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Research Note

Transparent Surfaces Defined by Implicit X Junctions

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An X junction is known to be a strong cue for transparency whereas a T junction typically indicates occlusion by an opaque surface. In this article, however, we will demonstrate two cases in which special T junctions (implicit X) can support the perception of a transparent surface. The T junction is perceived as having an additional illusory contour rendering it as an *implicit* X junction. There is physically realizable condition in which transparency can produce a T junction and the existence of this special case may explain why T junctions are not necessarily taken as cues for opaque surface. The similar processing for X junctions and implicit Xs to form transparent surfaces is suggested.

Implicit X junction X junction T junction Transparency

Figure 1(a) shows an example of transparency made by luminance combinations. We see two overlapping squares with one dark square visible through another lighter square. Within the overlapping region shared by the two squares, both surface qualities, light and dark, may be perceived simultaneously and appear to be assigned to the separate depth levels of the two surfaces. This observation runs contrary to the assumption of simple computational models that the external world is opaque and therefore that each location of the visual field is represented by only one value for each surface attribute such as brightness or color (see Watanabe & Cavanagh, 1991b, 1992a, 1993; Watanabe, Zimmerman & Cavanagh, 1992).

It has been suggested that transparency perception is triggered by the X junction formed by the junctions of contours of the transparent and opaque regions at the overlapping area (e.g. Cavanagh, 1987; Kanizsa, 1979; Freeman, 1992; however, see Kersten, 1991). In addition, the luminance contrasts defining X junctions must obey two rules: (1) the direction of luminance contrast across an opaque border cannot change in the transparent region; (2) the luminance difference across an opaque border must be reduced in the transparent region‡ (Metelli, 1974). When these rules are violated, transparency is less likely to be seen, as in Fig. 1(b). On the other hand, a T junction is known to be a strong cue for occlusion (e.g. Cavanagh, 1987; Freeman, 1991, 1992; Peterson & Hochberg, 1983). T junctions in Fig. 1(c) indicate that the front surface is opaque and the figure appears as two similar opaque sheets staggered one behind another.

In the present study, we will show that T junctions are not limited to occlusion by an opaque surface. In particular, we will show that T junctions can also induce an impression of transparency in the same way as X junctions.

IMPLICIT X WITH MONOCULAR VIEWING

In Fig. 2(a, b), one smaller rectangle in the center and two larger rectangles on both sides are perceived. The relation between the three rectangles, however, is multistable. One percept is that the central, small rectangle is overlaid by a transparent rectangle on the left but it occludes the rectangle on the right. The perception of transparency in the lefthand rectangle is caused by the two X junctions defined by the lefthand and central rectangles with the appropriate luminance combinations for transparency as in Fig. 3(a). The perception of occlusion of the central rectangle over the righthand one is due to the two T junctions defined by the central and the righthand rectangles. The other percept is that both flanking rectangles appear to be transparent, overlying the central rectangle as in Fig. 3(b). In this case, a contour for the righthand rectangle appears to continue through the overlapping area. However, the luminance edge between the righthand rectangle and the background stops in a T junction where the righthand rectangle overlies the central rectangle and there is no luminance difference for the contour in the overlapping area. Thus, the apparent contour is illusory and completes an *implicit* X junction as illustrated in Fig. 2(c) where solid lines represent a real

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‡Beck, Prazny and Ivry (1984) suggest that the rules are determined by lightness contrast rather than brightness contrast.

contour and the dotted line an illusory contour. From these figures, we can say that not only X junctions but also T junctions can define a transparent surface.

In order to examine the effect of luminance combinations defining the implicit X on the perception of transparency and compare it with the effect in real X junctions, we conducted an experiment in which luminance in a section of the figure was varied.

Experiment

Method

Materials. The stimuli were presented on a color video display (23 × 17.25 deg, Apple M0401, 640 × 480 pixel resolution) controlled by a Macintosh IIci and viewed at a distance of 57.3 cm from the observers' eyes. There were four conditions (X junctions or T junctions in the intersection between the small, central rectangle and the righthand, large rectangle vs dark or bright background): (1) X junctions with the dark background [Fig. 4(a)]; (2) X junctions with the bright background [Fig. 4(b)]; (3) T junctions (on the right side) with the dark background [Fig. 4(c)] and (4) T junctions (on the right side) with the bright background [Fig. 4(d)]. The numbers on each area of the figures represent luminance and $L2$ represents the luminance which was varied from 10 to 74 cd/m,^{2} by nine steps. All the figures had the two X junctions in the intersections between the smaller

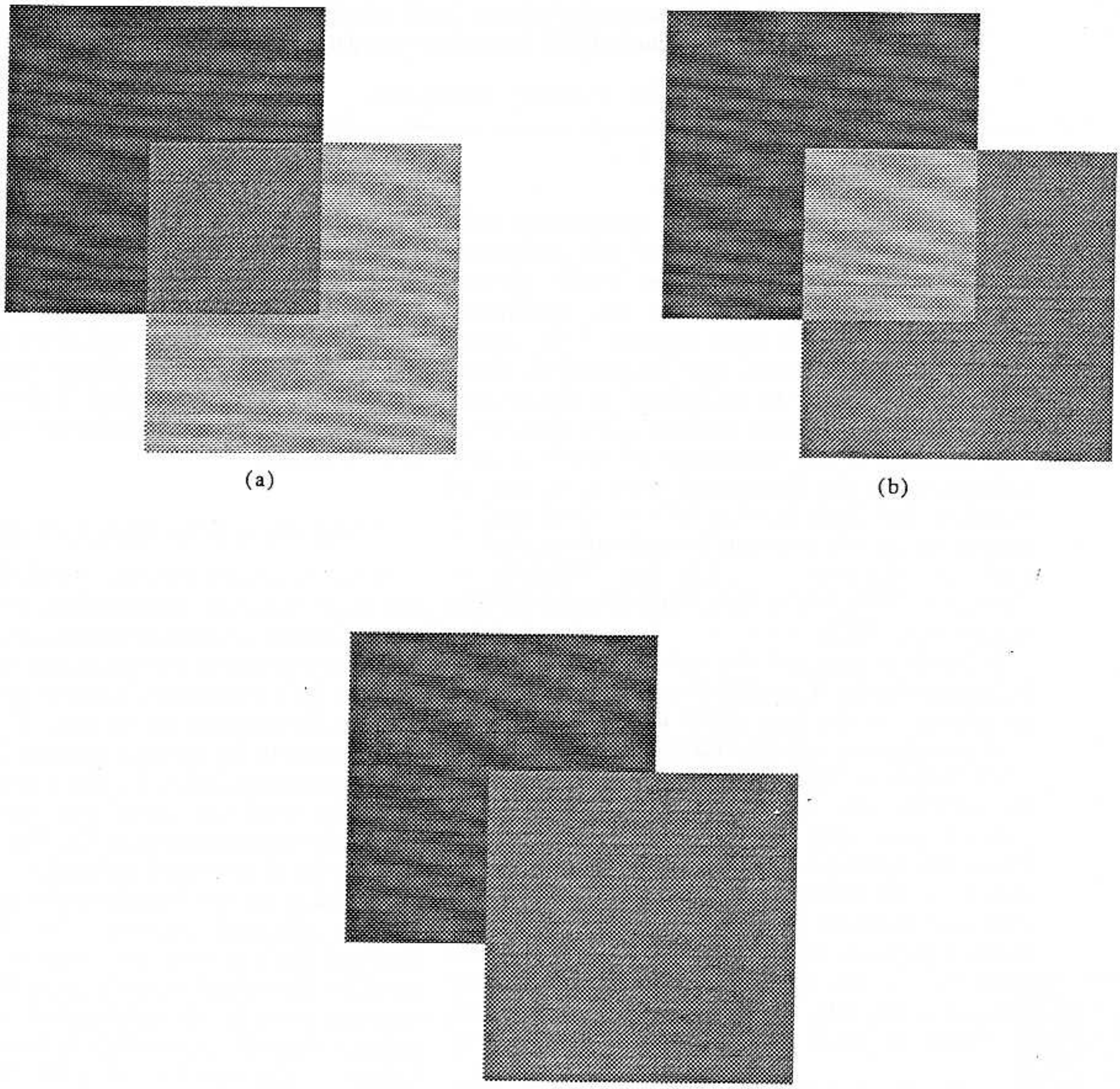

FIGURE 1. (a) An example of the perception of transparency. The bottom square appears to be a transparent sheet or filter lying over the top square. (b) If the direction of the luminance contrast across a transparent border changes in the transparent region, the perception of transparency weakens. (c) The bottom square appears to occlude the top figure. There are two T junctions in the intersections of the two squares.

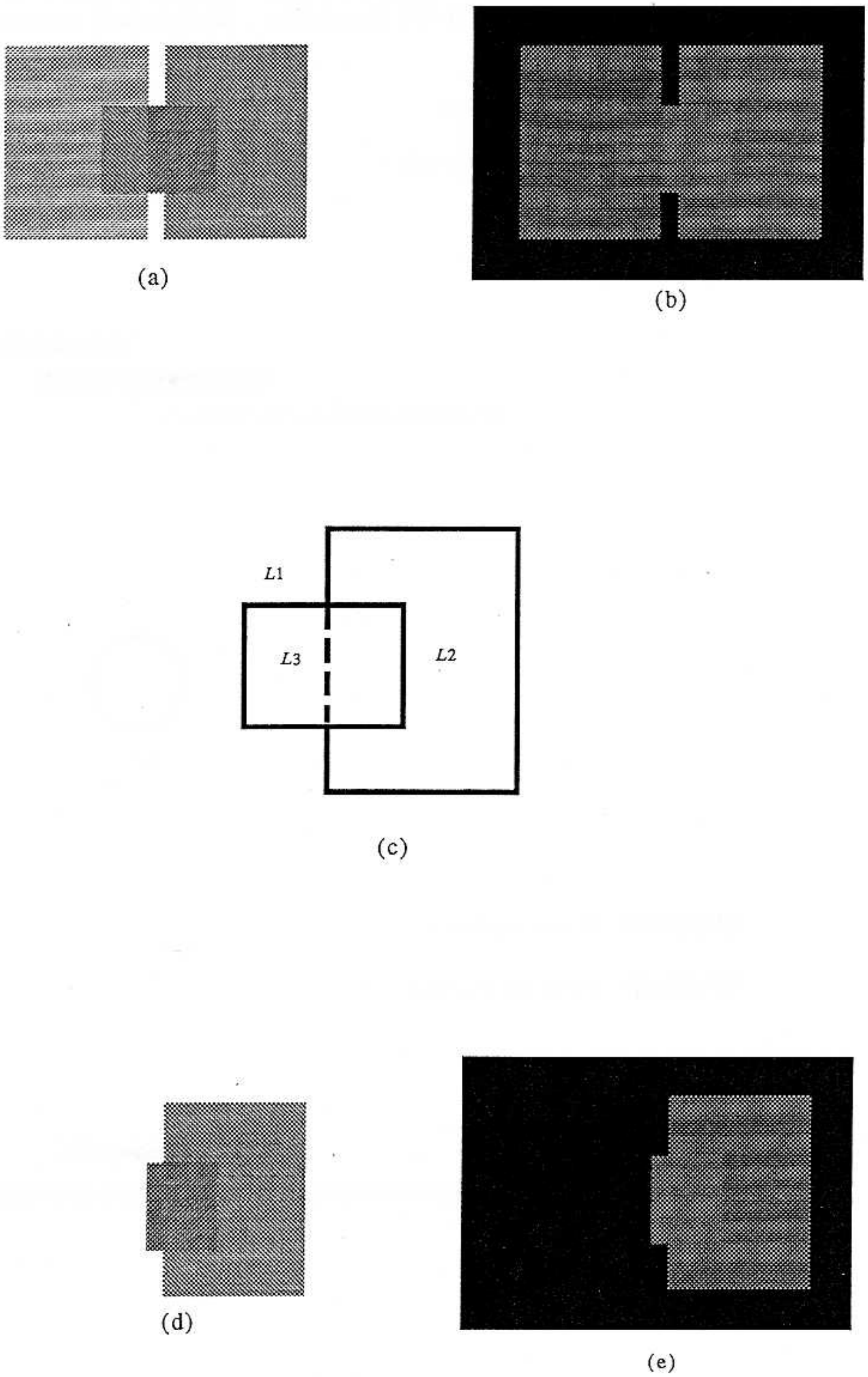

FIGURE 2. (a, b) Two organizations may be seen here. One is that a central small rectangle is partially covered by a transparent rectangle on the left but it occludes the rectangle on the right. The other perception is that both flanking rectangles appear to be transparent, overlying the central rectangle. An illusory contour of the righthand rectangle may be seen to continue through the overlapping area. (c) A schematic description of the central and the righthand rectangles in (a) and (b). $L1$, $L2$, $L3$ refer to luminances of each area. When $L2$ is in between $L1$ and $L3$, an illusory contour is seen as depicted as a dotted line. Thus we call the T junction an implicit X. (d, e) Transparency may be perceived even without neighboring X junctions although it is seldom the first organization that is seen.

central rectangle and the lefthand larger rectangle. These X junctions were defined by the luminance combinations valid for the physical transparency condition. Figure 4(a, b) had two other X junctions in the intersections between the central rectangle and the righthand rectangle. If the luminance $L2$ of the righthand rectangle was between 23 and 61 cd/m^2 the luminance combination defining the X junctions on the righthand was valid for

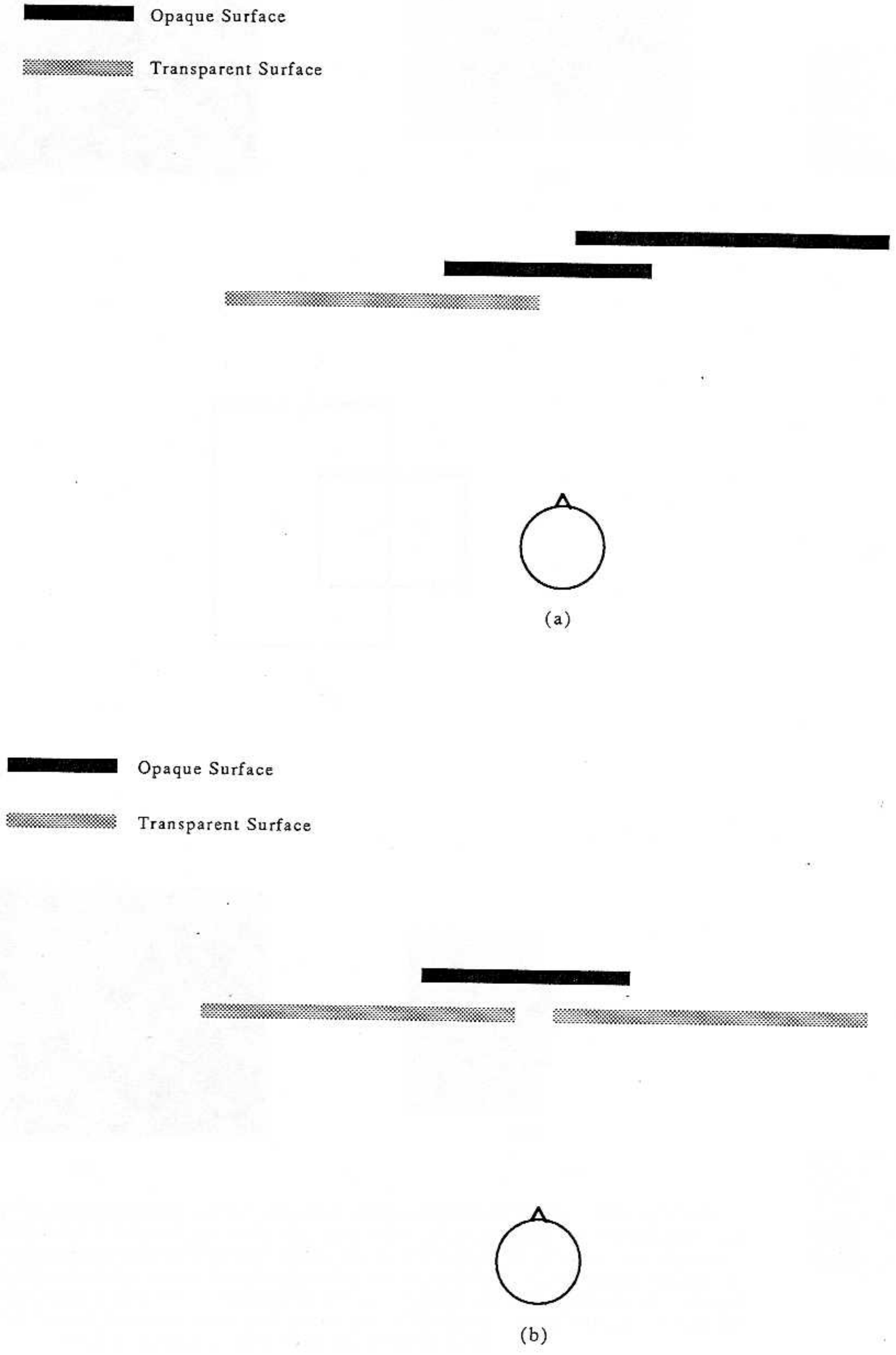

FIGURE 3. Schematic depictions of the bistable perception in Fig. 2(a, b).

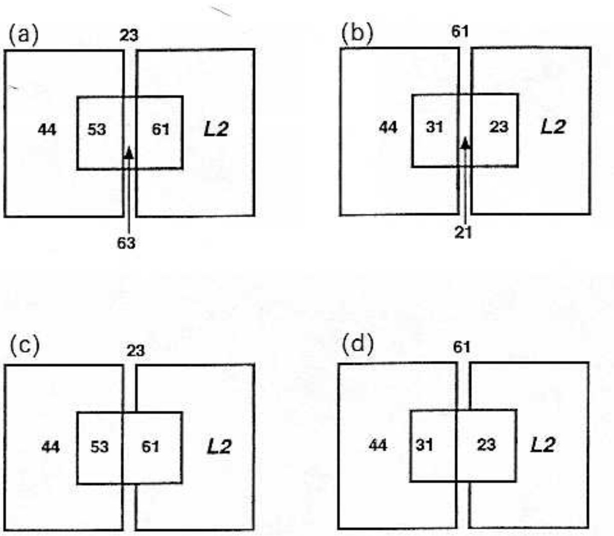

FIGURE 4. The stimuli used in the experiment. The numbers on each area of the figures represent luminance and $L2$ represents the luminance which was varied from 10 to 74 cd/m^2 by nine steps. In all of the four figures, there are X junctions in the intersections between the central and lefthand rectangles. In (a) and (b), there are X junctions also in the intersections between the central and righthand rectangles. In (c) and (d), there are T junctions in the intersections between the central and righthand rectangles.

the transparency condition.* Figure 4(c, d) have a pair of the T junctions in the intersections between the smaller central rectangle and the lefthand larger rectangle.

Observers. Three males and one female participated as observers between the ages of 23 and 35 yr. Three of them were naive for this experiment and one of them is one of the authors of this study (TW). They all had corrected-to-normal visual acuity (Snellen 20/20) and normal color vision (no errors in the Ishihara test).

Procedure. Each display was presented 10 times, so that the total number of trials was 4 conditions $\times$ 9 steps in the luminance $L2 \times 10$ repetitions = 360. The order of presentation was determined quasi-randomly. Before the start of the experiment, the observers were shown two figures [Fig. 3(a, b)] which described the two possible organizations of the three rectangles mentioned in the Introduction. In each trial, after a beep which lasted for 100 msec, the test stimulus was presented for 1 sec, followed by a mask pattern consisting of randomly arranged black and white squares which were 1 deg on each side, in order to erase the after image of the test stimulus. Then, the subjects had to answer which percept [Fig. 3(a) or 3(b)] they obtained, by pushing the corresponding key connected to the Macintosh IIci. 1 sec after the observers responded, they heard a beep for the next trial.

Results and Discussion

Figure 5 shows the results. The region which is between 23 and 61 cd/m^2 is called the transparency zone because the luminance combination defining the right pair of X junctions was valid for transparency within this luminance range. Surprisingly, there is a remarkable overlap between the curves for the X junction condition and the T junction condition. In addition, for both X junction

*Strictly speaking, $L2$ between 21 and 23 cd/m^2 in the dark background case and $L2$ between 61 and 63 cd/m^2 in the light background case are also valid for transparency with X junctions. Thus, the transparency zones are slightly different between the figures with X junctions and the figures with T junctions.

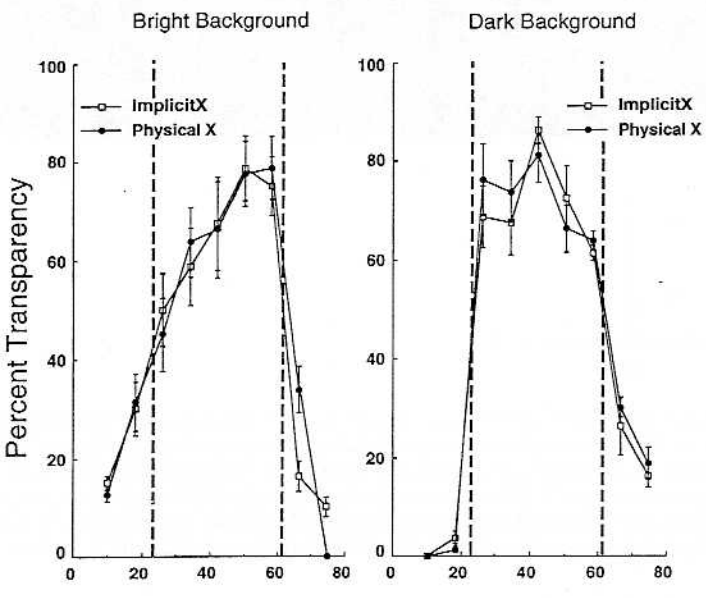

FIGURE 5. The percentage of the subjects' reports that classified the righthand rectangle as transparent as a function of the luminance $L2$ in Fig. 4 for the figures with X junctions and T junctions in the intersection between the central and right rectangles. The left graph is for the bright background and the right graph for the dark background. When $L2$ falls between 23 and 61 cd/m^2 (transparency zone), the luminance combinations defining X junctions in the intersections between the central and righthand rectangles were valid for transparency. Vertical bars represent $\pm$1SE across the four subjects. See footnote*.

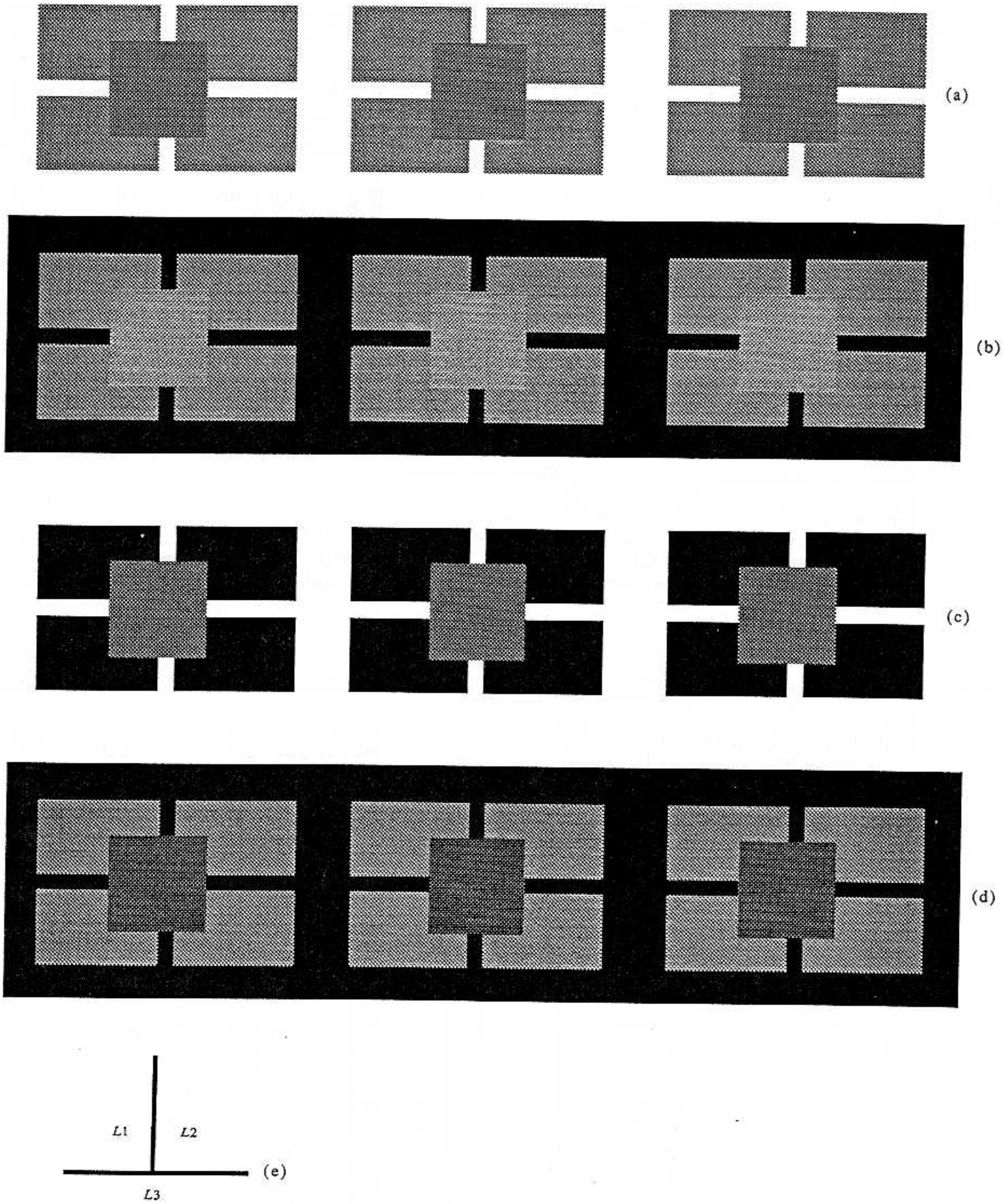

FIGURE 6. (a, b) Binocular stereograms provide another striking example of implicit X junctions that support transparency perception. When the four, incomplete peripheral rectangles appear to be in front of the central square (cross-fusing the right two images, or uncrossed fusing the left two images), the four rectangles appear to be transparent and to be completed by illusory contours. (c, d) If the luminance of the four rectangles [$L2$ in (e)] is lower than the background ($L1$) and the central square ($L3$), or it is higher than both of them, it is difficult to see transparency. Just as in Fig. 2, we found that transparency and illusory contours are observed only when the luminance combinations in T junctions fulfill $L1 < L2 < L3$ or $L1 > L2 > L3$.

and T junction conditions, the percentage of the subjects' perceiving transparency is higher within the transparency zone ($L2$ is between 23 and 61 cd/m^2) for both dark and bright backgrounds. These results suggest that the T junction can define a transparency surface as well as the X junction at least in the condition of the present experiment as long as the luminance of the righthand rectangle ($L2$) is between that of the background ($L1$) and the right part of the central rectangle ($L3$) as in Fig. 2(c).

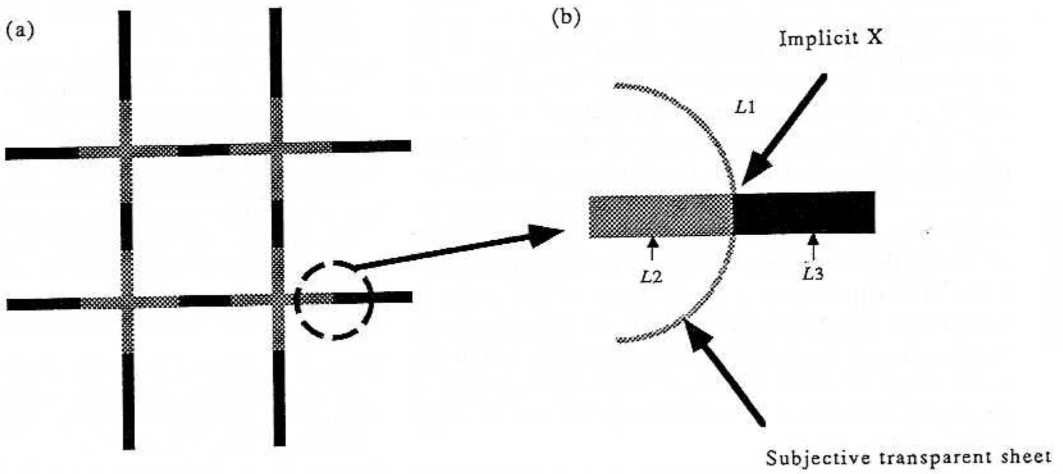

FIGURE 7. (a) The neon color spreading effect. The color (in this figure, gray) of the crosses spreads out of the containing contours and makes transparent sheets overlying the completed black grids. (b) A detailed examination of a single cross of the inducing figure shows that it contains T junctions and $L2$ must be in between $L1$ and $L3$ to have the neon color spreading, suggesting that T is acting as an implicit X junction in this illusion as well.

Do the X junctions in the intersections between the lefthand and central rectangles influence our percept of the righthand rectangle to be transparent? Several observers reported that it is possible to perceive the righthand rectangle as transparent in Fig. 2(d, e), even without the valid X junctions of the lefthand rectangle, but the perception of transparency is not the initial percept. From these observations, we may say that although the neighboring X junctions strengthen the salience of perception of transparency induced by T junctions, T junctions alone can induce transparency perception.

IMPLICIT X WITH BINOCULAR VIEWING

It has been pointed out that the tendency to perceive a surface as transparent increases when it is seen to be in front of the surrounding figures (Akerstorm & Todd, 1988; Nakayama & Shimojo, 1992; Watanabe & Cavanagh, 1992b). Figure 6 shows another example of the implicit X junction. Monocularly, the central square in Fig. 6(a) appears to be opaque, occluding the four peripheral rectangles. However, when the four incomplete, occluded rectangles have "near" disparity relative to the central square in Fig. 6(a, b), the missing corner of each rectangle is completed by illusory contours and the four complete rectangles appear to be transparent sheets lying over the central square. If the luminance of the four rectangles [$L2$ in Fig. 6(e)] is lower than the background ($L1$) and the central square ($L3$), as in Fig. 6(c), or it is higher than both of them, as in Fig. 6(d), it is much more difficult to perceive transparency and even a depth difference between the four rectangles and the central square.* That is, just as in Fig. 1, transparency and illusory contours are observed only when the luminance combinations in T junctions fulfill $L1 < L2 < L3$ or $L1 > L2 > L3$. Similar figures were made by Anderson and Nakayama (1992) independently for different purposes.

GENERAL DISCUSSION

We have shown that under certain conditions, a T junction can be an effective cue for transparency perception, which is at odds with the traditional idea that T junctions are strong cues for occlusion and X junction are required for transparency.

The implicit X junction may also be a cue to transparency in the illusion called the neon color spreading shown in Fig. 7 (Redies & Spillmann, 1981; van Tuijl, 1975). The color (in this figure, gray) of the crosses spreads out of its containing contours and appears to fill a transparent sheet overlying the completed black grids.† It has been reported that the luminance of the crosses must be in between the grids and the background to obtain the neon color spreading effect (Redies & Spillmann, 1981; van Tuijl & de Weert, 1979). We point out that the inducing figures consist of T junctions and that the required luminance values for the neon color spreading fulfill the same constraints as those for the implicit X as in Fig. 5, suggesting that the implicit X junction is the cue for transparency in this illusion as well.

*Coincidence between occurrence of transparency and depth perception by binocular disparity has been reported with figures with X junctions, too (Trueswell & Hayhoe, 1993). That is, both transparency induced with X junctions and depth difference are perceived when the Metelli's rules are valid but neither transparency nor depth difference are observed when they are not valid.

†The relation between the neon color spreading effect and transparency has been pointed out by several researchers (de Weert & Kruysbergen, 1987; Grossberg, 1987; Kanizsa, 1979; Kellman & Shipley, 1991; Meyer & Senecal, 1983; Nakayama & Shimojo, 1992; Ramachandran, 1990; Redies & Spillmann, 1981; Takeichi, Shimojo & Watanabe, 1992; Watanabe & Cavanagh, 1991a; Watanabe & Sato, 1989; Watanabe & Takeichi, 1990). In particular, Grossberg (1987) suggested that both the neon color spreading effect and transparency induced with X junctions are the results of feature filling in up to the contours made as a result of the interactions of boundary processing (Grossberg & Mingolla, 1985).

Why can T junctions support transparency? It may be because the disappearing border of a transparent sheet in the overlapping area with an opaque object is physically possible and the visual system assumes that a T junction can be a cue for transparency. A border of transparent sheet in the overlapping area with an opaque object can physically disappear when $r_1(1 - t^2) = r_2$, e.g. in Fig. 2(a), where r_1 refers to reflectance of the central opaque rectangle and r_2 and t refer to reflectance and transmittance of the righthand transparent sheet. However, mathematically, this equation is a special case of $L2$ being in between $L1$ and $L3$, suggesting that the visual system is flexible enough to reconstruct transparency within the wider range of valid luminance combinations than is physically valid which includes the special case of transparency with a T junction.

Does the visual system process X junctions and implicit Xs in the same way to form transparent surfaces. Our finding that $L2$ must be in between $L1$ and $L3$ in order for T junctions to induce transparency is consistent with the Metelli's rules as described in the Introduction: (1) the direction of luminance contrast across an opaque border does not change in the transparent region; and (2) the luminance difference across an opaque border is reduced in the transparent region. This suggests that if the directions of the luminance contrasts of two connecting lines are the same, the visual system can give a signal for transparent surface across the line with weaker luminance contrast of the two lines, whether the lines make X junctions or T junctions. The computational models which induce transparency with X junctions and occlusion with T junctions in a dichonomic way are too simple in this respect. Rather, the directions and relative strength of the contrasts of lines may be considered as more important.

In summary, we showed that T junctions which are typically strong cues for occlusion can also induce transparency in a special situation. In this case, the T junction is perceived as having an additional illusory contour rendering it an *implicit* X junction. As we argued, perhaps the T junctions do not veto transparency interpretation because the disappearing border is physically possible. The possibility of the same processing for X junctions and implicit Xs to form transparent surfaces is suggested.

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