Perceptual removal of transparent overlay

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A novel method for generating subjective disappearances of visual surface(s) was tested in perceptually transparent situations, as if seeing one surface through another. The striking phenomena after the selective removal of coloured transparent overlay(s), which remained physically present, were of colours perceived in the disclosed surfaces comparable to those perceived through transparent overlay(s). This might be attributable to an independency of chromaticity in the representation of perceptually transparent surfaces.

Viewing a visual target in Figure 1b, fixating on the central cross, we soon reach one of two interpretations, i.e., a cyannish transparent triangle is overlying a reddish triangle or a reddish transparent triangle is overlying a cyannish triangle, with the two seeming to alternate spontaneously. In either of the two interpretations, the gray region seems stratified as two independent continuums composed of a cyannish and a reddish triangle, as if one of them is transparent and overlying the other. With this dual nature of the gray region, a colour-dependent decomposition of all other regional surfaces into two different depth components (or layers) would be realized in perceptual space[1-4]. This process is called 'scission'[3,4]. We might ask: if scission underlays the perceptual transparency interpretation among surfaces, what is seen when one of these transparent surfaces is removed perceptually? Here, I report a novel finding addressing this question, by showing that the surfaces disclosed have similar colours to those perceived through a coloured transparent overlay.

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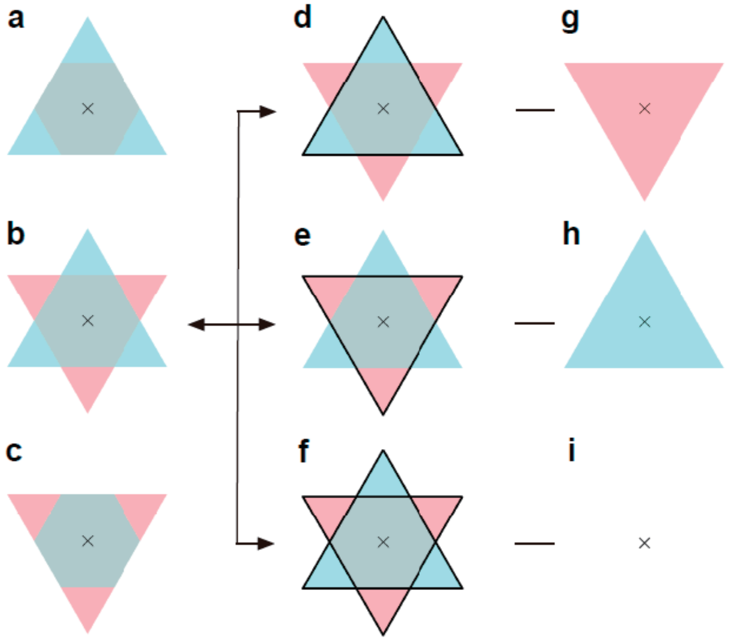

Figure 1

Outline erasure effects in the two-surface condition. *A common target composed of two surfaces (**b**), in which a cyannish surface is overlaying a reddish one in the 2D condition, is shown. From **d** to **f**, three tasks are shown to represent cases in which two transients were applied to the cyannish (**d**), reddish (**e**), and both surfaces (**f**). The typically reported colours for the remaining surface(s) after the two transients were reddish, cyannish, and white (background), as shown in **g**, **h**, and **i**, respectively. This suggests that the perceived colours of the remaining surface(s) were invariant before and after the removal of one or both of the composite surfaces. This colour constancy phenomenon was reported in 96, 95 and 99% of trials when the cyannish (**d**), reddish (**e**), and both surfaces (**f**) were deleted, respectively. No significant difference was found in the frequency of trials showing colour constancy among the three tasks* ($x^2(2)=0.100$, *ns*, $n=270$)*. (**a**, **c**), two surfaces in which three reddish or three cyannish regions composing one of two triangles in **Fig. 1b** were deleted beforehand, respectively. Note that in both cases, the same gray hexagon remains. The two transient stimuli were applied in the same way as in **Fig. 1d** and **1e**, respectively.*

To erase transparent surface(s) selectively in perceptual space (e.g., **Fig. 1b**), two successive transient stimuli were used. A real outline was placed on the contour of one of two triangular surfaces (onset transient, **Fig. 1d,e**) and the same outline was erased one second later (offset transient). Across the two transients, no regions of the two triangles were lost, and their physical colours were invariant over time. The present findings showed the aftereffects of the two transients on subsequent perception of the surfaces (**Supplementary Video 1** online). The observers reported that, following the onset transient, perceptual alternation in the depth order of two surfaces ceased, so that the outlined surface (e.g., the cyannish one in **Fig. 1d**) was definitely perceived as a coloured transparent one overlaying a reddish triangle. The subsequent offset transient induced perceptual disappearance of the cyannish surface, resulting in disclosure of the other surface for a few seconds. The striking phenomenon was the colour of the surface disclosed (**Fig. 1g**), which was uniformly red across the surface, similar to that perceived through a transparent overlay (**Fig. 1b, d**). Similarly, two transients applied to the reddish surface disclosed the cyannish surface, and the colour was similar to that perceived before the offset transient (**Fig. 1b, e, h** and **Supplementary video 1** online). This so-called colour constancy phenomenon was confirmed in two other cases when a reddish surface in Figure 1b was replaced with a greenish surface (**Supplementary video 2** online), or a cyannish surface in Figure 1b was placed behind a reddish surface (**Supplementary video 3** online).

For comparison, the same experiments were repeated using either a cyannish or a reddish triangle alone in Figure 1b (**Fig. 1a** or **c**, respectively). In both cases, no transparency cue was given for the gray region, and thus no perceptual alternation of the two surfaces was observed. Two transients applied to the contour of these triangles led to an instantaneous disappearance of the whole surface, except for a few cases in which the hexagonal region remained visible alone (**Supplementary video 4** online). Even in the latter case, the colour perceived in this region was neither reddish nor cyannish, but definitely gray. In both cases, the colour contrast between local regions did not involve edge assignments to interpret the colour of the hexagonal region as originating from a fusion of two surfaces of different colours (**Supplementary note** online). The lack of this clue may impede depth stratification and the resulting transparency interpretation among surfaces, causing an inability to disclose the colour of the underlying surface when its transparent overly is removed perceptually.

The colour constancy phenomenon was reconfirmed with three surfaces (**Fig. 2**) (**Supplementary video 5** online). Similar to the cases for the two-surface condition, the observers perceived spontaneous alternation in the depth order of the three surfaces. Also, once the onset transient was applied to any one of the three surfaces (**Fig. 2b,c,d**), the corresponding surface was definitely individuated as the foremost, transparent one, overlying the other two. The subsequent offset transient induced the disappearance(s) of the corresponding surface(s), leading to disclosure of the other two surface(s), whose colours were similar to those perceived before the offset transient (**Fig. 2e,f,g**, respectively). Similarly, when any two of the three surfaces were deleted in the same way (**Fig. 2h,i,j**), the perceived colour of the remaining one was similar to that perceived before the second transient (**Fig. 2k,l,m**, respectively).

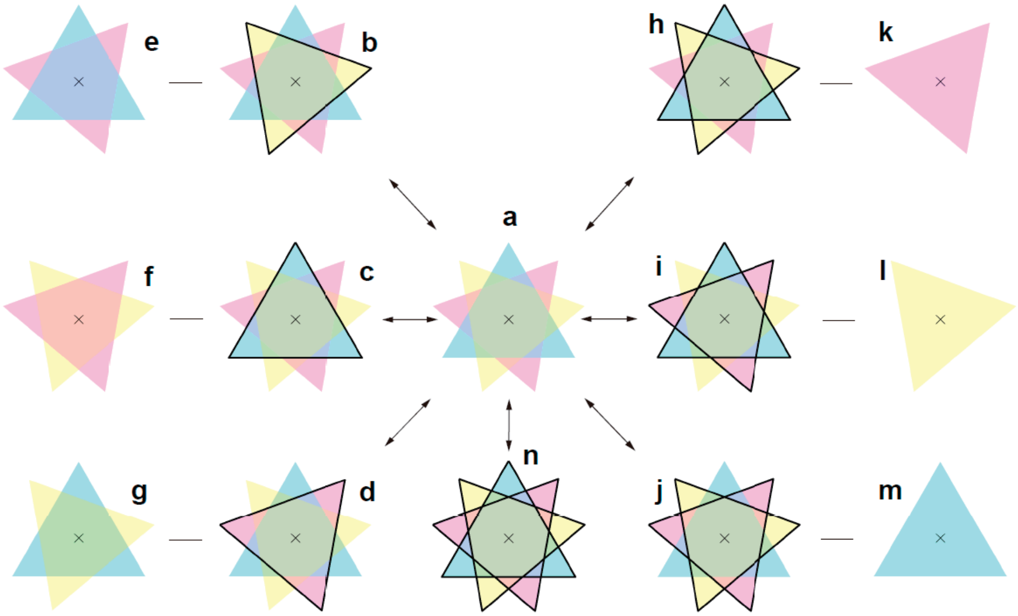

Figure 2

Outline erasure effects in the three-surface condition. *Seven patterns of stimulus presentation to examine colour constancy before and after the removal of one or two of three overlapping surfaces are shown. As a common target (**a**), three triangles of different colours are overlapped with a depth order of rearmost magenta, middle cyan, and foremost yellow. In the left (**b-d**) and right (**h-j**) columns, three patterns of transient stimuli to erase one and two surfaces are shown, respectively. (**e-g**, **k-m**), typically reported colour(s) of the remaining surface(s) after the offset transients shown in panels **b-d** and **h-j**, respectively. In **n**, two transients were applied to three surfaces simultaneously, and thus no surface was visible. The frequency of trials showing colour constancy varied from 90 to 97% in the seven tasks, and averaged 94%. Among these, no significant difference was found in the frequency of trials showing colour constancy in the remaining surfaces* ($x^2(6)=0.434$, *ns*, $n=630$).

In both the two- and three-surface conditions, furthermore, when two transients were applied to all surfaces at the same time (**Figs. 1f** and **2n**, respectively), they disappeared simultaneously, and thus a white background was seen alone (**Supplementary videos 1-3, 5** online). These results suggest that colour constancy of the remaining surfaces across the two transients held true regardless of the number or depth order of surfaces deleted.

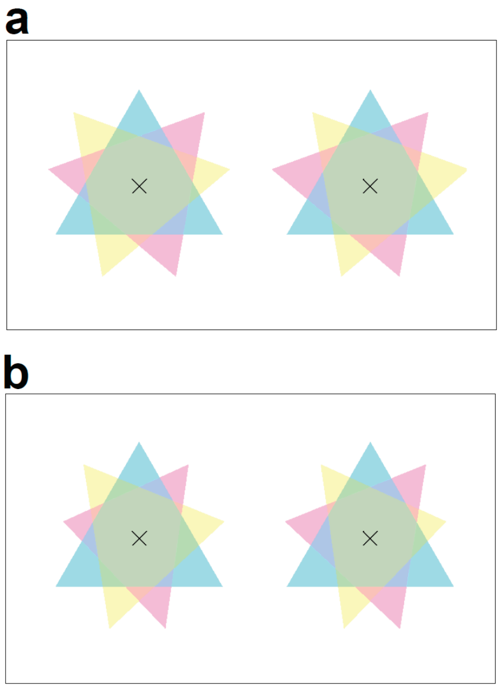

Figure 3

***Outline erasure effects in surfaces viewed in 3D conditions.** A pair of three surfaces of different colours (yellow, cyan, and magenta), used to examine colour constancy phenomena under the 3D condition, are shown. Cross-fusion of the two eyes was used to perceive two different patterns of configuration among the three surfaces in **a** and **b**, such that the three overlapping surfaces were layered in parallel or obliquely in 3D space, respectively (for details, see **Methods**). In both (**a, b**) conditions, a pair of cyannish surfaces is represented with the same configuration and distance, and referred to as a common cornerstone to place the other two surfaces in different positions in 3D space. In **a**, the horizontal distances of yellow surfaces of both sides are positioned closer relative to the cyannish surfaces, whilst those of magenta surfaces on both sides on the monitor are more distant relative to the cyannish surfaces. As a result, a cross-fused image composed of a foremost yellow surface, a cynanish surface in the middle, and a rearmost magenta surface was created in the depth direction. In **b**, the differences in disparity of the paired images were adjusted in order for the three surfaces to intersect diagonally in the depth direction, with the depth order of two surfaces (yellow and magenta) reversed at the vertical mid-line of the cyannish surface. To achieve these configurations, the horizontal width of the yellow surface on the right side was slightly reduced relative to the yellow surface on the left side, whilst the horizontal width of the left side magenta surface was reduced relative to the right side magenta surface (for details, see **Methods**). During the period of cross-fusion, the same one or two surfaces on both sides were removed by the two transients, similar to the sequence shown in **Fig. 2**. Seven tasks were executed using a different combination of stim-*

*uli applied to any one, any two, or all three surfaces. Among the seven tasks in a, the frequency of trials showing colour constancy varied from 87 to 97% of trials, and no significant difference was noted in their frequency ($\chi^2(6)=0.443$, ns, n=490). Similarly, for the seven tasks in **b**, the frequency varied from 87 to 98% among trials, with no significant difference in the frequency of trials showing colour constancy ($\chi^2(6)=0.737$, ns, n=420).*

Finally, we examined whether the same colour constancy phenomena occurred when the target surfaces were viewed stereoscopically. In this condition, perceptual alternation between multiple surfaces did not occur and the observers perceived a fixed depth order among multiple surfaces, as they were layered separately in 3D space. Similar to the 2D condition, the surface disappearances arising due to two transients applied to one or two of the overlapping triangles successfully disclosed the colours of the remaining surfaces (for the two-surface condition, see **Supplementary video 6** online). In the three-surface condition, for example, when any one or two of the three surfaces placed in parallel in the depth direction were erased (**Fig. 3a**), the other two or one surface(s), respectively, remained visible with the same colours as those perceived before the erasure (**Supplementary video 7a** online). Further, in cases where three surfaces intersected diagonally in the depth direction (**Fig. 3b** and **Supplementary video 7b** online), the deletion of outlines of one or two surfaces led to the disappearance of the corresponding surfaces, leaving the perceived colours of the remaining two or one surface invariant, respectively, relative to those perceived before the offset transients. These results suggest that in the 3D condition, the individuation of an outlined surface as the foremost, transparent overlay, as observed in the 2D condition, was not essential for erasure of the corresponding surfaces.

The present results were consistent regarding the matching of surface colours when perceived before and after the removal of the coloured transparent overlay(s). In these apparent colour constancy phenomena, a layer-based representation of regions may underlie the process of depth stratification of composite surfaces of different colours. The ‘scission’ might be a base mechanism by which the visual system accomplishes this stratification, whereby the effects it has on the perceived colour of overlapping surfaces can be directly experienced by erasing one or two composite surfaces in perceptual space.

In transparency situations, light rays coming from the transparent surface and those coming from the underlying surface do reach the same retinal location, triggering a single sensorial process. To interpret one surface through another, therefore, the visual system must somehow map the retinal information onto a perceptual representation in different layers. Many conditions for inducing perceptual transparency interpretation have been proposed[1-9] (**Supplementary note** online), in some of which the pattern of luminance contrast among regions was regarded as a critical cue of scission processing and the resulting perceptual transparency interpretation[3,9]. Although these studies typically employed achromatic targets, recent research provided supporting evidence that the scission process could potentially account for the colour induction to decompose multiple regions into a layered image representation of surfaces[1,4]. The present results revealed that not only the scission is phenomenologically very explicit in chromatic space, but the effects it has on the perceived colour of composite surfaces can be directly experienced by erasing one of them in perceptual space. In physical terms, a fusion of two colours produces a third colour, but the specification of a unique combination of two colours from a third colour is impossible. This inverse optics problem[2] could be solved in perceptual transparency situations when an overlapping region of two surfaces yields a third colour.

Methods

Observers. Nine observers (1 male and 8 females) with a mean age of 20.5 (± 2.4) years, took part in the experiments. All observers reported normal visual acuity and colour perception. The experiments were performed in accordance with the Declaration of Helsinki, and approved by the University Research Ethics Committee. Two participants who failed to see the target stereoscopically by cross-fusion were excluded from the corresponding experiments.

For all experiments, stimuli were presented on a PC monitor running at a refresh rate of 60 Hz and with a resolution of 1920 × 1200 pixels, controlled by a PC running Intel Core processor i3-8100. Stimulus presentation and data collection were controlled by MATLAB (R2018b, The MathWorks) scripts using self-made custom software, developed for each experiment.

Procedure. The same manner of stimulus presentation was used across all experiments. The observers were seated in a dark room at a viewing distance of 65 cm from the PC monitor. Once the target was presented, they were asked to fixate on a central black cross, subtending 0.44 degrees (°) in the centre of the target pattern using both eyes, while keeping their attention evenly distributed over the whole target. After 3 seconds of fixation, a solid line(s) was displayed along contour(s) of the targeted triangle(s) (onset transient) for 1 second, and then erased (offset transient), leaving the image of all surfaces intact. The offset state was kept for 2 seconds, and then the target image was replaced with multiple patches of different colours. These were lined-up in a row, to specify the perceived colour(s) of the remaining surface(s). They were represented by colours of individual triangles, a fusion of colours to represent the overlapped region, and white background. The observer pointed to one of these patches using a mouse to report the remembered colour of the remaining surface(s) perceived just after the offset transient.

Based on preliminary studies, the surface disappearances provoked by the offset transient continued for up to 3.0 (±1.08) seconds. Therefore, each subject's report of the perceived colour of the remaining surface(s) needed to be just after the offset transient. In each experiment, stimuli were presented to observers 10 times, with an inter-trial resting period of 10 s. During each trial, blinking was discouraged.

Colour composition of surfaces. The visual targets were composed of two or three partially overlapping equilateral triangles of different colours and in different orientations. In the two- (e.g., **Fig. 1**) or three-surface conditions (e.g., **Fig. 2**), relative to an upward facing triangle, the orientations of the other one or two triangles of the same size were rotated about their common geometric center, in steps of 60° or 40°, respectively. The vertices of these triangles were 9.06° distant from their common geometric center, where the central fixation point was located. Different colours were used to represent each of the two or three triangular surfaces, which were semi-transparent, displayed on a white background (143.1 cd/m^2). The luminance of a given surface colour displayed on the white background was constant across the experiments: red [Luminance (L)=74.6 cd/m^2, hue angle (H)=0°], cyan (L=116.0 cd/m^2, H=180°), green (L=124.1 cd/m^2, H=120°), yellow (L=130.0 cd/m^2, H=60°), and magenta (L=79.1 cd/m^2, H=300°).

The level of transparency of coloured surfaces is defined as opacity α, the degree to which light is not allowed to travel through. The colour is opaque when $\alpha=1$, and fully transparent when $\alpha=0$. In the two-surface condition (**Fig. 1**), the resulting pixel colour in the overlapping region Cnew is given by compositing pixels using a blend function10:

$$C_{new} = \alpha_f C_f + \alpha_b (1 - \alpha_f) C_b$$

where the two terms from left to right on the right side denote the pixel colours of the foremost (f) and rearmost surfaces (b), respectively. αf and αb, define the independent opacities of two surfaces, Cf and Cb, respectively. In overlapping situations, however, the opacity of the second term is scaled by its αb value to calculate its contribution correctly.

In the three-surface condition (**Fig. 2**), the case compositing the foremost image with the rearmost image, defined above as the result of compositing two images C_1 and C_2, becomes:

$$C_{new} = \alpha_f C_f + (1 - \alpha_f)\,[\alpha_1 C_1 + \alpha_2\,(1 - \alpha_1)\,C_2]$$

where subscripts 1 and 2 denote the middle and rearmost surfaces, respectively. Thus, α_1 and α_2 define the independent opacities of two pixel colours C_1 and C_2, respectively.

In both of the two- and three-surface conditions, α was set at 0.25 for all surfaces, such that the linear composite effect of colour blending in all terms yields apparent transparency. The pixel colours of overlapped regions depended on the depth order of the composite surfaces.

3D views of target. By crossing (converging) the eyes, the visual system can fuse two images into a single perception and convert the disparity between the two images into a perception of depth. With this method, transparent surfaces overlapped in the depth direction can be viewed as a single target in 3D contexts[11](e.g., **Fig. 3**). In both of the two- or three-surface conditions, a pair of equilateral, cyannish surfaces of the same size as used in the 2D condition, were separately displayed on the same monitor by a horizontal distance of 0.24 m. These two cyannish surfaces were cross-fused into a single one (perfect match), in order for their central fixation crosses to project to two corresponding foveas with *zero disparity*. The two cyannish surfaces were thereby fused into a single flat surface on a frontal plane. The horizontal positions or widths of other surfaces on both sides were slightly changed relative to each of the cyannish surfaces, in order for their projected locations on the retina to have non-zero, different disparities. By manipulating this difference in disparity (imperfect match) between the two views, the depth or orientation of the resulting fused surface (stereogram) can be easily changed in 3D space. We tried two spatial patterns of overlapping surfaces, i.e., two of three surfaces were placed at different distances in the depth direction (**Fig. 3a**) or were obliquely intersected relative to the frontal plane (**Fig. 3b**). To achieve the first condition (**Fig. 3a**), relative to the position of the cyannish surfaces on both sides, the other pairs of overlapping surfaces were positioned closer, or further, to place their fused surfaces in front of (*crossed disparity*) or behind (*uncrossed disparity*) the cyannish surface. For the second condition (**Fig. 3b**), when the disparity of one of two surfaces was reduced relative to the other, the stereograms of the corresponding surfaces appeared to be in the oblique layer, intersecting the cyannish surface.

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Additional information

Supplementary videos 1-6, 7a and 7b are seen in the following site.
https://www.youtube.com/channel/UCH2K4z5dDZ06dUw5-QXePRw/videos

Supplementary note

An important aspect in perceptual transparency is the ambiguity of interpretation of the depth order among surfaces, causing a spontaneous alternation in depth order[1] (e.g., **Fig. 1b**). In preliminary studies, we tested the effect of attentional allocation on the phenomenal impression of the target appearance in the 2D condition. In the target situation in **Fig. 1b**, for example, voluntary attention on one of two triangles tended to stop the perceptual alternation among them, and the surface focused on appeared as a coloured transparent overlay. The same effect was confirmed for other combinations of colours for two or three surfaces (**Fig. 2**). The voluntary attention allocated to a given surface could be an endogenous and thus conscious way to prevent the spontaneous alternation, leading to individuation of that surface from the others as a transparent overlay.

Similarly, the placement of an outline on the target surface(s) (onset transient) effectively stopped the perceptual alternations, such that manifestation of the contour assignment for a given triangle may lead to specification of the corresponding surface as nearer and transparent, relative to the background opaque surface(s). Actually, all observers reported that at the instant of placing a real outline on one of two triangles, their attention became allocated to the corresponding surfaces, leading to perception of this surface as a transparent nearer one overlying the other, far surface. The resulting manifestation of contour due to the placement of real line boundaries led to exogenous attention to select one domain over another, whereby scission of its gray substance into separate coloured components created a perceptual organization. Compared with the case when attention is endogenously allocated to the same triangles, the outline placement effect on the surface individuation is regarded as exogenous, because it was realized by placement of the outline on the aimed surface without intentionally allocated attention.

The effect of outline placement on a surface on its individuation as a transparent overlay from the others can be considered as specification of an edge assignment pattern, providing effective clues to individuate the outlined surface as nearer than the residuals. In the two-surface condition (**Fig. 1b**), for example, the colour contrast at each of the six-pointed regions of the hexagon depicts X-junctions, where surface decomposition would occur to individuate one surface from another. In the transparency situations, the apparent double-belongingness of the overlapping region depends, locally, on good continuation of contours meeting at X-junctions and, more globally, on the improvement of form regularity[2]. Metelli[3] emphasized the role of *good continuation* at X-junctions as a critical local factor supporting vivid impressions of transparency. In contrast, for example, in cases where T-junctions are formed at six-pointed regions of the gray hexagram (e.g., **Fig. 1a, c**), there is no clue to transparency interpretation between surfaces of different colors. Thus, an outline placed on edges of one of two triangles may act as an exogenous cue given to the X-junction, by strengthening of the figural boundary to decompose multiple regional surfaces into different surfaces (components)[4]. Owing to these effects, the corresponding surface is definitely perceived as the nearest, without any particular effect on its interpretation as a transparent overlay[4,5].

Of note here, however, is that in the 3D condition the depth order was constant among two or three surfaces. Therefore, attentional allocation is independent from the change of perceptual depth order of surfaces. In other words, in the 3D condition, the observers can allocate attention to one or two composite triangles without perceptual alternation of their depth order. However, a real outline placed on a given surface still provides an effective clue to allocate attention to one of two (or three) surfaces. All subjects noted that at the instant of placing the outline on one or two triangles, their attention became allocated to the corresponding surfaces, without any change in depth order among the composite surfaces. The manifestation of the boundary by placing a real line contour onto each of two or three triangles could be an effective way to allocate attention to the corresponding surface(s), similar to the 2D condition.

Visual surfaces can be erased in many different ways. The Troxler effect[6] is regarded as a typical case of a visual disappearance phenomenon involving adaptation of edge detectors[7,8], but the fading time is typically long and is essentially unpredictable. Recently, Antis et al.[9] reported that adaptation to just the flickering edges or outline of an achromatic shape, by temporarily removing the edges, can reduce the perceived contrast of the whole shape when subsequently viewed. They suggested that in normal viewing conditions a brightness filling-in process is constrained by oriented boundaries, which thereby define separate regions of the visual scene, whilst contour adaptation due to repetitive transients on its contour can weaken the boundary and thereby allow brightness signals to merge together, rendering the target surface indistinguishable from the background. This phenomenon closely resembles those found in our studies, in that a visual transient applied to the contour of targeted surfaces can erase the corresponding surfaces. However, in the study of Antis et al., the surfaces to be erased were achromatic, and the outlines placed on the contour of the surface among different luminance fields was repeatedly presented for several seconds. In our case, the examined surfaces were chromatic and erasure of outlines placed on the targeted surfaces was derived by a single offset transient alone. Thus, it is unlikely that their proposal fully explains our results.

As predicted in studies of the Troxler effect, the adaptation of edge detectors due to stabilization of the retinal image by fixation may contribute to the fading by reducing the gain of edge signals. The placement of an outline may act to prevent this border erosion process by maintaining the separation of two surfaces for longer periods. However, once the outline is physically erased, the resulting low-gain contrast among surfaces might lead to the sudden initiation of a border-erosion process. It is likely that the manifestation of contours due to outline placement may in turn contribute to enhancement of obscurity of the contours of surfaces after the erasure of that outline. The resulting weakness of edge signals relative to the removal of real outlines may have a negative effect on the constant perception of colours of corresponding surfaces.

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