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Luminance edges are not necessary for visual completion

TESSA C. J. DE WIT, CHARLES M. M. DE WEERT, and ROB VAN LIER
Radboud University Nijmegen, Nijmegen, The Netherlands

Luminance edges seem to have an important role in visual feature binding and, more specifically, in visual completion because luminance differences are important for the perception of depth. We investigated this claim in two experiments in which the primed-matching paradigm was used. In Experiment 1, we investigated conditions under which either a partly occluded shape or an occluder was isoluminant with respect to the background. In Experiment 2, the partly occluded shape and the occluder were isoluminant with respect to each other. Evidence was found for visual completion in all cases, and we therefore conclude that luminance edges are not essential for visual completion.

In our visual experience, partly occluded objects give rise to sensations of whole objects; the process that accomplishes this has often been referred to as *visual completion*. For example, in Figure 1A, the left shape can be seen as occluded by the right shape. In Figure 1B, the left shape is now placed in front of the right shape and is completed, so that a regular shape appears. Various factors have been suggested to be important to visual completion, including such factors as the texture of the occluded region (Yin, Kellman, & Shipley, 1997), the size of the partly occluded region and the time for completion (Guttman, Sekuler, & Kellman, 2003; Rauschenberger & Yantis, 2001; Shore & Enns, 1997), the spatial context (Rauschenberger, Peterson, Mosca, & Bruno, 2004), the concept of relatability (Kellman & Shipley, 1991), and the simplicity of the overall shape (van Lier, 1999; van Lier, van der Helm, & Leeuwenberg, 1994, 1995; van Lier & Wagemans, 1999). Besides these factors, the perception of depth also seems to play a crucial role in the completion process. Consider the two contours that meet at the point indicated by the arrows in Figure 1A: If there were no difference in depth between these, the two crossing contours would belong either to the same object or to two objects, as in a mosaic. Hence, it is reasonable to assume that the absence of the perception of the objects as being positioned in different planes that are parallel in depth would hinder the process of visual completion. Luminance differences between objects in the visual field have been claimed to be a cue for the perception of depth. This claim has also been used to explain the degrading effect isoluminance has on visual illusions (Livingstone & Hubel, 1987). In their influential article on visual completion, Kellman and Shipley (1991) also used luminance differences as a way of specifying contours. Apart from depth perception, luminance has also been indicated as having a role in visual feature binding (e.g., Lehky, 2000; Leonards & Singer, 1998), a process also important in visual completion, where visible parts separated by an occluder are bound. For example, in Figure 1A, the arrow-indicated contours of the left shape can be bound by visual completion, as indicated in Figure 1B. Because of the important role luminance edges have in depth perception and the role luminance can play in visual feature binding in general, luminance may have a deciding role in the generation of visual completions, which we will examine in this article.

A number of studies have shown impaired processing under isoluminant conditions (e.g., Brussell, Stober, & Bodinger, 1977; de Weert, 1980; Gregory, 1977). Gegenfurtner, Brown, and Rieger (1997) have shown an effect of isoluminance on the processing speed for illusory contours in Kanizsa-like displays. When participants have to detect the location and the orientation of an illusory contour induced by isoluminant pacmen (three-quarter disks), this process is markedly slower than it is in high- and low-contrast (pacmen) conditions. However, this slowdown in detecting was not found for real contours: Here, low-contrast and isoluminant conditions result in similar processing times. Gegenfurtner et al. therefore concluded from this that isoluminance affects only the processing of illusory contours, a process that has been suggested to share many similarities with visual completion (Kellman & Shipley, 1991). Lehky (2000) has shown an effect of isoluminance on visual feature binding, using illusory conjunctions. When different colored letters were flashed briefly, participants had to identify the center letter and its color. Under luminant conditions, illusory conjunctions are sometimes made between letters and colors, but under isoluminant conditions, these illusory conjunctions

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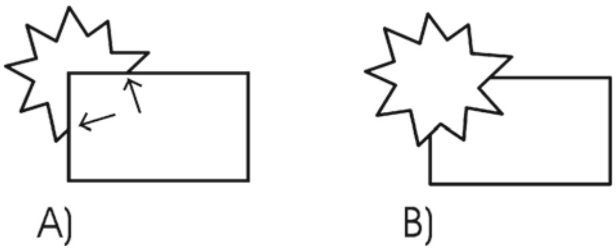

Figure 1. (A) The shape on the left is partly occluded by the rectangle. (B) The left shape is now placed in front of the rectangle and is completed in a regular way (shapes from de Wit & van Lier, 2002).

occur more often. This may indicate slower visual processing under isoluminant conditions or, more specifically, a slower feature-binding process. This has also been suggested by Leonards and Singer (1998), who found slower temporal dynamics for texture segmentation that was based on temporal definitions. Note here that feature binding is also an important component in visual completion, because spatially separated lines (or surfaces) have to be connected.

A study by Brown and Koch (2000) showed that when isoluminant, partly occluded numbers and letters were identified, it took more time to identify these isoluminant, partly occluded shapes than isoluminant fragmented shapes (consisting of the same contours as the partly occluded shapes, but without an occluder). However, it seems hard to compare the two conditions with respect to the degree to which visual completion is at work, because in both conditions a form of contour integration is executed. In a study that also dealt directly with visual completion (Puts, 2001), it was shown that performing a task under isoluminant conditions resulted in performance that indicated the absence of visual completion. Using a visual search task, Puts found that the detecting of a deviant bar that was partly occluded by an isoluminant vertical bar did not result in reaction times similar to those for bars partly occluded by a luminant vertical bar. Instead, performance was more similar to that for detecting two nonoccluded deviant bar parts. For the displays used in these experiments on visual completion, both the occluder and the partly occluded shape could be isoluminant with the background. For both conditions, depth information concerning one of the two objects in front of a background could be missing. In our first experiment, to be discussed below, we examined both instances of depth information loss.

Research has suggested an important role for luminance in depth perception and stereopsis (de Weert, 1979; de Weert & Sazda, 1983; Kingdom, Simmons, & Rainville, 1999; Livingstone & Hubel, 1987; Lu & Fender, 1972). The question, then, was how isoluminance would affect visual completion. Although stereoscopic cues seem to speed up visual completion (Bruno, Bertamini, & Domini, 1997), different planes of depth can also be perceived in the absence of stereoscopic cues (e.g., completion has been found for surfaces that were not defined by contours but by spatiotemporal boundaries, as in Shipley & Kellman, 1994), and visual completion can still take place. Therefore, the role of luminance edges in pictorial depth perception should also be taken into account. Taken together, the research we describe has presented different views on the effect of isoluminance. Whereas some authors have suggested quite an effect of isoluminance on the feature-binding processes (Gegenfurtner et al., 1997; Lehky, 2000; Leonards & Singer, 1998) and, more specifically, on visual completion (Brown & Koch, 2000; Livingstone & Hubel, 1987; Puts, 2001), other authors seem to have isolated differential effects from isoluminance only on stereoscopic depth and, more specifically, on random dot-stereograms (de Weert, 1979; Kingdom et al., 1999). Therefore, the question remains whether luminant edges are necessary for visual completion.

Following the research on the role of luminance edges on visual completion, we first wanted to examine the role of luminance differences in two conditions: between occluder and background and between partly occluded shape and background. We used the primed-matching paradigm that had proven to be a useful tool in investigating visual completion in a number of earlier studies (de Wit, Schlooz, Hulstijn, & van Lier, 2005; de Wit & van Lier, 2002, 2005; Sekuler, 1994; Sekuler & Palmer, 1992; van Lier, Leeuwenberg, & van der Helm, 1995). In this paradigm, the task for the participant is to decide whether or not two shapes (the test pair) are identical, which can be facilitated by showing a prime before the test pair. The rationale behind the paradigm is that the degree of facilitation that a prime has on a decision regarding the similarity of a test pair depends on the similarity between the prime and the test pair. In this case, a partly occluded shape is shown as a prime, followed by a test pair consisting of either completed forms of the shapes (i.e., the *full test pair*) or mosaic forms of the shape (i.e., the *mosaic test pair*; see Figure 2). When a partly occluded prime does not facilitate a full test pair, no completion process has been taking place, but when a full test pair is facilitated, a completed form of the partly occluded shape has been generated. Each prime consists of two shapes—namely, an experimental shape that is also used in the test pair following the prime, to be referred to as the *shape of interest*, and an accompanying shape that is not involved in the decision regarding the test pair. In this experiment, we used two versions of partly occluded shapes as primes: an isoluminant shape of interest that was partly occluded by a luminant accompanying shape (see the left column in Figure 2A) and a luminant shape of interest that was partly occluded by an isoluminant accompanying shape (the right column in Figure 2A). As a baseline, we also used full primes (see Figure 2B) and mosaic primes (see Figure 2C) in both luminance conditions.

Each prime was followed by an isoluminant or a luminant test pair (see the left and the right columns of Figure 2D, respectively). In the experiment, the two main conditions could result in different priming effects. In the isoluminant

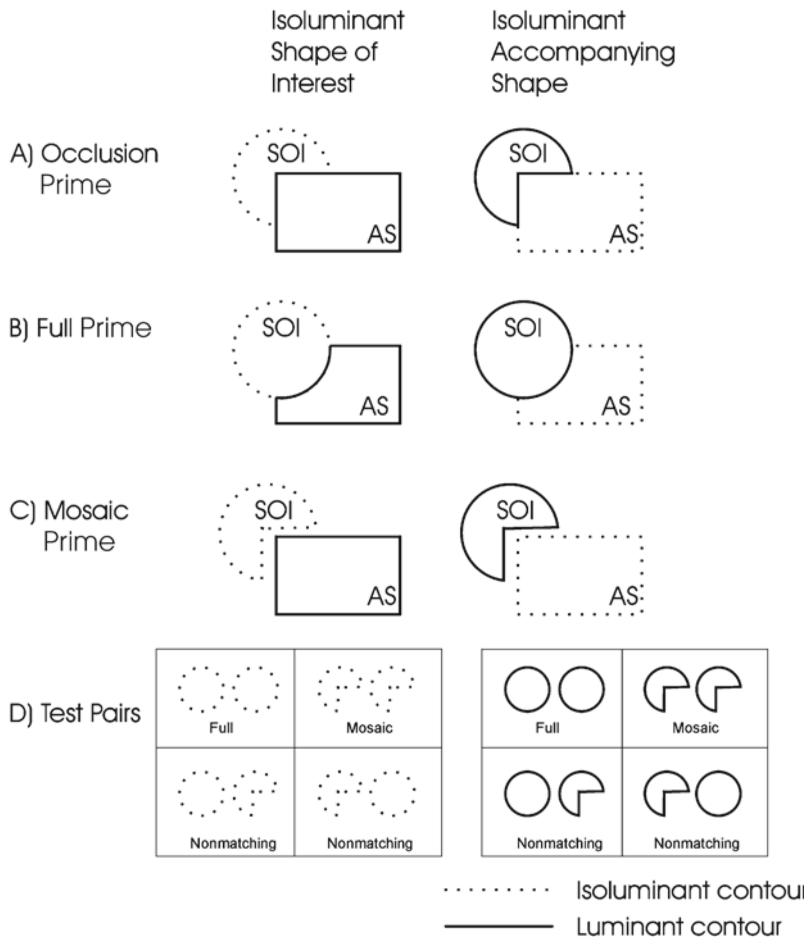

Figure 2. The different conditions in Experiment 1. In the left column is shown Condition 1, in which the shape of interest (SOI) was isoluminant with the background. In the right column is shown the condition in which an accompanying shape (AS) was isoluminant with the background. The rows depict the (A) occlusion prime, (B) full prime, (C) mosaic prime, and (D) the test pairs (the matching full test pair, the mosaic test pair, and the nonmatching test pairs).

shape of interest condition, in which an isoluminant shape was partly occluded by a luminant shape (Figure 2A), only luminance differences between the occluder and the background could be seen; there were none between the partly occluded shape and the background. If isoluminance between a partly occluded shape and a background disturbs the completion process, as was suggested by Brown and Koch (2000; e.g., because of a lack of depth information), no priming effect would be expected from this prime on a full test pair, but it might result in a priming effect on the mosaic test pairs. If, however, isoluminance does not have a degrading effect on visual completion, a priming effect would be expected for full test pairs (Figure 2D). Similar predictions held for the isoluminant accompanying shape condition, in which a luminant shape was partly occluded by an isoluminant shape. If isoluminance between the occluder and the background disturbs the completion process (e.g., Puts, 2001), a priming effect would not be expected for the full test pairs. However, if the absence of luminance differences does not inhibit visual completion, a priming effect would be expected on the full test pairs (Figure 2D). Note that there was a luminance difference between the shape of interest and the accompanying shape in both conditions. Therefore, if luminance edges are necessary for visual completion, the partly occluded shape of interest with an isoluminant accompanying shape should representationally be most similar to the mosaic prime.

EXPERIMENT 1

Method

Participants. Twenty participants took part in this experiment. All had normal or corrected-to-normal vision. The participants were students at Radboud University Nijmegen and received either payment or course credit.

Stimuli. Two sets of stimuli were used: In one set, a circle was positioned to the left and a rectangle to the right (see Figure 2), and in the other set, this was reversed. The left shape was always the shape of interest, meaning that a version of this shape was always used in the test pair. The accompanying shape also appeared in the test display, but it was not involved in the decision task. There were two luminance conditions for the primes: In the first condition, the shape of interest was isoluminant, and the accompanying shape was luminant (achromatic; see the left column of Figure 2); in the second condition, the shape of interest was luminant (achromatic), with an isoluminant accompanying shape (the right column of Figure 2). There were four forms of primes: The shape of interest could be partly occluded by the accompanying shape (occlusion prime; Figure 2A); the whole shape of interest could be in front of the accompanying shape (full prime; Figure 2B); there could be a mosaic version of the (occluded) shape of interest with the accompanying shape (mosaic prime; in Figure 2C, it can be seen that for the mosaic prime, the shape of interest and the accompanying shape were now slightly displaced with respect to each other, to show a clear mosaic shape); and finally, a dot could function as the *no prime* for the no-prime conditions. The full and the mosaic primes were so-called *foreground primes*; these were structurally identical to the test pairs, and they therefore were used as a control condition, to see whether the identical test pairs would be facilitated. The visual angle of the prime was 1.5º, and this was 4.1º for the test pair.

The test display consisted of two completed forms from the same set as the shape of interest in the prime (full test pair), or two mosaic versions of the shape of interest (mosaic test pair), or a mosaic–full combination (nonmatching; see Figure 2D). For the latter, left–right position was balanced. The test shapes were either isoluminant or luminant (achromatic), so a shape of interest could be structurally congruent with the test pairs and luminance could be congruent with the test pairs. All these different combinations were shown equally often, and matching test pairs were shown as often as the nonmatching test pairs. The test pairs appeared on both sides of the prime, to prevent masking by the prime (e.g., Sekuler & Palmer, 1992). The right shape of the prime appeared on the lower part of the screen, to prevent the illusion that the rectangle moved and changed into one shape of the test pair, which could also exercise a hindering influence on the priming effect (e.g., Sekuler & Palmer, 1992).

Procedure. The participants sat in a dimly lit room with their head stabilized by a chinrest approximately 2 m from the screen. Before starting the primed-matching paradigm, the threshold of each participant's luminance values was tested by having each perform a photometric flicker task, in which a green square was alternated with a yellow square on a black background at a frequency of 20 Hz. The participant adjusted the RGB values of the yellow square, changing luminance but keeping chromaticity coordinates constant, until the flickering of the green–yellow square became minimal (the logic behind this being that luminance differences cause the flicker, which thus should be minimal when luminance differences are minimal). The square was positioned at the same location on the monitor as that at which the actual primes in the experiments would appear. To get a more accurate estimation, each participant repeated this three times, and every time the starting luminance value of yellow varied. The participants were given sufficient time to be confident that the flickering had disappeared. The green color (CIE chromaticity coordinates, $x = 0.3024$, $y = 0.6028$; a luminance of 69.23 cd/m^2) was used in the actual stimuli, in the primed-matching paradigm, as the color of the background; the resulting value of yellow (CIE chromaticity coordinates: $x = 0.4177$, $y = 0.5093$) was used for one of the shapes, and the luminant shape was gray (CIE chromaticity coordinates: $x = 0.3118$, $y = 0.3300$; a luminance of 21.78 cd/m^2).

In the primed-matching paradigm, a fixation cross was presented in the middle of the screen for 500 msec. After a blank had been shown for 50 msec, a prime appeared on the screen for 500 msec. After a 17-msec interstimulus interval, the test display was shown until the participant responded with a buttonpress (Figure 3). The order of the presentation was randomized for each participant, and the reaction time (RT) was measured to the nearest millisecond. The trials were presented continuously, and after every 100 trials, a pause was given. To respond to a matching or a nonmatching test pair, half of the participants used their dominant hand for *same* responses and their nondominant hand for *different* responses; this was reversed for the other half. During the whole experiment, auditory feedback was provided for inaccurate responses, to keep the participants alert.

The participants were instructed to pay extra attention to the left shape of the prime (i.e., the shape of interest) and to respond as accurately and as quickly as possible. The experiment started with 10 practice trials in which feedback was also provided. There was a total of 448 experimental trials: set (2) × primes (4: occlusion, full, mosaic, or none) × isoluminant part of the prime (2: shape of interest or accompanying shape) × test pair (4: full–full, mosaic–mosaic, full–mosaic, or mosaic–full) × luminance of the test pair (2: luminant or isoluminant) × repetition (4), minus 64, because there was no luminance version of the no-prime dot. The paradigms were run with Presentation, Version 5.2 (Neurobehavioral Systems).

Results

We have analyzed all correctly answered matching test pairs (93.4%). Note that priming effects seemed to occur only for identical test pairs (Beller, 1971). The priming effect (PE) is defined as the difference in RT between a prime condition and a no-prime condition:

$$\mathrm{PE}(\mathrm{TP} \mid \mathrm{P}) = \mathrm{RT}(\mathrm{TP} \mid \mathrm{NP}) - \mathrm{RT}(\mathrm{TP} \mid \mathrm{P}),$$

where TP is any test pair, P stands for any prime, and NP is the no-prime condition. In Figure 4, mean priming effects are plotted for congruent primes and occlusion primes as a function of the full and mosaic test pairs and of prime and test pair luminance. It can be seen that panels A, C, and D show a similar pattern, whereas panel B shows a total absence of priming effects. A repeated measures ANOVA was performed for priming effect, with set (2), prime (3), isoluminant part of the prime (2), test pair (2), and luminance of the test pair (2) as factors. This revealed a prime × isoluminant part of the prime interaction [($F(2,18) = 12.48$, $p < .001$] and three-way interactions for prime × isoluminant part of the prime × luminance of the test pair [($F(2,18) = 9.23$, $p < .005$], for prime × test pair × luminance of the test pair [($F(2,18) = 4.66$, $p < .05$], and

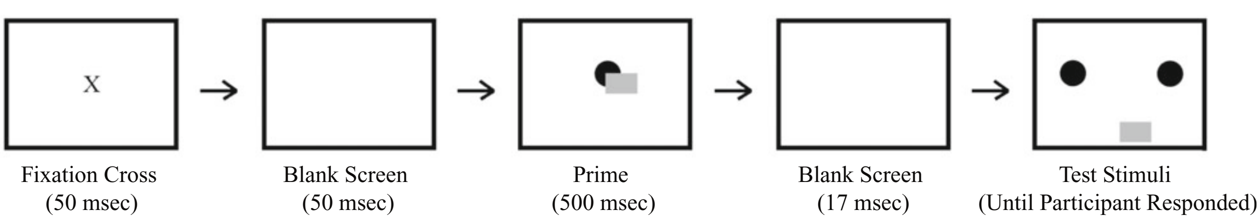

Figure 3. The procedure in the experiments.

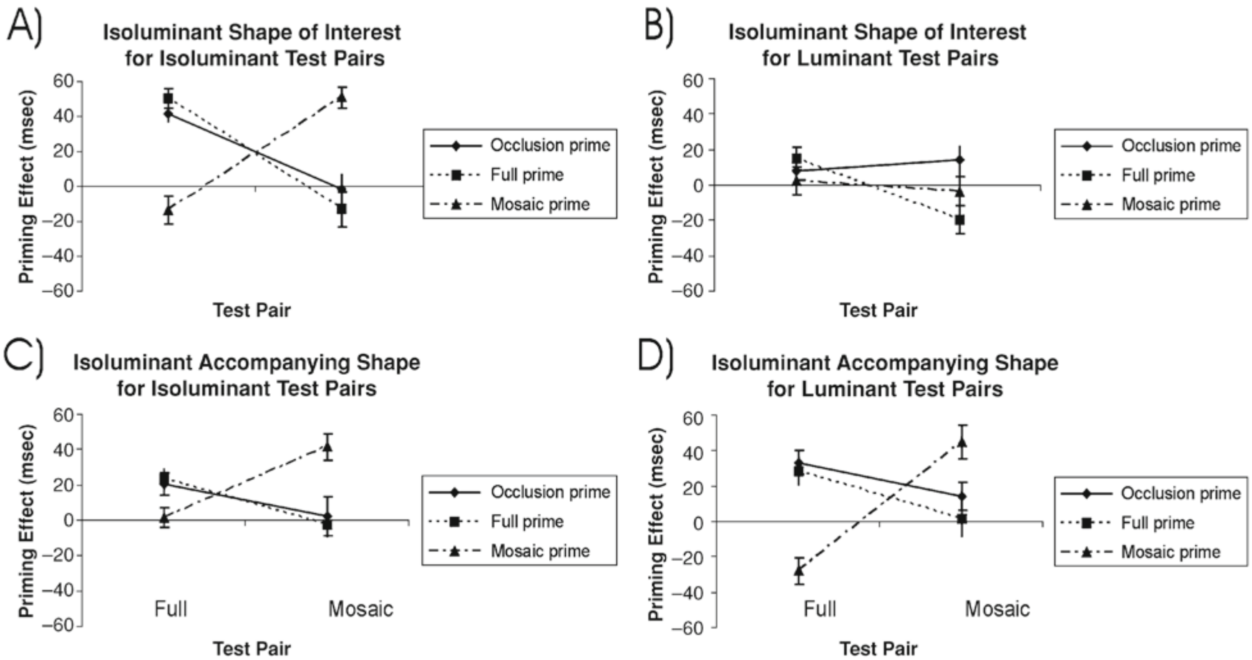

Figure 4. Mean priming effects for foreground primes and occlusion primes as a function of the full and mosaic test pairs and of prime and test pair luminance.

for isoluminant part of the prime × test pair × luminance of the test pair [$F(1,19) = 4.61, p < .05$].

Planned comparisons were performed to investigate the effect of the foreground primes (i.e., the nonocclusion primes) on identical test pairs, as compared with the no-prime condition for the two sets together. This showed that in the isoluminant shape-of-interest condition, decisions for isoluminant test pairs were facilitated [Figure 4A; $PE_{\text{iso–test pair|iso–shape of interest}}$: $F(1,19) = 36.05, p < .001$], but not for luminant test pairs [Figure 4B; $PE_{\text{test pair|iso–shape of interest}}$: [$F(1,19) = 0.20, p = .66$]. In the isoluminant accompanying shape condition, decisions for isoluminant and luminant test pairs were facilitated, Figure 4C and 4D [$PE_{\text{iso–test pair|iso–accompanying shape}}$; $F(1,19) = 13.52, p < .005$; $PE_{\text{test pair|iso–accompanying shape}}$; $F(1,19) = 6.00, p < .05$]. This shows that for most conditions, normal priming effects were present. Next, planned comparisons were performed to investigate the effect of the occlusion primes on different test pairs, as compared with no-prime conditions. As can be seen in Figures 4A and 4B, in the isoluminant shape-of-interest condition, occlusion primes facilitated only decisions for isoluminant full test pairs [($PE_{\text{iso–test pair|iso–shape of interest}}$; $F(1,19) = 16.84, p < .005$], but not those for the other test pairs. In the isoluminant accompanying shape condition (Figure 4D), occlusion primes (with isoluminant occluders) facilitated decisions for luminant full test pairs [$PE_{\text{test pair|iso–accompanying shape}}$: $F(1,19) = 5.94, p < .05$], but not for the others.

Discussion

As can be seen in Figures 4A, 4C, and 4D, we found the same pattern of results as that in earlier studies (Sekuler & Palmer, 1992), in that the full primes facilitated decisions for full test pairs and mosaic primes facilitated decisions for mosaic test pairs, which serves as a control to show that normal priming effects were present. For the isoluminant shape-of-interest condition, it can be seen in Figure 4A, that the isoluminant shape of interest facilitated only decisions for isoluminant, structurally congruent test pairs; however, no priming effect was found for luminant, structurally congruent test pairs (Figure 4B). For the isoluminant accompanying shape condition, the luminant foreground prime facilitated decisions for all structurally congruent test pairs, which held for both isoluminant (Figure 4C) and luminant (Figure 4D) test pairs. The reason for the lack of a priming effect from an isoluminant shape of interest on congruent luminant test pairs in general could perhaps be found in the absence of chromatic information when there already was no luminance information. Whereas in the isoluminant shape of interest there was color information available, there was no comparable chromatic information available in the luminant test pairs. Therefore, the general process of priming could possibly be hindered just by the absence of color information between the isoluminant shape of interest and the test pair. There is an asymmetry, however, because in the reversed condition with the achromatic luminant shape of interest, facilitation was found for isoluminant test pairs. To see whether this asymmetry could be attributed just to the absence of chromatic information in the test pair, we performed a control experiment, in which we also wanted to replicate the lack of a priming effect of the isoluminant shape of interest on luminant, achromatic test pairs. Therefore we additionally tested the effect of the isoluminant prime on achromatic, as well as on chromatic (blue), luminant test pairs. The same pattern of results was found for the isoluminant shape of interest that was followed by luminant, achromatic test pairs. That is, an absence of priming effects was replicated (as in Figure 4B). For the isoluminant shape of interest and the luminant, chromatic test pair, we did find a facilitating effect on these test pairs. More important, for the isoluminant occlusion shape of interest, a priming effect was found for the luminant full test pair (similar to Figure 4D). We therefore concluded that the lack of priming effect from an isoluminant shape of interest on luminant, achromatic test pairs can be overcome by using chromatic test pairs. Thus, the lack of priming effect of the isoluminant shape of interest on the luminant test pair was due to the absence of chromatic information in the test pair.

Our main question concerned the effect of isoluminance on completion: would the completion process diminish due to isoluminance? There were two conditions in Experiment 1: one in which the partly occluded shape of interest was isoluminant with the background and one in which the accompanying shape was isoluminant with the background. In both cases, separation of depth between occluder and background, or between partly occluded shape and background, was likely to be impaired. In the first condition with the isoluminant, partly occluded shape of interest, there was a degraded perception of depth difference between the shape of interest and the background. As can be seen in Figure 4A, the isoluminant full test pair was primed, so in any case a completion was formed. This goes against the findings of Brown and Koch (2000), who claimed that there was no visual completion for isoluminant, party occluded shapes. However, their condition was similar to our condition in which an isoluminant shape of interest was combined with luminant test pairs, and in our experiment, this condition resulted in a total absence of priming effects for any prime–test-pair combination (Figure 4B).

In the second condition, with the isoluminant accompanying shape, the lack of luminance differences between the occluder and the background also did not inhibit a priming effect from an occlusion prime on a full test pair. This means that if there were no luminance edges that could signal depth differences between the occluder and the background (i.e., the occluder did not seem to lie in front of the background), the completion process could still take place. However, the priming effect was present only for luminant full test pairs, not for isoluminant full test pairs (Figure 4D). This absence of a priming effect may be attributed to three factors that decrease the priming effect. One factor is that priming effects of partly occluded primes for full test pairs are always somewhat smaller, as compared with those for full primes and full test pairs, because there is no perfect similarity between the prime and the test pair. Besides this shape incongruency, another factor involved is the decrease in priming effects caused by luminance-incongruent primes and test pairs: Luminant foreground primes exert a smaller priming effect on isoluminant test pairs (luminant to isoluminant) than on luminant test pairs. The third factor is the color incongruency between the prime and the test pair in this condition. All of these factors may have contributed to the absence of a priming effect for luminant occlusion primes on isoluminant full test pairs. Nevertheless, when the shape of interest was partly occluded by an isoluminant accompanying shape, luminant full test pairs were primed; thus, visual completion did still take place.

Whatever the exact nature of the lack of some of the priming effects described, these studies provide evidence for the presence of completion processes under isoluminant conditions. These processes are significant within the same color characteristics: After an isoluminant, partly occluded shape of interest has been seen, isoluminant completions are primed, and after a luminant (achromatic), partly occluded shape of interest, luminant completions are primed, so in both of these cases completions are formed. Overall, these findings do not fit with the results in the studies described in the introduction, in which it has been claimed that feature integration or, more specifically, visual completion is critically impaired under isoluminance (e.g., Brown & Koch, 2000; Livingstone & Hubel, 1987; Puts, 2001).

In this experiment, we tested the importance of luminance differences between an occluder and a background, or between a partly occluded shape and a background. One could argue that there still is a luminance edge surrounding the shape of interest, because the shape of interest is not isoluminant with the occluder. If this argument holds, a priming effect would be expected that would be similar to the priming effect of the mosaic prime, since in that case there is also a luminance edge at the contour of the mosaic shape. This was not the case: Whereas the mosaic prime had a facilitating effect on the mosaic test pair, the partly occluded shape of interest had a facilitating effect on the full test pair. Livingstone and Hubel (1987) claimed that when there are no luminance edges between the shape of interest and the accompanying shape, visual completion is impaired. Although we have shown that the isoluminant accompanying shape with an occlusion prime is not representationally similar to the mosaic prime (they have different priming effects), we performed a second experiment, in which we looked explicitly at the effect of isoluminance between a partly occluded shape and an occluder on visual completion. Again, using the primed-matching paradigm, we expected that, if luminance edges are necessary for visual completion, partly occluded shapes that are isoluminant with their occluders will not facilitate decision on a full test pair. If luminance edges between the partly occluded shape and the occluder are not necessary for visual completion, we would expect no priming effect on the full test pair but, possibly, a priming effect on the mosaic test pair.

EXPERIMENT 2

Method

Participants. Nineteen participants took part in this experiment. All had normal or corrected-to-normal vision. The participants were students at Radboud University Nijmegen and received either payment or course credit.

Stimuli. The stimuli were identical to the stimuli in Experiment 1, with a few changes (see Figure 5). For all the primes, shape of interest and accompanying shape were isoluminant with respect to each other; in half of the cases, the shape of interest was green and the accompanying shape was yellow, whereas this was reversed in the other half of the cases. Again, there were four forms of primes: an occlusion prime, a full prime, a mosaic prime (Figure 5), and a dot that functioned as the no-prime in the no-prime situation. The test display again could be a full test pair, a mosaic test pair, or a mosaic–full combination (nonmatching). For the latter, the left–right position was balanced. All of the test shapes had the same luminance and color (RGB values) as the shape of interest they followed. Again, all different combinations were shown equally often, and the matching test pairs were shown as often as the nonmatching test pairs.

Procedure. The procedure was identical to that in Experiment 1, now with a total of 512 experimental trials: set (2) × primes (4: occlusion, full, mosaic, or none) × color of the prime (2: green or yellow) × test pair (4: full–full, mosaic–mosaic, full–mosaic, or mosaic–full) × repetition (8).

Results

We have analyzed all correctly answered matching test pairs (96.0%). In Figure 6, mean priming effects are plotted for all primes as a function of the full and mosaic test pairs. A repeated measures ANOVA was performed for priming effect with prime (3) and test pair (2). This revealed a nearly significant main effect for test pair

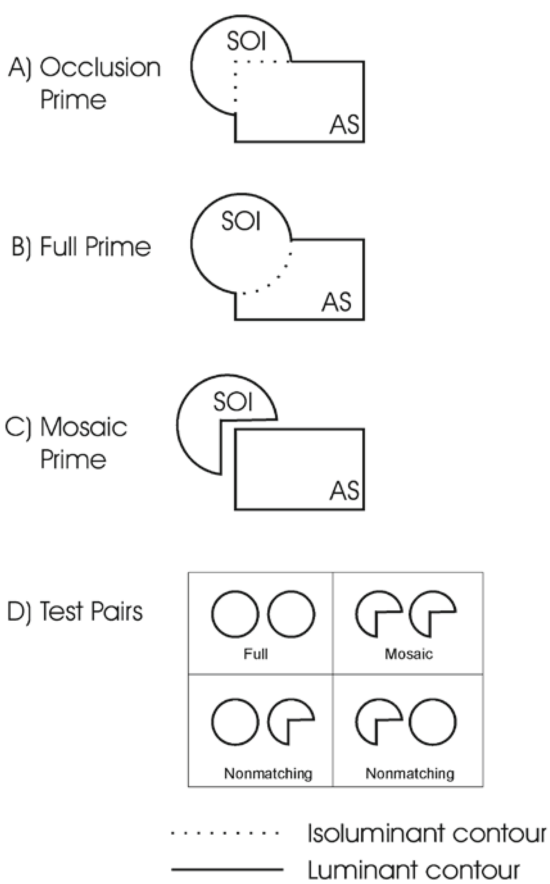

Figure 5. The different primes and test pairs in Experiment 2. In this experiment, there were no luminance edges between the shape of interest (SOI) and the accompanying shape (AS).

[$F(1,18) = 3.96, p = .062$] and a significant prime × test pair interaction [$F(2,17) = 7.93, p < .005$].

Planned comparisons were performed to investigate the effect of the foreground primes (i.e., the nonocclusion primes) on identical test pairs, as compared with the no-prime condition for the two sets together. The full prime facilitated decisions for the full test pair significantly [$PE_{full|full}$: $F(1,18) = 10.70, p < .005$], and the mosaic prime facilitated decisions for the mosaic test pair significantly [$PE_{mosaic|mosaic}$: $F(1,18) = 12.06, p < .005$]. This shows that for most conditions, normal priming effects were present. Exploring the effects of the occlusion prime, we found that it significantly facilitated decisions for the full test pair [$PE_{full|occlusion}$: $F(1,18) = 17.18, p < .005$], but not for the mosaic test pair [$PE_{mosaic|occlusion}$: $F(1,18) = 0.51, p = .48$].

Discussion

In this experiment, we investigated the presence of visual completion when there were no luminance edges between a partly occluded shape and an occluder. First, we looked at general priming effects in terms of the effect of the full and mosaic primes. The full primes exerted a facilitating effect for the full test pairs, and the mosaic test pairs facilitated decisions for the mosaic test pairs. Therefore, under these conditions, normal priming effects were at work. More interesting, the occlusion primes had a priming effect for the full test pairs, but not for the mosaic test pairs. These results fit in with those of the previous experiment, again showing that luminance edges are not necessary for visual completion. However, one can think of one extra condition that we did not test: All planes can be isoluminant to each other. Of course, this is the most extreme condition, but by showing that there is generation of visual completion under conditions in which already one of two depth cues is missing, we already go against the claim made in earlier studies of a diminishing effect of isoluminance on visual completion.

GENERAL DISCUSSION

Experiment 1 showed the presence of visual completion in cases in which partly occluded shapes were isoluminant with the background and in cases in which the occluder was isoluminant with the background. Experiment 2 showed that visual completion was also still present in cases in which the partly occluded shape was isoluminant with the occluder. Luminance edges, therefore, are not crucial to visual completion. In the reasoning on the importance of luminance edges for visual completion, we can make two assumptions: Luminance is critical for the perception of depth, and depth cues are necessary for visual completion. However, the role of depth cues in visual completion is not unequivocally clear. When depth information on figure and background or occluder and background is degraded, the partly occluded shape is still completed. As has been mentioned already, with respect to the first assumption, an important role for luminance in depth perception and stereopsis has indeed been suggested

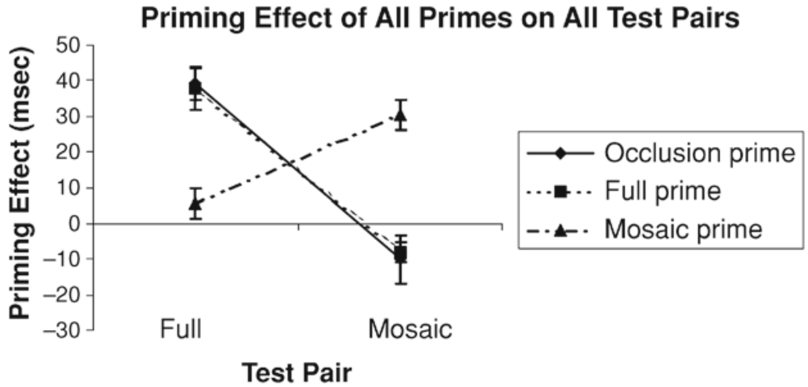

Figure 6. Mean priming effects for foreground primes and occlusion primes as a function of the full and mosaic test pairs.

(de Weert, 1979; de Weert & Sazda, 1983; Kingdom et al., 1999; Livingstone & Hubel, 1987; Lu & Fender, 1972). Now, in the stimuli we have used, there have been only pictorial cues for depth, and pictorial depth also seems to be hindered by isoluminance (e.g., Livingstone & Hubel, 1987). Therefore, not all pictorial cues may be sensitive to isoluminance. Alternatively, with respect to the second assumption in the reasoning, pictorial depth cues may not be crucial for visual completion.

Another way of looking at why we did not find a degrading effect of isoluminance on visual completion might be that there is no strict separation between the paths in which color and luminance information are processed. A lot of supporting evidence has pointed to there being two main routes in the brain: a slower parvocellular path for color processing and a faster magnocellular path for luminance processing (e.g., Livingstone & Hubel, 1987). However, it is currently acknowledged that these paths are strongly intertwined (e.g., Van Essen & DeYoe, 1995), so that it is almost impossible to totally switch off activity of one of these pathways. For example, the dorsal visual path is dominated by magnocellular input (Maunsell, Nealey, & DePriest, 1990), but there is also evidence for some parvocellular input (Sawatari & Callaway, 1996). This also can be connected to a hypothesis concerning the slowdown of visual processing under isoluminance that was presented in the introduction (Lehky, 2000; Leonards & Singer, 1998). Turning off most of the magnocellular activity might result in compensation by the slower parvocellular path, resulting in a slower processing. But because there is collaboration between the paths, the completion process might still be influenced by the magnocellular path. In our experiments, prime durations were somewhat longer than the minimal time that is needed to obtain visual completion (Sekuler & Palmer, 1992), which might thereby have masked a possible slowdown of overall visual processing, or of visual completion, because the visual system was provided with enough time to process the stimuli present in the prime. On the other hand, priming effects were absent when the shape of interest and the test pair differed in luminance, showing a differentiation between the two paths. However, this does not affect the most important conclusion from this article: that luminance edges are not necessary to generate visual completion.

CONCLUSIONS

Conditions in which either partly occluded shapes or occluders were isoluminant with respect to the background did not necessarily block visual completion. In addition, when partly occluded shapes and occluders were isoluminant with respect to each other, visual completion could still arise. We therefore conclude that the presence of luminance edges is not a necessary requirement for visual completion.

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