminance the illusion was eliminated. But irradiation in the sense of overlapping of diffusion circles into neighboring regions exists not just when a light field borders on a dark one, but everywhere from a light region area onto the neighboring areas. That is, as Lehmann[86] also mentioned, irradiation when heterochromatic equiluminous parts of a field border on each other; here the diffusion circles of both fields overlap each other.

If Lehmann sees the basis of the illusion etc. in irradiation, this does not mean that he suggests that no irradiation was present in his main experiments with equiluminance, but rather that the illusion is only present (according to Lehmann) to the extent that the irradiation effect is unilateral.

Even at equiluminance, irradiation can cause a fading of contours and forms, as well as figural changes, if no simple straight boundary between the two areas exists.

Most of the facts mentioned in the above point §1, however, cannot be explained through irradiation. Furthermore the following should be mentioned.

1. The irradiation effect with equiluminous colors set at a certain level should be twice as large as when just one color is at this level and the other is dark; but its strength with an equiluminous arrangement is the same as one would expect if one side were slightly lighter without, however, producing blurring.

2. The irradiation effect grows when the brightnesses of the irradiating fields are increased; with equiluminous surfaces the effect must therefore simply increase systematically when the common level of brightness is increased, and definitely decrease when the level is lowered. The first is confirmed well by the strong increase of the effect with very strong light intensities (use of radiating light, strong intensity[87]); however, we did not find that the blurring effect was as clearly and everywhere *diminished* with lowering of the light into darker levels.

3. If one changes the brightness from a high value to zero and vice versa, then one would expect, because of the physical origin of irradiation, that the irradiation effect would change gradually. Indeed, the experiments of Benussi – Liel are based on this fact. If, according to Lehmann, irradiation is the basis of the geometrical optical illusions in question, then it must not only decrease or even disappear with the equiluminance of figure and ground, but the strength of the illusion must constantly decrease on reducing the brightness difference by a small amount, without affecting the region of equality. The various figures would have to become gradually more blurred as the brightness difference is diminished to zero.

[86] *Pflügers Arch. f. d. ges. Physiol.* **103** 90.

[87] For example, Pierce especially stressed (loc. cit.) that the use of strong radiating light intensity affects the illusions in the described sense. With strong intensities the typical 'discomfort glare' occurs especially in the critical zone; but the actual phenomenal qualities of such glare states—the shimmering, flowing, ill-defined, active, aggressive—are also present at medium intensities in the optimum region of the critical zone.

In reality Benussi–Liel were mistaken about this as we mentioned in Chapter II, §2; the changes of the strength of the illusion are generally to be expected only in a relatively narrow zone, which we call the critical zone. The course of the experiments did not show a steady increase of the blurring with a decrease of the brightness difference starting from any point, but rather it arises quite steeply in the relatively narrow critical zone. Without further evidence it cannot be conceived how this curve shape could come about with a pure irradiation effect.

4. If irradiation has a certain magnitude with equiluminance, then it must *grow*, even if only *one of the two* brightnesses is increased. However, the opposite is the case for the phenomenal changes—the blurring effect—on leaving the critical zone. If one raises one of the two brightnesses starting from the critical zone, one comes out of the critical zone and everything becomes beautifully sharp again as soon as a sufficient brightness *difference* is reached.

Through this last point alone it is clear that it is impossible to conceive of the appearances of the critical zone as irradiation effects.

We would like to remark at this point that the explanation of particular *geometrical optical illusions* through one-sided irradiation is not as simple as it could at first appear (we also avoid the question of the conclusiveness of Lehmann's experiments). This follows already from the discussion of Heymans[88] and Münsterberg[89]. Heymans's argument against the irradiation thesis was that on replacement of the black sites by white ones and vice versa, the white ones by black ones, the irradiation effect would obviously have to be reversed. Münsterberg's answer does not seem in any way to completely refute this argument. (In fact the illusion is not reversed, as we established further with special experiments, if one turns everything around and views, instead of a black figure on a white ground, a white one identical in every respect on a black ground.) The same goes for Heymans's second argument, which is important in itself: Heymans believes that, mistakenly, only half of the irradiation effect is being considered, and that the other half must act in an opposite manner. Correspondingly he shows that on more detailed examination Lehmann's irradiation explanation[90] of the tilt effect would require *additional factors* other than irradiation. He says that with the checkerboard figure, the vertical changes into a zig-zag line. The bends, however, are so small that the whole line is seen as a straight line tilted to the right or to the left. This is also true of his drawing, curve E, p. 89 which shows some of the tilt. But why does it do it? *In any case, not for irradiation reasons.*

If one combines the 3 short lines from his figure B, which correspond to *his drawing E* (we speak only of the left vertical row of figure B, namely the left lower edge of the right square, a piece of the free vertical line, the right upper corner of the left square), then one gets in fact, corresponding to drawing E, an inclination in this short stretch from lower left to upper right. *But if one proceeds from the right upper edge* of the left square past the wide black stretch to the lower edge of the right square, then one gets an opposite inclination. One sees that the step from figure E to the explanation of the inclination in B is theoretically not so simple.

§3. The situation is different if, instead of attempting a deviation of changes in the critical zone through mere summation of local visual acuity relations, one considers the condition of the critical zone from a *Gestalt theoretical* basis.

The perception of figures rests supposedly on an emergence, *a central physiological segregation of an area* in a field. It is likely that it does not depend purely on the sum

[88] *Z. f. Psych.* **14** 118 ff, 1897.
[89] *Z. f. Psych.* **15** 184 ff, 1897.
[90] p. 88, loc. cit.

of local conditions; the segregation will probably be determined in a larger field. But there is also a tendency from the outset to produce a (relatively) 'good' form. If the disparity conditions of the stimulus are not sufficient then blurring will result physiologically, as well as an indefinite flux, etc. With the emergence of forms under relatively unsharp conditions, the field will tend to develop in the direction of a relatively simple configuration.

Our experimental results thus mean that color processes in the absence of brightness difference are much less capable of producing demarcating forces in the field than processes that act when brightness differences are present.

This allows us to draw from the experimental results certain conclusions concerning the nature of color processes as opposed to brightness processes.

Recall that there was a series of paradoxical facts concerning visual acuity—we mean those specifically mentioned in the 6 points of §1—which required an entirely different and special type of auxiliary assumptions. This then leads to a somewhat indeterminate but consistent point of view.

On the basis of this view it appears quite possible to do justice to all the departures from the predictions based on visual acuity mentioned in points 1 – 6, in that the experimental results simply reflect how general field processes emerge from a dynamic principle. Here stimulus – retinal relations must obviously be considered as 'boundary conditions'.

§4. We would especially like to draw attention to an observation which more and more strongly emerged when we experimented with equiluminous conditions; it is possible that it could be quite important for the theory of the effects considered here.

If one produces with a color difference an equiluminance, then in most cases it is not possible for both colors to be in a condition of maximal saturation: one (or both) are made 'too dark' or 'too light'. (If one tries, for example, to produce equiluminance with blue – yellow, then either the blue will have to be made too bright so that its saturation suffers, or the yellow too dark, or when set to a medium level the blue as well as the yellow suffers; both become 'poor' colors.) Here one must consider that, in general, less saturated colors blur more easily than saturated ones. One could moreover suppose that a tendency to a color being distinct plays a decisive role: a yellow that is too dark would have the tendency to pull brightness from the surroundings, a blue that is too bright would have the tendency to give up its brightness. It is conceivable that processes resulting from this are involved in the occurrence of blurring.

This gives rise to certain experimental questions which need to be answered.

I give my heartfelt thanks to Prof. Köhler for suggesting this work and to the members of the Institute for advice and help with its realization.

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