Shin'ya Takahashi, Kazuo Ohya, Keiko Arakawa & Yuko Ishisaka

Perceived Strength of Edge, Depth and Brightness of the Kanizsa Illusion as a Function of the Color Contrast between Figures and Background

1. Introduction

The Kanizsa illusion[1] (Kanizsa, 1955), one of typical subtypes of the illusory contour, is a particularly intriguing phenomenon for considering the dynamics of our visual object perception (Fig.1). It has been stimulating interests of many researchers in this field for the last several decades. As Kanizsa (1955) originally discussed, this illusion is characterized by three distinct phenomenal properties; illusory edge, apparent depth and apparent brightness. This multi-dimensional property has been undoubtedly the most fascinating feature of the Kanizsa illusion. At the same time, it has been the cause of a divergent discussion on the nature of this illusion, giving rise to various theories that try to explain its generating mechanism. Roughly, these theories fall into two categories: One category emphasizes visual organizational processing such as a figure-ground segmentation (e.g., Gregory, 1972; Bradley & Dumais, 1975; Rock & Anson, 1979); the other regards it as a special case of the simultaneous brightness contrast (e.g., Brigner & Gallagher, 1974; Frisby & Clatworthy, 1975). Then, such categorical distinctions invite the question: Is the Kanizsa illusion essentially a *figural illusion* or a *brightness illusion*?

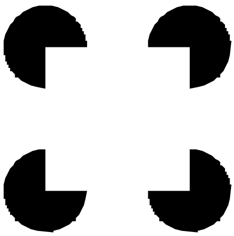

Fig. 1 Kanizsa Illusion

[1] As an anonymous reviewer pointed out, use of the term 'illusion' for this phenomenon might be more or less controversial. Although we use the term 'Kanizsa illusion' for convenience's sake, we think it's better than 'subjective contour' or 'illusory contour' which should be applied to broader phenomena.

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In addressing the above question, a key issue for resolving the controversy relates to the effects of eliminating a luminance difference (contrast) between figures and their background upon the strength of the Kanizsa illusion. Several experimental studies (Frisby & Clatworthy, 1975; Brussell, Stober & Bodinger, 1977) and phenomenal observations (Gregory, 1977; Frisby, 1979; Cavanagh, 1987; Livingstone & Hubel, 1987) have been made so far to explore this issue. The results of all these studies agree on the point that the strength of the Kanizsa illusion becomes much weaker in the patterns with eliminated (or reduced) luminance contrast than in a normal black-and-white pattern. However, there is an apparent disagreement as to whether the illusion completely disappears or not in so-called equiluminant patterns, particularly among observational studies. For instance, Livingstone and Hubel (1987) reported that it did disappear, while Gregory (1977) reported it didn't. It may not be so surprising, however, to see this disagreement because a judgment of the illusion's disappearance could be quite difficult when being made and sometimes it would be heavily influenced by the observer's subjective criterion. Therefore, we should consider quantitative results of psychophysical studies more than qualitative reports of observational studies.

The results of previous psychophysical studies of the Kanizsa illusion in patterns with eliminated (or reduced) luminance contrast are rather unfavorable for the viewpoint that the luminance contrast is necessary for the generation of the Kanizsa illusion. For instance, Jory and Day (1979) asked observers to rate the clarity of illusory edge and the magnitude of apparent brightness of the Kanizsa illusion in chromatic patterns using equivalent Munsell Values for figure and background properties. Their results showed that the mean rating on a 10-point scale (1 indicated the lowest and 10 the highest) was around 4 for edge clarity and around 3 for the apparent brightness. Takahashi, Kaihara, Takemoto, Ido, and Ejima (1992) employed inducing patterns presented as an increment of monochromatic light with various wavelengths upon an achromatic background, and measured the threshold for the Kanizsa illusion perception, that is, an intensity of the monochromatic light required to yield a just-perceptible illusion. Their results, the spectral sensitivity function for the Kanizsa illusion perception, showed a curve with three sensitivity peaks which roughly corresponded to the sensitivity peaks of our three cones when the background illuminance was high, suggesting that the visual processing for the Kanizsa illusion involves the opponent-color mechanism as well as the luminance mechanism. More recently, Ohya, Takahashi, Arakawa, and Ishisaka (2003) measured the magnitude of the illusion in chromatic patterns in which the luminance of green figures was varied from -32 % (darker) to +35 % (brighter) relative to a red background. Their results showed that even in the condition that yielded the minimal illusory effects, all observers perceived stronger illusion than in the control pattern where inducing figures (so-called 'Pac-men') were rotated to turn away from each other. Furthermore, Takahashi, Ohya, Arakawa, and Tanabe (2007) employed a visual search task to explore the early stages of visual processing for the Kanizsa illusion perception. They found that the Kanizsa illusion (or more precisely, a pattern generating it) was detected quite efficiently among non-target patterns (i.e., it 'popped-out') even in the equiluminant condition.

All of the above studies suggest that the luminance difference between inducing figures and their background may not be necessary for generating the Kanizsa illusion. Rather, it is possible that the luminance contrast is one of several regulating factors that influence the magnitude of the illusion. Thus, if the crucial figural information is effectively processed by the visual system, initial processing for the generation of the Kanizsa illusion may be triggered regardless of whether the information is given in the form of a luminance difference or in other forms, such as a color difference. Indeed, there is no doubt that the luminance channel of visual pathway has a significant advantage over the color channel for conveying such figural information because of its much higher spatial resolution property. It would, however, be possible to make a condition where the color channel plays a decisive role for generating the Kanizsa illusion. The most likely case for such a condition would be the equiluminant vision, that is, an observing condition where the luminance channel cannot work.

Consequently, the present study attempted to show a contribution of the color channel to the Kanizsa illusion perception in the equiluminant condition. As described above, there have been several studies that examined the equiluminant Kanizsa illusion. Most of these studies focused on the question of whether the illusion disappears or not in a particular equiluminant condition; that is, they employed only one equiluminant condition and compared the illusion perceived in that condition with the illusion in other non-equiluminant conditions. Such an approach may not, however, be the best way to elucidate a role of the color channel in the Kanizsa illusion perception, because the critical result (the illusion in the only equiluminant condition) may be influenced not only by the observer's criterion (as mentioned above), but also by a little residual luminance difference that can be caused by both the equipment's and the observer's properties. Instead, a more direct way for considering the role of the color channel would be to compare the illusion in some equiluminant conditions with changing amount of color difference. Thus we adopted such an approach, by examining the effect of the color difference between figures and background, while keeping the luminance difference minimal, on the perceived strength of the Kanizsa illusion. To achieve this purpose we systematically manipulated the excitation purity of chromatic inducing figures presented against an equiluminant achromatic background. Moreover, for the sake of detailed analysis we separately measured the strengths of three phenomenal properties of the Kanizsa illusion;

edge, depth and brightness. We expected that all or some of these measures would show monotonic increase with increasing color difference between figures and background in spite of the absence of the luminance difference, thereby providing evidence for a contribution of the color channel to the Kanizsa illusion perception.

2. Methods

2.1 Participants

Four authors (two males and two females) served as observers. All had normal or corrected-to-normal visual acuity and normal color vision (by self-reports).

2.2 Apparatus

Stimuli were generated by a personal computer (DELL OptiPlex GX110) equipped with VSG 2/5 graphic board (Cambridge Research Systems) and presented on a high-resolution 21-inch monitor (SONY Trinitron GDM-F520).

2.3 Stimuli

We used a Kanizsa-type illusory square inducing pattern that consisted of four green sectors (Pac-men) against a gray background. As an experimental variable, the excitation purity of the Pac-men was varied in six levels from 0.1, 0.2, 0.3, 0.4, 0.5, to 0.6 (Table 1). Luminance of the Pac-men was always around 52 cd/m^2. The background was achromatic and its luminance was determined individually by means of minimum flicker photometry (see below) for each excitation purity condition. In addition to these experimental patterns, a configuration of the same four Pac-men whose open mouths faced outward was used as a control pattern. The chromaticity of the Pac-men and the luminance of the background of the control pattern were set identical to those of 0.6 excitation purity condition in each observer. The size of the pattern was 2.1 in visual angle.

Excitation purity	x	y	Luminance
0.0 (achromatic background)	.310	.316	Varied (determined via minimum flicker photometry in each excitation purity condition for each observer)
0.1	.306	.356	52.8 cd/m^2
0.2	.303	.397	51.8 cd/m^2
0.3	.299	.437	52.2 cd/m^2
0.4	.296	.476	51.6 cd/m^2
0.5	.291	.517	51.6 cd/m^2
0.6	.288	.557	52.0 cd/m^2

Table 1 Chromaticity coordinates (CIE xy) and a luminance of the background and six conditions of figures

2.4 Procedure

2.4.1 Luminance calibration: Minimum flicker photometry

Before the main experiment, the first phase of this study required each observer to serve in a calibration task using minimum flicker photometry in order to determine individual equiluminant settings. In this task, a small (0.6 in a diameter) circular light alternating between green and gray at 15 Hz was presented on the monitor. Luminance and chromaticity of the green light was set at any one of six excitation purity conditions described above (Table 1), while the luminance of the gray light was adjustable. A participant observed it binocularly, and adjusted the luminance of the gray light by pressing buttons so as to eliminate (or minimize) a perceived flicker. The background on the monitor was also gray with a luminance of 52.2 cd/m^2. In each condition (i.e., the excitation purity of the green light), thirty-two adjustments were taken over the course of two separate sessions. Thus, each participant served in a total of twelve sessions with the order of conditions being randomized. In each session, a 10-minute adaptation to the gray background (with no flickering light) preceded sixteen trials of adjustment. One-minute rest, during which the observer watched the same gray background, occurred between trials. Each session took approximately 45 minutes.

2.4.2 Illusion measurement

Next, the experiment went on to the second phase, the main body of this research. The strengths of the Kanizsa illusion in terms of three phenomenal properties (illusory edge, apparent depth and apparent brightness) in each excitation purity condition were measured using the method of paired comparisons. We used the method of paired comparisons because the illusion strengths were weak in most patterns employed and, thus, the judgments observers had to make should have been as simple as possible. Two patterns were presented side by side on the monitor (Fig.2). A pair could comprise any two of the seven patterns (six experimental patterns and one control pattern), except for a coupling of the same patterns. The luminance of each bipartite gray background was set to be equiluminant with green figures in given excitation purity conditions according to the results of the flicker photometry (averaged value over thirty-two adjustments). A slightly darker (49.7 cd/m^2) gray strip with 0.3 width was inserted between these bipartite fields. This strip was employed in order to prevent observer from comparing the absolute brightness of the two backgrounds directly.

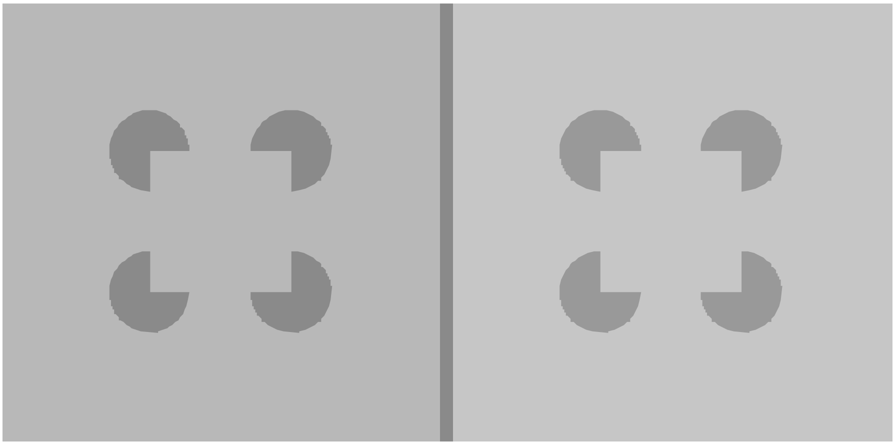

Fig. 2 A sample of paired-comparison display used in this experiment. In the actual display, Pac-men on both sides were presented in green, and each bipartite background was presented in equiluminant gray.

In each trial, a participant observed two patterns binocularly with his/her head resting on a chin-support located 80 cm away from the monitor, and judged which of the two patterns produced the stronger illusory effect in terms of one of three phenomenal properties; edge, depth or brightness. The phenomenal property for judgment was fixed throughout a single experimental session. Each session consisted of 420 trials (20 repeats for each of 21 combinations of seven patterns). As in the case of flicker photometry, each session started with a 10-minute adaptation to the uniform gray field. Then, after 20 practice trials, 420 experimental trials were carried out with one-minute rest every 105 trials. All participants received two sessions (840 trials) for each phenomenal property. The order of sessions for the phenomenal properties was randomized. Consequently, they made in total 2,520 judgments (40 repeats per pair x 21 pairs x 3 phenomenal properties) in six sessions. Each session took approximately one hour.

3. Results

Judgment data provided by each participant were converted into scale values according to the Thurstone method (case V). Fig.3 shows the individual results. In these graphs, scale values for six experimental patterns are plotted as a function of the excitation purity of the figures. Each plot indicates a difference from the value for the control pattern. A one-way repeated-measure analysis of variance showed that the excitation purity had significant effects on the scale values for all properties; edge: $F\,(5,15) = 239.61$, $p < .001$, depth: $F\,(5,15) = 474.83$, $p < .001$, and brightness: $F\,(5,15) = 9.38$, $p < .001$.

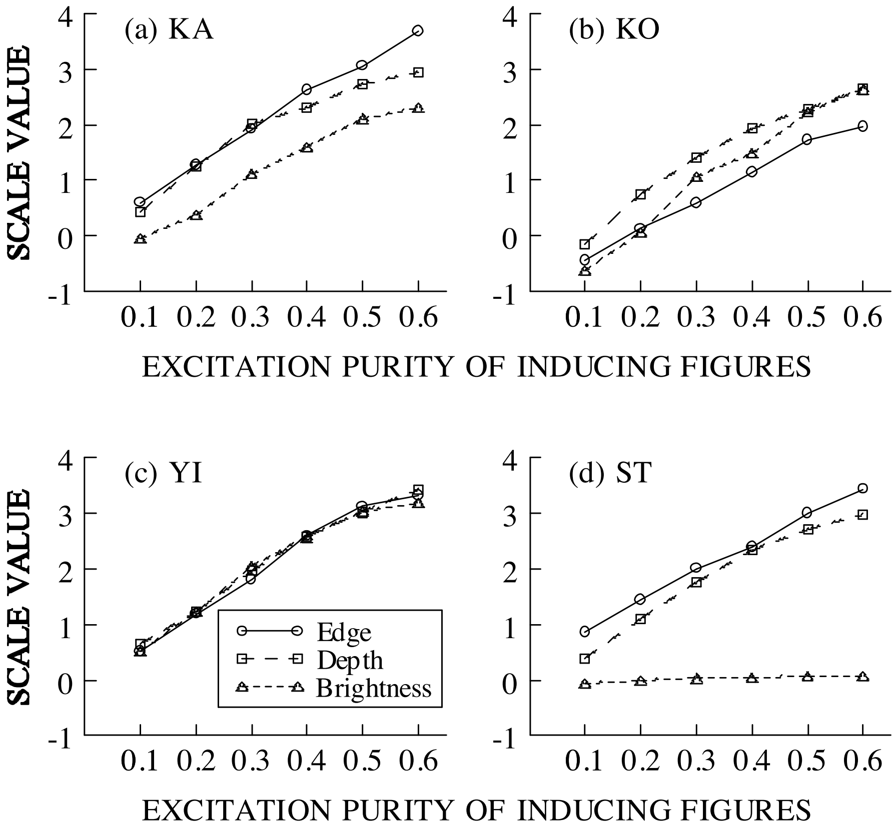

Fig. 3 Scale values for perceived strengths of edge, depth and brightness as a function of the excitation purity of figures

4. Discussion

We found that the strength of the Kanizsa illusion increased monotonically with increasing excitation purity of figures presented against an equiluminant achromatic background. The results shown in Figure 3 indicate that this effect holds for all three phenomenal properties (edge, depth and brightness) in three out of four observers. The only exception from this trend was with judged brightness in participant ST, in which the scale values were minimally influenced by the excitation purity.

To our knowledge, these are the first data to directly show that the color difference affects the strength of the Kanizsa illusion. As described in the introduction, thus far the effect of the luminance difference has been mainly focused upon in the past and the color difference has not been highlighted in eliciting this illusion. While it is very likely that any impact of the luminance difference is far greater than that of the color difference, this may have led to a misunderstanding that the luminance channel is the only visual pathway that contributes to the generation of the Kanizsa illusion. However, the present results clearly showed that the color channel, or more restrictedly stating a red-green channel, can contribute to the Kanizsa illusion in a certain condition. This finding is quite in line with Takahashi, et al. (1992) who argued that the visual processing for the Kanizsa illusion perception involves both the chromatic and achromatic (luminance) mechanisms.

The above argument suggests that the most crucial factor in eliciting the Kanizsa illusion is not the luminance difference between figures and background, but the configuration of a pattern that contains particular figural information such as an incomplete form of the inducing figures (Pac-men) and the alignment of their arrangement (Rock & Anson, 1979). Thus, in this experiment, increasing the excitation purity of figures appeared to enhance their visibility against the achromatic background, thereby rendering the figural information easier to process. Given this perspective, the Kanizsa illusion may become essentially a figural illusion, not a brightness illusion.

As reviewed in the introduction, evidence from the previous studies examining the Kanizsa illusion in patterns with reduced or eliminated luminance contrast are generally consistent with our view that the luminance contrast is not decisively needed for the generation of this illusion. Most results showed the illusion could be perceived in these patterns, even though much weaker than the illusion perceived in a normal black-and-white pattern. The only exception may be the result by Li and Guo (1995), who reported that the Kanizsa illusion was not perceived in the equiluminant condition. They argued this by showing that the Ponzo illusion was not induced in the equiluminant Kanizsa-triangle configuration. However it has been doubted that the strength of the Ponzo illusion perceived in such a configuration could be an appropriate index of the strength of the Kanizsa illusion itself (Kanizsa, 1979). Moreover, Takahashi, Ohya, Arakawa, and Ishisaka (2004) have shown quite different results from those of Li and Guo (1995) when they replicated their experiment: The Ponzo illusion was effectively induced in the equiluminant condition. The discrepancy between these results might have been due to large individual differences in the perceptual processing of the Ponzo illusion, since it should not be generated by such a simple mechanism that the saliency of illusory edges of the Kanizsa illusion solely determines its magnitude. This means the strength of the Ponzo illusion (and any other geometrical illusions put in the Kanizsa illusion configuration) would not be a good indicator of the strength of the Kanizsa illusion.

Returning to the present results, they offer further insight for considering the nature of an apparent brightness change that accompanies the Kanizsa illusion. In three of four observers, we found that the scale values for the apparent brightness increased monotonically as the excitation purity increased, much as found with the other two phenomenal properties (edge and depth). Here, we underscore the fact that all patterns employed in this experiment contained no (or at least the minimal) luminance difference. In other words, the present results showed that the strength of the apparent brightness can change even in the absence of a luminance difference in the stimulus pattern. This finding suggests that the apparent brightness change in the Kanizsa illusion is quite different from lower-level brightness effects such as, for example, the Mach bands and the Hermann grid illusion, which may be determined primarily by the local luminance difference between adjacent areas. Rather, it should be considered as a consequence of some more complicated visual processing at a higher level in which figural information is undertaken by the mechanism responsible for a visual organization.

As mentioned before, the only exception to the present results is found in the performance of observer ST with respect to the apparent brightness judgment. Because the scale values for edge and depth in ST's data showed same monotonic increase as found for the other observers, the fundamental finding that increasing color difference enhances the Kanizsa illusion would not be questioned by this result. Nevertheless, this particular finding is puzzling. Although conclusive explanations are not possible, we can speculate that the anomalous profile of brightness judgments by ST reflects reliance upon a different response criterion than that used by the other observers. That is, ST may have adopted a less strict criterion that did not distinguish among slight differences in illusion strengths, whereas more strict criteria of the other observers allowed for finer distinctions between the same differences. It would be reasonable to expect that these results are likely to be affected by criterion differences because the perceived illusion in employed patterns is not strong in general. In other words, eliminating luminance difference would have decreased the influence of stimulus factors, thereby increasing the relative impact of various subjective factors on the judgment. In any case, individual differences, including the role of criterion-setting, remain a problem for further investigations.In conclusion, the present study showed a contribution of the color channel (the red-green channel) to the generation of the Kanizsa illusion. The primary condition that triggers the visual processing for the Kanizsa illusion perception appears to be its unique configuration. In principle, such figural information can be conveyed through both the luminance and the color channels, however the former must have a definite priority over the latter. In other words, when the pattern contains even a small luminance difference, the luminance channel may play an almost exclusive role in generating the Kanizsa illusion with considerable strength. It has been suggested 5% (Livingstone & Hubel, 1987) or even less (Li & Guo, 1995) luminance contrast is enough to yield a clear illusion. In such cases, an additional color difference processed by the color channel should have little influence. It may even have an opposing effect; that is, de Weert (1983) found that the threshold luminance contrast needed for the generation of the Kanizsa illusion was minimized when a pattern contained no color (hue) difference. On the other hand, when the pattern does not contain a luminance difference above a certain threshold amount (as in the present experiment), the color channel will emerge to work. In that case, the figural information could be processed by the color channel to trigger the initial processing for the Kanizsa illusion, but a lack of the luminance contrast would then, probably at later stages, interfere with the subsequent processing for a formation of the clear illusory percept. In this sense, the luminance contrast is indeed necessary for the Kanizsa illusion to be entirely emerged. What should be noted is, however, that it would not be necessary to *trigger* the visual processing for the illusion.

Finally some limitations of the present study should be made clear along with the remaining tasks for the future studies. First, as mentioned above, individual differences, both in the perceptual domain and the judgmental domain, must be fully considered in future studies. Second, the present study examined only one color (green) for the figures. In order to thoroughly understand how the color channel contributes to the perception of the Kanizsa illusion, it is necessary to examine other colors, at least one on the yellow-blue axis as well as on the red-green axis. Two opponent-color mechanisms, the red-green system and the yellow-blue system, are expected to contribute to the Kanizsa illusion differently, since it has been shown by Ejima and Takahashi (1988) that the threshold purity for the illusory contour perception in an equiluminant abutting gratings pattern was smallest for colors on the red-green axis and largest for colors on the yellow-blue axis. Furthermore, it would be necessary to directly compare the influence of a luminance difference and of a color difference upon strength of the illusion in order to elucidate possible interaction of the luminance and the color channels in the generative mechanism of the Kanizsa illusion.

Summary

The contribution of the color channel of the visual pathway to the generation of the Kanizsa illusion (Kanizsa's anomalous surface) was examined. The excitation purity of green figures was varied against an equiluminant achromatic background. Four observers judged the strength of the resulting illusion in terms of each of three phenomenal properties of the Kanizsa illusion; edge, depth and brightness. Results showed that the strength of the illusion increased monotonically with increasing excitation purity of the figures, that is, the color difference relative to the background. Implications for theories about the mechanism underlying the Kanizsa illusion are discussed, emphasizing a

primary role of the figural information that would be processed by the color channel as well as by the luminance channel.
Keywords: Kanizsa illusion, equiluminant patterns, luminance difference, color differences, excitation purity.

Zusammenfassung

Der Beitrag des visuellen Farbkanals für die Entstehung der Kanizsa-Täuschung (anomale Fläche im Kanizsa-Dreieck) wurde untersucht. Die Farbreinheit grüner Figuren wurde vor einem gleichmäßig beleuchteten farblosen Hintergrund variiert. Vier Betrachter beurteilten die Stärke des jeweils entstandenen Effekts hinsichtlich der drei anschaulichen Merkmale des Kanizsa-Effekts: Kante, Tiefe und Helligkeit. Die Ergebnisse zeigten, dass die Stärke des Effekts mit dem Anstieg der Farbreinheit der Figuren, das heißt mit der Farbdifferenz zum Hintergrund, stetig zunahm. Folgerungen aus diesem Befund für den Mechanismus, der der Kanizsa-Täuschung zugrundeliegt, werden diskutiert. Für diesen wird eine grundlegende Rolle der figuralen Information postuliert, die sowohl über den Farbkanal, als auch über den Helligkeitskanal verarbeitet wird.
Schlüsselwörter: Kanizsa-Effekt, gleichmäßig beleuchtete Muster, Helligkeitsdifferenz, Farbdifferenz, Farbreinheit.

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