Partial modal completion under occlusion: What do modal and amodal percepts represent?

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In the occlusion illusion, a partly occluded object is perceived as though it were less occluded than it actually is (Palmer, Brooks, & Lai, 2007). We confirm and extend this finding using a stimulus with a moving occluder. In agreement with Palmer et al.'s (2007) findings and their partial-modal-completion hypothesis, we found that the illusion is indeed related to the sensory evidence for occlusion. Our experiments also confirm their speculation that the occlusion illusion involves an intriguing, seemingly paradoxical percept. In our experiments, subjects viewed an opaque disk with an open sector rotating in front of a background and indicated the perceived angular extent (a) of the occluder and (b) of the part of the background experienced as directly visible through the open sector. While the former was judged quite accurately, the latter was clearly overestimated. Thus, the angular extent of the background experienced as occluded and the extent experienced as directly visible sum to more than 360°, which makes the total percept an impossible figure. We argue that the key to resolving this paradox is to question the seemingly self-evident assumption that occluded and unoccluded portions of a visual scene are represented by amodal and modal percepts, respectively. Instead, we propose that visual percepts are experienced as modal whenever they are based on sufficiently conclusive sensory evidence and are otherwise experienced as amodal. Functionally, this perceptual representation of the conclusiveness of the sensory evidence underlying perceptual inferences might be more useful than estimates about optical visibility.

Introduction

Due to ecological regularities in our ambient visual environment, the proximal image of a visual scene contains information not only about parts of the visual scene that are directly visible but also about parts that are occluded. The human visual system is known to use this kind of information and to form perceptual representations of occluded regions (Anderson, Singh, & Fleming, 2002; Kanizsa, 1979; Michotte, Thinès, & Crabbé, 1991). In Figure 1, for instance, it is immediately clear that the buildings do not have holes where they are occluded by the trees but rather that they extend behind the trees.

Traditionally, one distinguishes between modal and amodal perceptual representations. Depending on whether the representations exhibit visible sensory qualities (e.g., color or texture) or not, they are classified as modal and amodal, respectively. Modal percepts are conceived of as perceptual representations of directly visible regions of a visual scene, while amodal percepts are thought of as perceptual representations of occluded regions.

Research on the so-called occlusion illusion (Kanizsa, 1979; Palmer, 1999; Vezzani, 1999; see Figure 2) raises some interesting conceptual issues related to this theoretical dichotomy. The basic phenomenon to be explained is that the black half-disk next to the gray rectangle (left) looks larger than the one that is presented in isolation, although they are physically identical. Palmer, Brooks, and Lai (2007) argued in favor of an explanation in terms of their partial-modal-completion hypothesis. This hypothesis appeals to the familiar notion of how cues to occlusion may lead to amodal completion of the half-disk into a full disk. Crucially, though, the partial-modal-completion hypothesis contends that a part of the perceptually completed region is experienced as modal (i.e., directly visible) rather than as amodal. That is, the hypothesis states that the occluded object is "perceived as though it were less occluded than it actually is" (Palmer & Schloss, 2009, p. 1083).

The experimental evidence presented by Palmer and colleagues speaks very strongly in favor of the partial-modal-completion hypothesis, so on empirical grounds

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Figure 1. A real-world example of amodal completion. The buildings seem to extend behind the trees.

it should definitely be taken seriously. On the theoretical side, though, it raises two interesting issues that warrant closer scrutiny.

First, as pointed out by Palmer et al. (2007, p. 669), assuming that the hypothesis is indeed correct raises the "perplexing" issue of "how to understand the nature of the partial-modal-completion hypothesis." The hypothesis essentially posits that the visual system fills in a thin strip along the occluded edge, which immediately raises the question of where this thin strip is located in the visual field. Since this thin strip originally is not part of the visual field but rather pops out from behind the occluder, as it were, it would seem logical that other parts of the visual field would need to be perceptually displaced in order to make room for it. Palmer et al. (2007, p. 669) considered this logically possible but suspected instead "that the visual system somehow manages to see the partly occluded object as spatially extended perpendicular to the occluding edge without perceiving any difference in the positions of the regions attached to the edge." Acknowledging that this may seem strange, they pointed out that "the visual system manages to achieve equally bizarre results in other illusions" (p. 669). We believe that Palmer and colleagues are right in suggesting that the occlusion illusion involves this kind of paradoxical percept, despite the apparent absurdity of the proposition. But we do think that the paradox requires a coherent resolution at the theoretical level, which goes beyond the mere reference to the existence of equally bizarre paradoxes in other domains of perception. Second, the partial-modal-completion hypothesis is incomplete in the sense that it does not explicitly explain *why* a part of the perceptual completion of the disk is experienced as directly visible (modal) instead of as occluded (amodal).

Figure 2. The occlusion illusion. The two half-disks are physically identical, yet the occluded one looks considerably larger. Adapted from Palmer (1999).

In this article, we present a dynamic illusion that is conceptually similar to the occlusion illusion but that produces a much stronger and more compelling effect and proves the existence of the paradox hinted to by Palmer et al. (2007) in a more direct and conclusive manner. We also offer a logically consistent and complete theoretical resolution of the paradox. We argue that the paradox can be resolved by giving up the seemingly self-evident but unproven assumption that the phenomenal experience of visibility is a perceptual representation of optical visibility. We propose that it is instead a perceptual representation of the conclusiveness of the sensory evidence available for perceptual inferences regarding qualitative attributes of the visual scene. That is, we question the theoretical basis for the conceptual dichotomy between modal and amodal percepts as representations of unoccluded and occluded regions of the visual scene, respectively.

Basic demonstration

A basic demonstration of our dynamic version of the occlusion illusion can be seen in the Supplementary Demonstration. On the left side, a half-disk is rotating in front of a background containing a striped ring. Physically, both the disk sector and the visible ring segment subtend 180° of the circular display at any given moment of time. As can be expected based on the literature on amodal completion, the partly occluded ring is amodally completed into a full ring. The observation of primary interest here, though, is that substantially more than the objectively visible 180° of the ring are experienced as directly visible (modal). At the same time, the angular extent of the occluding half-disk is perceived approximately veridically (180°). Taken together, these two observations imply that more than 360° of the circular display is experienced as directly visible. This observation, which we refer to as the visibility paradox, is analogous to the "bizarre" percept discussed by Palmer et al. (2007) in connection with the occlusion illusion.

A major advantage of our stimulus over that studied by Palmer and colleagues, however, is that the existence of the paradox can be demonstrated directly. By virtue of the circular spatial layout, the paradox becomes immediately apparent if any perceptual enlargement of the angular extent of the background ring experienced as directly visible occurs without a corresponding perceptual decrease in the angular extent of the occluding disk sector. A second advantage is that the effect observable in our dynamic occlusion illusion is stronger and more compelling than the rather modest effect observable in the static occlusion illusion, which makes it harder to dismiss the paradox as a minor artifact and makes it easier to measure the effect quantitatively.

The stimulus shown on the right side of the Supplementary Demonstration is identical to the one on the left side except that the rotating half-disk has been removed. The visible ring segment, which is perceived as part of a stationary full ring in the version on the left in which the occluder is present, is now perceived to be a curved stripe moving on a circular path. It is known that adding cues to the existence of an occluder accounting for changes in the stimulus that would otherwise evoke the impression of motion can abolish the motion percept (Ekroll & Borzikowsky, 2010; Shimojo & Nakayama, 1990a; Sigman & Rock, 1974). Thus, it is not surprising that the visible ring segment is perceived to move when the occluding rotating disk is removed. It should be kept in mind, though, that removing the rotating disk sector does not remove *all* the potential cues to occlusion from the stimulus. Importantly, the dynamic accretion and deletion at the two ends of the curved stripe may, in combination with its stationary texture, serve as a cue to occlusion. Note that, like the stimulus on the left side, the stimulus on the right side is compatible with the existence of a rotating half-disk—provided the disk sector has the same color as the background. Such motion of an "illusory occluder" (Kanizsa, 1979) in the presence of dynamic occlusion cues has been observed in studies of apparent motion (Petersik & McDill, 1981) and may even be responsible for the enigmatic phenomenon of pure phi motion (Ekroll, Faul, & Golz, 2008; Steinman, Pizlo, & Pizlo, 2000; Wertheimer, 1912). Thus, the hypothesis that the perceptual extension of the ring in the stimulus on the left is due to the influence of occlusion cues predicts that the extension of the curved stripe should be less, but not absent, in the stimulus on the right. In accordance with this logic, there seems to be a perceptual extension of the curved stripe also in the stimulus on the right, but it seems to be less than the extension of the ring segment in the stimulus on the left.

Experiment 1

The aim of our first experiment was to check these informal observations. Specifically, we were interested in establishing the existence of the visibility paradox; that is, a perceptual extension of the ring segment experienced as directly visible without a corresponding decrease in the perceived angular extent of the occluding disk sector. We also aimed to confirm the observation that the perceptual extension of the ring segment is reduced when the visible occluder is removed.

Method

We presented animations, as illustrated in Figure 3, to naive subjects and asked them to match the perceived angles of the disk sector (β_{occluder}) and the perceived angles of the portion of the striped ring experienced as directly visible (β_{ring}) using corresponding static comparison stimuli. The angle of the occluding disk sector (Figure 3A) was varied in four steps ($\alpha_{\text{occluder}} = 30°$, $150°$, $210°$, and $330°$), resulting in corresponding variations of the visible portions of the striped ring ($\alpha_{\text{ring}} = 360° - \alpha_{\text{occluder}}$). In order to verify that the overestimation of the angle of the striped ring ($\beta_{\text{ring}} - \alpha_{\text{ring}}$) depends on occlusion cues, we also included a control condition in which the visible occluder was left out so that only portions of the striped ring were visible (Figure 3B). As already mentioned, the absence of the visible occluder changes the percept radically: Instead of a disk sector rotating in front of a stationary ring being partly occluded, one perceives portions of a striped ring segment moving on a circular path.

We presented the dynamic stimuli on a cathode ray tube monitor running at 85 Hz with a dark gray background and a white fixation spot in the center. The disk sector was gray in the experimental condition and dark gray—like the background, and thus invisible—in the control condition and rotated at 0.94 revolutions/s. Viewed from an approximately 80-cm distance, its diameter was about 9°. Its angle was varied in four steps (30°, 150°, 210°, and 330°). The striped ring segment had a width of about 0.5° and an inner diameter of about 4.5°. The alternating black and white stripe texture of the ring was stationary in all conditions, and the width of each element of the stripe texture corresponded to $360°/60 = 6°$ along the circle.

Before each trial a text caption indicated whether the perceived angle of the disk sector (in the experimental condition only) or the angle of the portion of the striped ring experienced as directly visible (in both

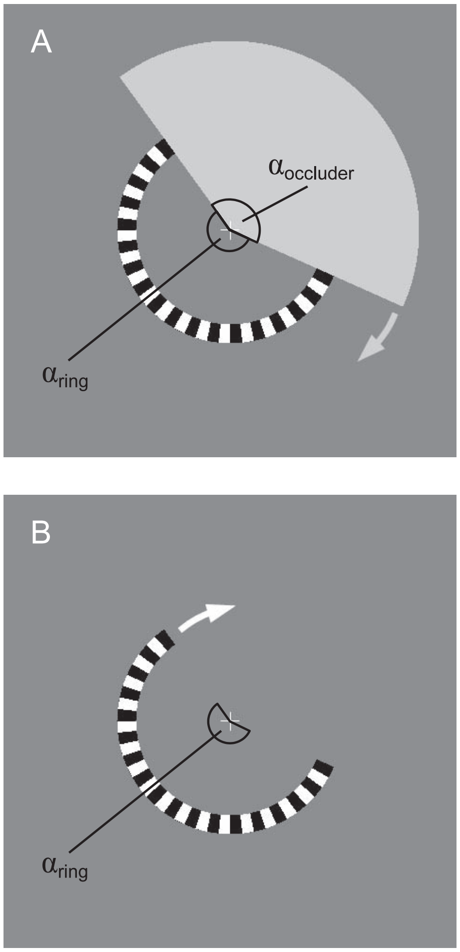

Figure 3. Stimuli used in Experiment 1. (A) In the experimental condition, a gray disk sector rotated in front of a stationary ring. The angle of the disk sector, $\alpha_{occluder}$ (here 150°), was varied between trials, resulting in corresponding variations of the visible portions of the ring, α_{ring} (here 210°). (B) In the control condition, the disk sector was removed so that only an incomplete curved stripe, now experienced as moving on a circular path, was visible. Its angle (i.e., length) was varied between trials as in the experimental condition.

conditions) were to be matched. The animation started 2 s later. When the subjects pressed a key the animation stopped and only the stimulus element to be judged remained statically visible, whereby its angle deviated from the objective angle in the animation in random direction and by a random absolute amount in the range of 20° to 45°. It could then be adjusted with the arrow keys in order to match the visible angle in the animation as accurately as possible. The subjects were encouraged to switch between the animation and the adjustment screen until they were satisfied with their adjustment. In total, there were 12 task–stimulus combinations (2 tasks × 4 stimulus variations in the experimental condition and 1 task × 4 stimulus variations in the control condition), each repeated 10 times, resulting in 120 trials presented in pseudorandom order.

The observers were 13 students from the University of Kiel who were naive to the purpose of the study. The data of one subject, who obviously matched an amodal percept, were discarded.

Results

The average data from the experimental condition, which are visualized in Figure 4 and plotted as a bar chart in Figure 5, reveal the visibility paradox: While the matches of the disk sector angle were quite accurate (–4° to +6°), the angle of the ring segment was overestimated by up to 36° ("extension effect"). Accordingly, the sum of the perceived angles $\beta_{occluder}$ and β_{ring} exceeded 360° in all four angle conditions by 3° to 43° (average = 23°). The effect was highly significant—one-tailed t test: $t(11) > 3.10$, $p < 0.01$—in all conditions except the condition in which $\alpha_{ring} = 330°$. We believe that our measurements actually underestimate the true magnitude of the dynamic occlusion illusion. This is because subjects may have been aware of the paradox and may have made settings reflecting logical reasoning rather than the immediate percept.

Figure 5 shows the data from the experimental and control conditions together. The white bars show the difference ($\beta_{ring} - \alpha_{ring}$) between the perceived angle and the physical angle of the striped ring for each level of α_{ring} in the experimental condition. Analogously, the gray bars show the difference ($\beta_{occluder} - \alpha_{occluder}$) between the perceived angle and the actual angle of the gray disk sector. The sum of the gray and the white bars represents the magnitude of the paradoxical effect. The black bars show the extension effect in the control condition, which was on average only about half as strong as in the experimental condition.

Discussion

The results of this experiment suggest that the perceptual extension of the background ring segment is related to the perception of occlusion. In the control condition, in which the visible occluding disk sector (but not all cues to occlusion; see the Basic demonstration section) was removed, the perceptual extension was reduced. More importantly, the results of this experiment show that the perceptual extension of the part of the background ring experienced as directly visible is not accompanied by a corresponding decrease in the perceived angular extent of the occluding disk sector. Thus, the visibility paradox seems to be a real

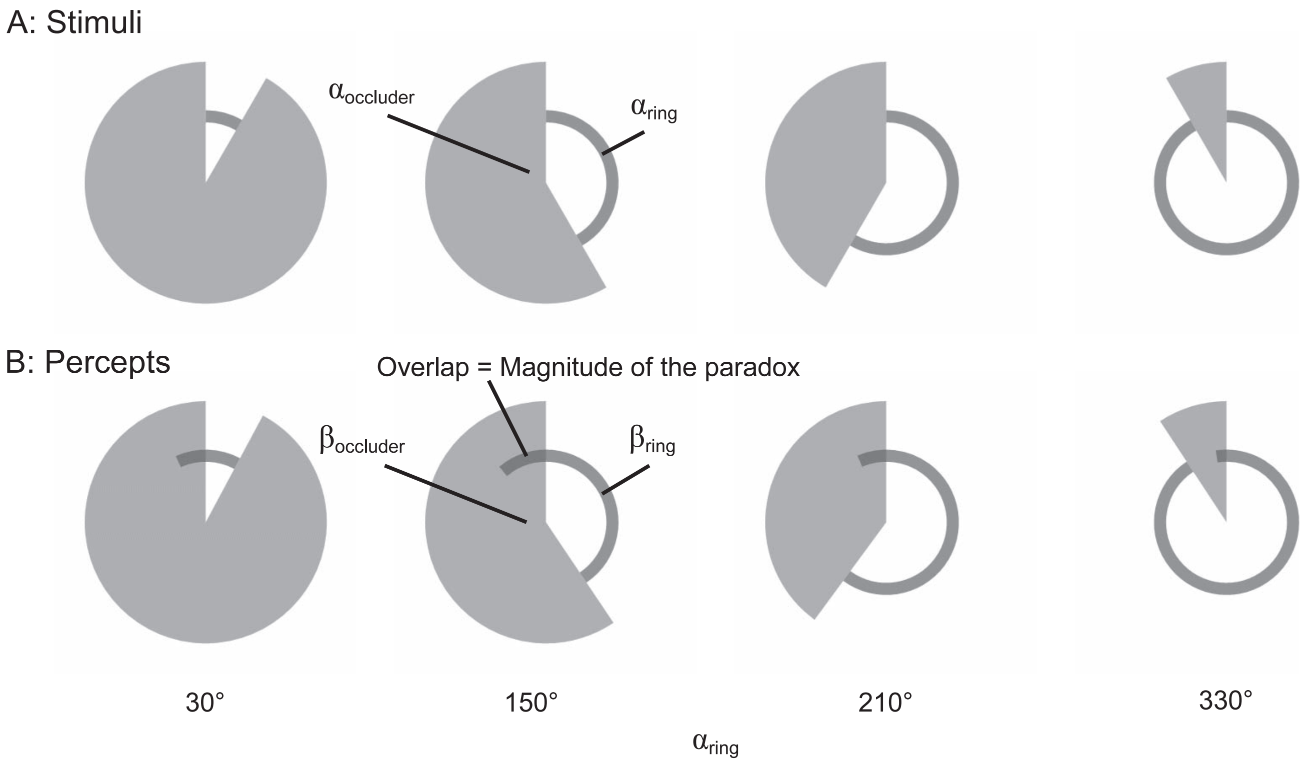

Figure 4. Stimuli and corresponding percepts in the experimental condition in Experiment 1. (A) Sketch of the actual extents α of the stimulus elements. (B) Visualization of the subjects' percepts β based on their mean responses. While the extent of the disk sector was adjusted quite accurately ($-4°$ to $+6°$), the visible portion of the ring was overestimated by up to 36° (in the 150° condition), suggesting the paradoxical conclusion that portions of both stimulus elements must have been perceived as directly visible at the same position simultaneously (overlapping regions). In this plot, we arbitrarily aligned the ring segment and the disk such that the paradoxical overlap is concentrated on one side. How the total overlap is phenomenologically distributed on both sides cannot be determined based on the subjects' settings, but we surmise that it occurs primarily at the trailing edge of the stripe.

phenomenon requiring substantive theoretical explanation.

Methodological issues

A number of objections may be raised based on methodological considerations. First, it remains possible that the influence of the occlusion cues on the perceptual extension of the ring segment in the experimental condition is indirect. As can be appreciated in the Supplementary Demonstration, removing the visible occluding disk sector leads to perceived motion of the ring segment, as can be expected based on work demonstrating the influence of occlusion cues on the perception of motion (e.g., Ekroll & Borzikowsky, 2010; Shimojo & Nakayama, 1990a; Sigman & Rock, 1974). Thus, the immediate cause of the different perceptual extensions of the ring segment may be related to the differential activation of motion mechanisms rather than to the difference in the occlusion cues per se.

Second, one might argue that the logically incompatible measurements of angular extent constituting the visibility paradox are due to memory effects. Informal inspection of the Supplementary Demonstration suggests that this is not the case because the two incompatible percepts seem to be simultaneously present in visual awareness. On the other hand, it is not unlikely that the well-documented phenomenon of boundary extension (Intraub, 2010; Intraub & Bodamer, 1993; Intraub & Richardson, 1989), which is conceptually similar to the extension effect occurring in the static occlusion illusion and in our displays, but which is primarily conceived of as a memory effect, may have contributed to the effect measured in our experiment.

Third, although the matching task used to measure the perceived extent of the background ring experienced as directly visible may seem straightforward, we experienced it as subjectively difficult. This may be related to the well-known observation that judging the shape of regions of the visual field experienced as ground is far more difficult than judging the shape of regions experienced as figure (Kanizsa, 1979; Koffka, 1935; Palmer, Davis, Nelson, & Rock, 2008; E. Rubin, 1915; N. Rubin, 2001). Confronted with this subjective difficulty, it is not unlikely that the subjects may sometimes have reverted to the strategy of matching the

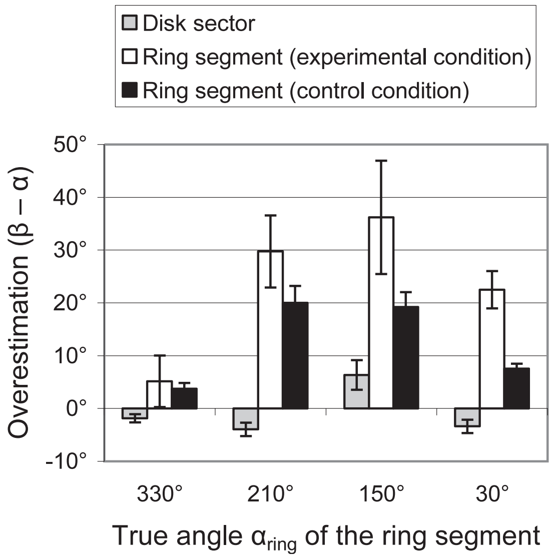

Figure 5. Results of Experiment 1. Each bar shows the difference ($\beta - \alpha$; in degrees) between the perceived and the physical angles of one stimulus element. The fact that the overestimation of the visible portions of the ring segment in the experimental condition (white bars) was not compensated by the (quite accurately) estimated extent of the disk sector (gray bars) demonstrates the visibility paradox. The control condition shows that the "length" of the circular stripe (black bars) was also overestimated in the absence of the occluding disk sector, but only half as much as in the experimental condition. The error bars represent ±1 *SEM*.

adjustable ring segment to the open sector of the occluding disk itself rather than to their perception of the ring segment experienced as visible through the opening. Furthermore, this measurement method is prone to making the paradoxical nature of the percept obvious to the subjects. Again, this may incite subjects to rely on cognitive strategies in order to appear consistent. The finding that the visibility paradox was almost absent at the largest angle (330°) of the open sector in the occluding disk (see Figure 5) may be related to this kind of problem: If the dynamic occlusion illusion is actually as strong as in the other conditions (about 30°), the subjects would have to match the stimulus with a full circle, which would obviously be logically inconsistent with the clear percept of a 30° disk sector covering it. All of this is unproblematic in that it would only lead to more conservative estimates of the paradoxical effect, but alternative measurement methods avoiding or reducing these problems would clearly be desirable.

Fourth, the results of the experimental condition show an asymmetry between the extent estimates of the occluding disk sector on one hand and the ring segment on the other hand. The latter is perceptually extended, whereas the former is not, which is to be expected based on the idea that the perceptual extension is related to occlusion cues. Since the occluder and the background were differently colored, however, it remains possible that the asymmetry is somehow related to the coloring of the stimulus elements rather than to the distinction between occluder and background.

Experiment 2

In order to clarify the issues addressed above we performed a second experiment in which we (a) varied the sensory evidence for occlusion while eliminating perceived motion of the ring segment in both conditions; (b) minimized the potential contribution of memory effects; (c) employed an alternative method of measurement, aiming to reduce the awareness of the paradoxical nature of the percepts; and (d) included a condition minimizing the color differences between occluder and background.

Method

The stimuli used in this experiment (Figure 6) were broadly similar to those used in the experimental condition of Experiment 1 but differed in many details. We also used an alternative procedure for measuring how much of the background was experienced as directly visible.

In this experiment, the occluding disk sector rotated in front of a textured background on which 12 white dots were evenly distributed on the circumference of a virtual circle (see Movies 1, 2, and 3 and Figure 6). As in Experiment 1, the perceived angular extent of the rotating disk sector ("occluder") was measured by asking the subjects to adjust the angle of a corresponding static disk sector such that it appeared to have the same angular extent ("matching task"). Instead of matching the background dots as well, however, the task of the observers was to report how many of the dots were experienced as directly visible ("counting task"). Given the fixed center-to-center distance between any two neighboring dots ($360°/12 = 30°$), this number can be converted into the visible angular extent of the background ring constituted by the 12 dots. The counting task used in this experiment is more indirect than the matching task used in Experiment 1, but it also seems to have important advantages. First, we experienced it as more natural and less confusing than the matching task. This observation may seem surprising and raises interesting theoretical questions regarding the phenomenology of the percept in its own right. At this juncture, however, we merely note that this seems to be the case. Second, by virtue of its indirectness, the counting task makes

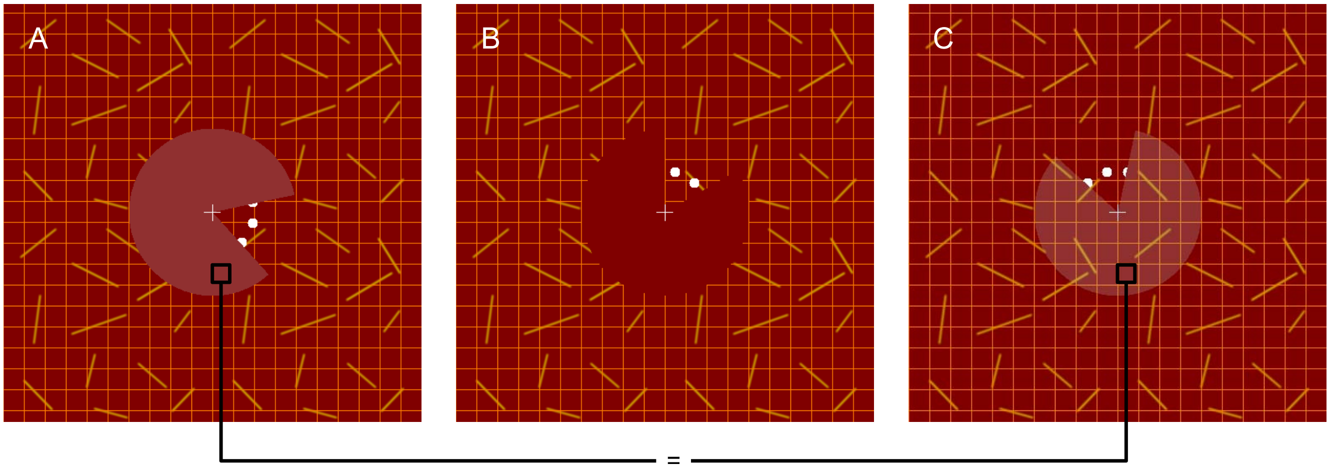

Figure 6. Stimuli used in Experiment 2. (A) Opaque, real occluding disk. (B) Opaque, illusory occluding disk. (C) Transparent disk. Although the patterned background is visible through the transparent disk, the white dots are visible only in the open sector as if the disk surface were opaque. The local physical color information was identical in the black outlined squares in parts A and C. The angle of the open sector is 60° in this figure.

the paradoxical nature of the percept less obvious to the observers. Thus, they are less likely to apply cognitive criteria in order to appear consistent.

We used three kinds of occluders: a real, opaque disk sector (Figure 6A); an illusory, Kanizsa-type disk sector (Figure 6B); and a transparent disk sector (Figure 6C). The Kanizsa-type disk sector was used because it minimizes the color differences between the target and the surround. The purely subjective contour of this disk emerges through modal completion of the points at which the illusory disk erases the grid and the line segments distributed on the background (Kanizsa, 1979). The transparent disk was constructed in order to reduce the consistency of the cues to occlusion while mimicking the proximal stimulus properties of the real, opaque disk as closely as possible. Using the standard technique of alpha blending (Foley, van Dam, Feiner, & Hughes, 1996; Metelli, 1970), we rendered the disk as transparent. Thus, the texture of the background remained visible through the transparent disk. The white target dots, however, were rendered in exactly the same way as in the other conditions; that is, they were rendered as visible in the open sector of the disk. Crucially, the transparency of the occluding disk with respect to the background texture contradicts the interpretation that the dots continue to exist behind the disk. Thus, if cues to the presence of the target dots behind the occluder are indeed responsible for the dynamic occlusion illusion, it should be reduced in this condition. Note that the color and transmittance of the transparent disk sector were chosen such that the proximal color in the region of the disk sector was exactly the same as that of the real, opaque disk sector (see small outline squares in Figure 6A, C). This means that the only physical differences between the real, opaque disk sector and the transparent disk sector pertain to the small subset of the disk regions corresponding to the background texture elements.

The animation was shown in the left half of the screen in all trials. In half of the trials, a static disk sector was displayed in the right half of the screen and the task of the observer was to adjust its angle (using the arrow keys of the keyboard) so that its perceived angular extent matched that of the rotating disk sector in the left half of the screen (i.e., matching task). In the other half of the trials the matching disk sector in the right half of the screen was replaced by a text caption indicating that the counting task had to be performed, and the task of the observer was to indicate the number of target dots experienced as simultaneously visible. The observers could choose among integer values and intermediate values such as one to two dots, two to three dots, and so on. In the data analysis, the latter judgments were counted as 1.5 dots, 2.5 dots, and so on. Since the judgments in the right half of the screen were carried out while the animation was running in the left half of the screen, it is unlikely that they were influenced by memory effects.

The angle of the open sector of the rotating disk was varied in two steps (30°, 60°). We used these smaller openings in order to keep the number of dots within the range allowing for quick and effortless counting ("subitizing"; cf. Kaufman, Lord, Reese, & Volkmann, 1949).

The number of target dots experienced as directly visible yields an indirect measure of how much of the background region was experienced as directly visible. Since the center-to-center distance between two neighboring dots along the circle corresponds to $360°/12 = 30°$, an open sector of 60° implies that two (Figure 6B) or three (Figure 6C) dots are objectively visible, depending on the position of the open sector. Thus, the number of objectively visible dots oscillates between

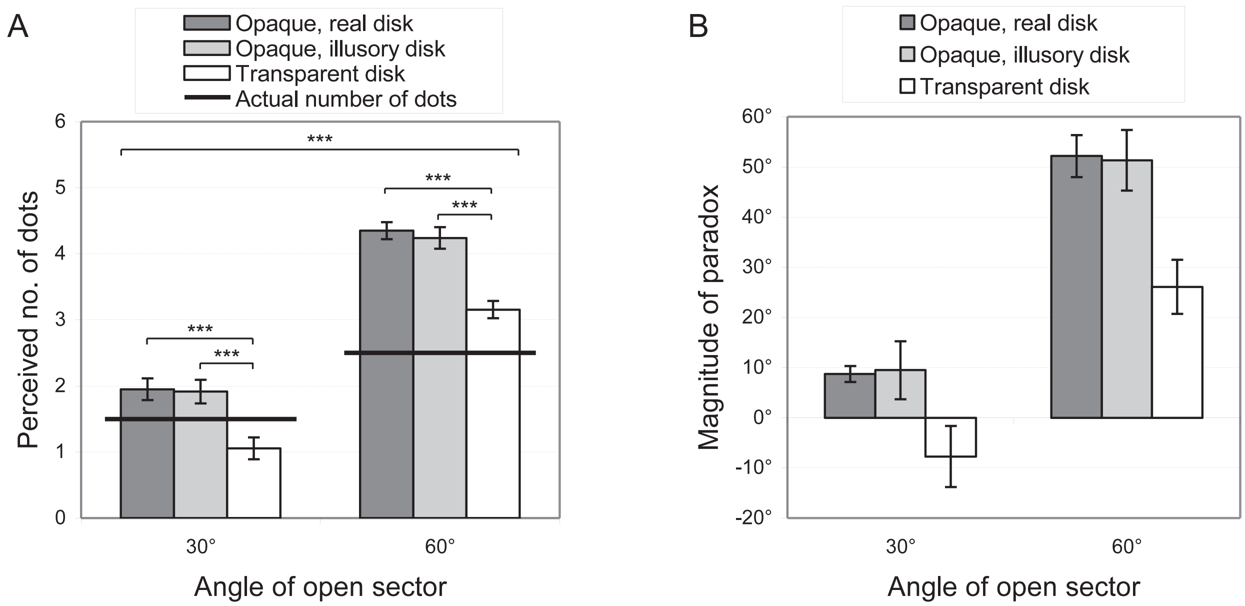

Figure 7. Results of Experiment 2. (A) Each bar shows the mean number of dots reported as simultaneously visible for three different occluder types and for two angles of the open disk sector used in the experiment. The black horizontal lines indicate the mean number of dots physically present in the corresponding display. (B) The mean magnitude of the paradoxical effect resulting from the perceived mean angle of the disk sector (not shown in the figure) and the perceived angle of the background, which can be calculated based on the mean number of dots perceived simultaneously (see text for details). The error bars represent ±1 *SEM*.

two and three as the disk rotates. Analogously, the number oscillates between one and two for the disk with the 30° open sector.

The background was dark red textured with an orange grating and arbitrarily distributed yellow line segments (Figure 6) and subtended about 11° of visual angle. The surface of the disk sector, rotating at 0.94 revolutions/s as in Experiment 1, was a lighter red than the background in the real-occluder condition (Figure 6A), the same dark red as the background in the illusory-occluder condition (Figure 6B), and transparent in the transparent-disk condition (Figure 6C). To facilitate the counting task we arranged the dots not too far from each other by setting the inner diameter of the circle constituted by the 12 dots to 1.5°. The diameter of the rotating disk was approximately 4.5°, and the diameter of the individual dots was about 0.3° of visual angle.

In total, there were 12 task–stimulus combinations (2 tasks × 3 disk types × 2 angles of the open sector), each repeated 10 times, resulting in 120 trials presented in pseudorandom order. Twelve new naive students from the University of Kiel participated in the experiment. The data from three subjects who in the briefing reported perceiving dot motion in the open sector instead of stationary dots behind the rotating disk were discarded.

Results

Figure 7A shows the number of dots experienced as directly visible for each stimulus condition. The bars represent the averages across all observers. The black horizontal lines indicate the time-averaged number of dots physically present in the corresponding display.

Three general trends are readily apparent. First, when the occluding disk sector was opaque, more dots were experienced as simultaneously visible than when the disk sector was transparent; one-tailed t test: $t(8) > 6.08$, $p < 0.001$ in both the 30° and 60° conditions. Second, the results obtained with the real and illusory kinds of the opaque disk were essentially identical, which implies that more dots were experienced as simultaneously visible in the presence of the illusory occluding disk sector than in the presence of the transparent disk sector; one-tailed t test: $t(8) > 5.42$, $p < 0.001$ in both the 30° and 60° conditions. Third, relative to the number of physically visible dots, more dots were experienced as visible when the open sector was 60° than when it was only 30°; one-tailed t test: $t(26) > 13.25$, $p < 0.001$.

The perceived angle β_{occluder} of the occluding disk agreed closely with the physical angle: The condition-wise averages across all observers deviated from the true value by only $-5°$ to $+7°$ (data not plotted). In Figure 7B these small deviations from veridical perception of the occluding disks are taken into account to derive estimates of the paradoxical effect. To this end the number (N) of dots experienced as directly visible (see Figure 7A) was converted to an equivalent angular extent $\beta_{\text{background}}$ according to the equation $N = \beta/\Delta + 0.5$, where $\Delta = 30°$ is the fixed center-to-center angular separation between any two neighboring dots along the circle. The values shown in Figure 7B represent the paradoxical effect, defined as $(\beta_{\text{occluder}} + \beta_{\text{background}}) - 360°$.

Discussion

The results of this experiment agree with those of Experiment 1 in demonstrating the existence of the visibility paradox. Additionally, the results show that the paradoxical effect was clearly reduced when the interpretation that the target dots continued to exist behind the disk was contradicted by the transparency of the occluding disk. This suggests that the effect is indeed due to occlusion-related visual completion. The close correspondence between the results obtained with the real and the illusory occluders supports this interpretation further. The fact that the paradoxical effect was much less prominent when the open sector in the occluder was small (30°) than when it was large (60°) is also compatible with the idea that the effect is caused by mechanisms aiming to create a representation of the partly occluded background. In the former case, less information about the background is transmitted through the open sector, which may constitute a poorer basis for modal extrapolation.

Discussion

The present demonstration and the two experiments document a dynamic illusion that is similar to the static occlusion illusion (Figure 2) in at least two regards. First, the central feature of both illusions is the perceptual extension of a region abutting on a region that can be interpreted as an occluder. Second, as documented by the present findings and by investigations of the static occlusion illusion (Palmer et al., 2007; Palmer & Schloss, 2009), both illusions seem to depend critically on the sensory evidence for occlusion. Accordingly, the partial-modal-completion hypothesis proposed by Palmer et al. (2007) neatly captures not only the main features of the static occlusion illusion but also those of the dynamic illusion investigated in the present study. The observation that the partial modal completion observed with our dynamic stimuli is stronger than the relatively weak effect observed in the static occlusion illusion can be attributed to the fact that the successive views of the background provide stronger sensory evidence for the continuation of surface features such as luminance and color. Thus, our findings may be said to further strengthen the plausibility of the partial-modal-completion hypothesis and to demonstrate that it can be applied outside of the specific context of the static occlusion illusion. This is in agreement with the idea that the occlusion illusion is "a very general phenomenon that occurs whenever an object or surface is perceived as partly occluded by a shared edge" (Palmer et al., 2007, p. 667).

As mentioned in the Introduction, though, the partial-modal-completion hypothesis raises the question of how space is made for this modal extension in the visual field. Whereas an amodal extension is naturally accommodated behind an occluder, the modal extension requires extra space in the visual field, which would seem to require a corresponding perceptual displacement of the surrounding regions. Yet Palmer et al. (2007, p. 669) surmised "that the visual system somehow manages to see the partly occluded object as spatially extended perpendicular to the occluding edge without perceiving any difference in the positions of the regions attached to the edge." The present findings strongly suggest that this is indeed the case. Accordingly, this visibility paradox must be regarded as a real phenomenon in need of substantive theoretical explanation. A second issue raised by the partial-modal-completion hypothesis is that although it contends—in accordance with the empirical findings—that a part of the perceptual completion of the partly occluded object is experienced as modal instead of amodal, it does not offer any explanation for *why* this happens.

Why does amodal completion turn modal?

The existence of the visibility paradox shows that the occlusion illusion is more than just a visual illusion. Like Escher's and Reutersvärd's famous paintings or other well-known impossible figures such as the Penrose triangle, our stimulus gives rise to a percept with an internal structure that is incompatible with any consistent real-world interpretation whatsoever (Cowan, 1977; Gregory, 1980; Hochberg, 2003; Huffman, 1971; Kulpa, 1983, 1987; Penrose & Penrose, 1958). As illustrated in Figure 8, the modal extension of the background element implies that it is being experienced as directly visible at a point of the visual field at which it is also experienced as being occluded by the rotating disk. Although the partial extension of a background surface behind an occluding surface, in itself, is certainly possible, the simultaneous visibility of the occluder and regions in the scene occluded by it obviously is not. Thus, this paradoxical percept is analogous to known impossible figures provided that the aspect of visibility, understood in terms of geometrical optics, is considered as part of the physical situation. How can this seemingly paradoxical observation be explained?

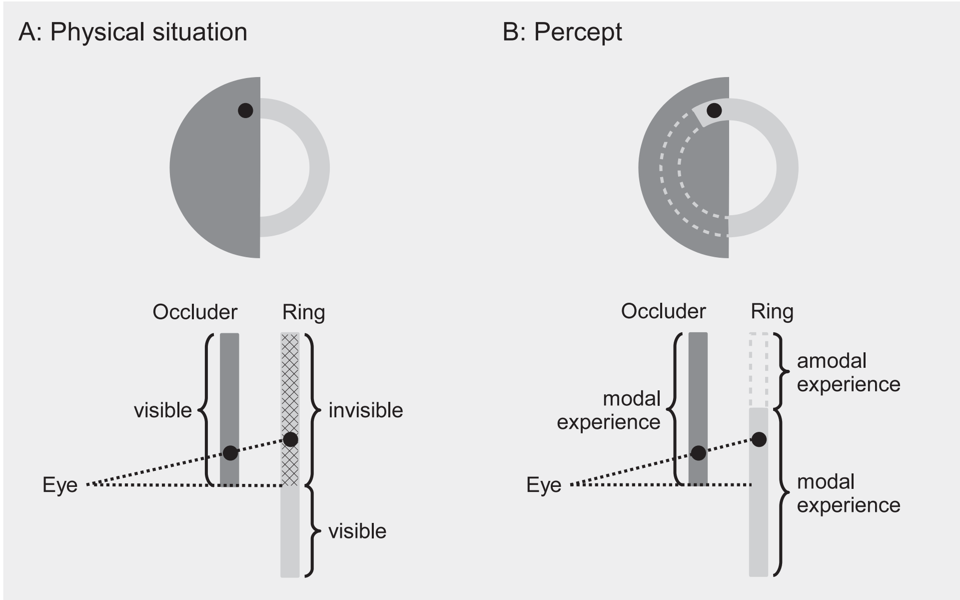

Figure 8. Schematic structure of the stimulus (A) and of the visibility paradox it evokes (B). (A) In purely optical terms, the background ring is invisible (light gray, crosshatched) wherever it is occluded by the half-disk (dark gray). (B) In the percept, portions of the background ring are experienced as directly visible (modal percept; light gray) and as occluded (amodal percept; outline). However, the background ring and the occluder (dark gray) overlap each other partly (as indicated by the black dots in the line of sight), meaning that these portions of the background ring are perceived as directly visible and occluded at the same time.

A theoretical resolution of the visibility paradox

We believe that the key to resolving this paradox is to question the seemingly self-evident and widespread assumption that occluded portions of a visual scene are represented by amodal percepts, while unoccluded portions of a scene are represented by modal percepts (e.g., Kellman & Shipley, 1991, p. 143). Essentially, the static occlusion illusion and, in particular, the present dynamic version of it tangibly demonstrate that this cannot be the general rule because here an occluded portion of the visual scene is represented by a modal percept. This is also, in essence, what the partial-modal-completion hypothesis contends.

Abandoning the tacit assumption above, however, immediately raises the question of why some percepts are experienced as modal, whereas others are not. We propose that visual percepts are experienced as modal whenever they are based on sufficiently conclusive sensory evidence for particular attributes of the visual scene. Conversely, they are experienced as amodal when this is not the case. Generally, this hypothesis makes almost the same predictions as the original tacit assumption, simply because the conclusiveness of the sensory evidence regarding unoccluded regions of a visual scene tends to be much stronger than the sensory evidence regarding occluded regions. This relationship is not perfect, though. In rare cases, the sensory evidence available for perceptual inferences regarding qualitative attributes pertaining to occluded regions of the scene may in fact be rather strong and conclusive. This is arguably the case for the static occlusion illusion and even more so for our dynamic display. More specifically, one could argue that the sensory evidence pertaining to the parts of occluded background that are closest to the leading edge of the occluding disk (at any given moment of time) is particularly conclusive because those parts were directly visible just a brief moment earlier. This factor would add to the influence of mere spatial proximity to unoccluded parts that presumably underlie the static occlusion illusion.

From this perspective, it is not surprising that certain parts can be experienced as directly visible (modal) even though they are optically occluded. Figure 8 illustrates how this reasoning resolves the visibility paradox: Although it is logically impossible for the two black dots located on the same line of sight in different depth planes to be simultaneously visible because one occludes the other, the sensory evidence regarding both of them may be quite conclusive.

Our hypothesis is compatible with Palmer et al.'s (2007, p. 650) finding that the magnitude of the occlusion illusion varies with the "strength of the evidence for occlusion." According to our proposal, though, the critical variable is not the strength of the evidence for occlusion per se but rather the conclusiveness of the sensory evidence available for perceptual interpretations regarding optically invisible scene regions. It is clear, though, that the latter is intimately linked to the former.

Although our tentative hypothesis that visual percepts are experienced as modal whenever they are based on sufficiently conclusive sensory evidence for particular attributes of the visual scene and as amodal otherwise may be regarded as rather counterintuitive, we think it deserves being taken seriously because it is, to the best of our knowledge, the only logically consistent approach explaining the visibility paradox proposed thus far. It should be pointed out, though, that this hypothesis raises two new issues that need to be addressed.

"Modal versus amodal" as a continuous variable?

Linking the distinction between modal and amodal percepts to the conclusiveness of the underlying sensory evidence suggests that there must be a threshold value above which the sensory evidence becomes conclusive enough to evoke a modal percept rather than an amodal one. If this were indeed the case, it would have to be worked out what this threshold value is and how it can be theoretically motivated. One preliminary speculation would be that the percept becomes modal whenever the posterior distribution over all candidate interpretations is peaked sharply enough to render a single interpretation that is vastly more likely than all others. It should be noted, though, that once we abandon the assumption that modal and amodal percepts are linked to the dichotomy between unoccluded and occluded scene regions, there is no principled reason why the phenomenological variable "modal–amodal" has to be dichotomous. Thus, in principle, it could also be a continuous variable, which depends continuously on the conclusiveness of the sensory evidence.

Different visibility of different perceptual attributes?

Because our hypothesis links modal and amodal visual experiences to the conclusiveness of the underlying sensory evidence rather than to occluded and unoccluded regions of the visual scene, and because the conclusiveness of the sensory evidence regarding different perceptual attributes (e.g., object unity, contour, shape, texture, color, or luminance) may be different within a region of the visual field, it is possible that some of the attributes pertaining to an occluded region of the visual field may be experienced as phenomenally clearly specified and distinct (i.e., visible), whereas others may be not specified and distinct or poorly specified and distinct (i.e., invisible or vaguely visible, respectively). This idea may shed light on the somewhat confusing phenomenology of many cases of amodal completion. Consider, for instance, the following quotation from Michotte et al. (1991, p. 144, our italics): "[C]ompletions that are '*present*' in this manner should be termed 'amodal' . . . . Thus the term amodal has initially a purely negative significance, since it indicated the absence of visual qualities (luminance and color) from the completion of the figure. On the other hand, it should be stressed that *the impression of the whole shape and the unbroken character of its contour is entirely compelling for the subjects . . . . In the case of continuity of color there is not so compelling an impression*." Consider also a similar quotation from Kanizsa (1985, p. 29): "But the continuation behind the covering surface, although it is *amodal*, that is, without the chromatic attributes of the visual modality, can be a genuinely *perceptual presence* . . . ."

Why is it that the contour and shape are experienced as entirely compelling, whereas the color is not? And why are luminance and color, but not contour and shape, considered to be visual qualities? What is the significance of the term *perceptual presence*? Is not the notion of perceptual presence in the absence of visual qualities almost a contradiction in terms? Note that Michotte et al. (1991) and Kanizsa (1985), both firmly committed to defining the concepts of modal and amodal percepts in purely phenomenological terms, carefully avoid reference to physical or physiological categories in their definitions. The way they implicitly define "visual qualities" (Michotte et al., 1991) and "attributes of the visual modality" (Kanizsa, 1985), however, suggests that they have not been entirely consistent in avoiding those references. The notion that luminance and color are visual qualities while contour and shape are not may be motivated through reference to ideas from sensory physiology, but it is difficult to see how it can be justified if the concept of visual qualities is to be understood in purely phenomenological terms. In terms of immediate visual experience, it would seem reasonable to regard contour and shape as visual qualities on par with luminance and color.

Based on our hypothesis, however, it becomes possible to frame these important observations in a theoretical language that avoids the issues addressed above. For instance, the observation that the contour and shape of an object are experienced as highly definite and visually present in many well-known cases of amodal completion, whereas the luminance and color of an object are not, can be taken to mean that the perceptual attributes of object contour and shape are experienced as modal (i.e., specified, or visible), whereas those of luminance and color are not or are experienced only as vague (i.e., unspecified, or invisible). This may be the case because the sensory evidence pertaining to the perceptual attributes of object unity, contour, and shape are more conclusive than the sensory evidence pertaining to an object's surface luminance and color. In this connection, it is interesting to note that object unity, shape, and contour are intrinsically nonlocal properties that necessitate the

Figure 9. Virtual lines, the perceptual presence of which "has only an amodal character" (Kanizsa, 1987, p. 44). (A) Dots connected by an open curved line. (B) Dots connected by a closed contour. Adapted from Kanizsa (1987, figures 4.1a and 4.3, pp. 41 and 42).

integration of distributed global stimulus information (Gestalt formation) even in the absence of occlusion. Hence, the perceptual extraction of these properties may be expected to be particularly robust against the local changes in the input produced by local occlusions.

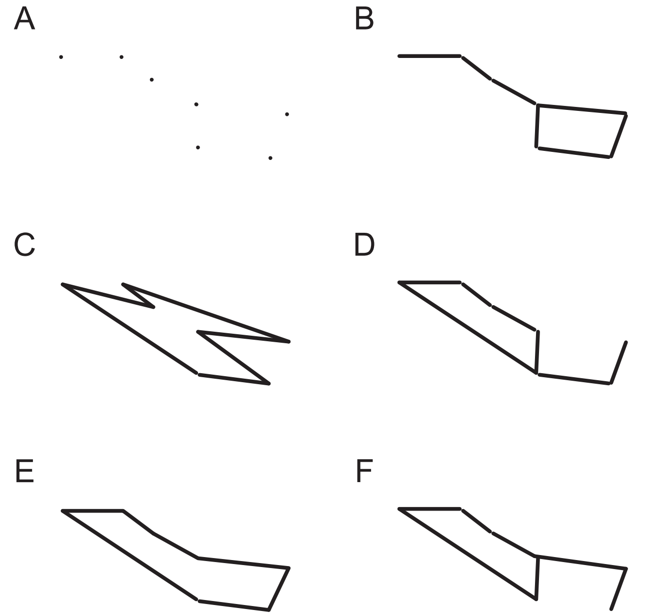

Figure 10. The collection of dots in A, which corresponds to the stars in the constellation called the Big Dipper, are experienced as having a definite shape corresponding to "bridge lines" (Metzger, 1975) or "virtual lines" (Kanizsa, 1987) connecting different pairs of dots. While these lines are not experienced as visible, they are perceptually present, much like amodally completed contours. As demonstrated by the examples in C through F, it is logically possible to conceive of many different shapes as resulting from interpolations between the dots in A, but a very specific one is perceived—namely the one shown in B. Note that the line segments in C through F indeed go through exactly the same points as those in B, although this may be not obvious from the visual impressions. This phenomenon may be taken to indicate that amodal perception may occur even when there is no occlusion involved. Adapted from Kanizsa (1987, figure 4.2, p. 41).

Amodal percepts without occlusion?

According to our hypothesis, the phenomenological variable "modal versus amodal" is a perceptual representation of the conclusiveness of sensory evidence. Thus, on one hand, the hypothesis predicts that occluded regions can be experienced as modal instead of amodal provided that the sensory evidence is unusually conclusive, in agreement with our experimental findings. Conversely, though, the hypothesis also suggests that it should be possible to experience amodal percepts in the absence of occlusion if the sensory evidence is unusually inconclusive. Metzger (1975; see Metzger, Spillmann, Lehar, Stromeyer, & Wertheimer, 2006, for an English translation) and Kanizsa (1987) described a phenomenon called "bridge lines" (Metzger's terminology) or "virtual lines" (Kanizsa's terminology) that may be taken to suggest that this is indeed the case. This phenomenon—which is not to be confused with the more well-known phenomenon of subjective (or illusory) contours, although the latter is often also called "virtual contours"—is demonstrated in Figure 9A and B. The point of interest is that collections of dots are experienced as having definite shapes corresponding to virtual lines (or curve segments) connecting one dot with the other. In much the same way as amodally completed contours, these lines are perceptually present, although we do not see them in the literal sense. Furthermore, the perceptual nature of these virtual lines can be demonstrated appealing to the same argument that has been used for demonstrating the perceptual nature of amodally completed contours. Consider the dots in Figure 10A, which correspond to the stars in the constellation called the Big Dipper. As illustrated by the examples in Figure 10B through F, it is logically possible to conceive of many different shapes as resulting from interpolations between the dots in Figure 10A, but a very specific one is perceived—namely the one shown in Figure 10B. In accordance with this, Kanizsa (1987, p. 44) wrote that the presence of these "virtual lines" has an "amodal character," although there is no occlusion involved.

A further potentially interesting similarity between typical cases of amodal completion and the phenomenon of bridge lines or virtual lines is this: In the preceding paragraph, we argue that phenomenal visibility is a continuous, multidimensional variable that can differ for different attributes of perceptual objects such as object unity, contour, shape, texture, color, or luminance because the sensory evidence for the different perceptual attributes may differ. Based on this idea, we suggested that the sensory evidence for perceptual attributes such as object unity, contour, and shape is often more conclusive than the sensory evidence for attributes such as surface luminance and color and that this explains why typical cases of amodal completion involve distinct impressions of shape without clear impressions of luminance and color.

Interestingly, the same seems to be the case for the phenomenon of bridge lines or virtual lines: The impression of shape is fairly distinct, but there is no impression of texture, luminance, or color.

Can sensory evidence from other modalities also influence phenomenal visibility?

According to our hypothesis, the phenomenal visibility of a perceptual interpretation is determined by the conclusiveness of the sensory evidence in its favor. In principle, the conclusiveness of the sensory evidence may be determined by many factors, including information from other modalities. Intriguingly, it has been reported that a positive afterimage of the observer's own hand crumbles more quickly when the hand is moved in total darkness (Carlson, Alvarez, Wu, & Verstraten, 2010; Davies, 1973; Gregory, Wallace, & Campbell, 1959; Hogendoorn, Kammers, Carlson, & Verstraten, 2009; Ritchie & Carlson, 2010). The movement of the hand, which is inconsistent with the unchanged retinal afterimage, may be said to reduce the overall conclusiveness of the sensory evidence in favor of the afterimage percept. Recently, it has also been reported that the motion of one's own hand in front one's blindfolded eyes can be experienced as phenomenologically visible (Dieter, Hu, Knill, Blake, & Tadin, 2014).

Does the visual system have access to the conclusiveness of sensory evidence?

According to our hypothesis, the visual system renders a particular perceptual interpretation as phenomenologically visible or invisible depending on the conclusiveness of the underlying sensory evidence. Thus, it presupposes that the visual system has access to some kinds of estimates about this conclusiveness. This assumption sits well with an important idea in the field of cue integration, according to which different cues are weighted according to their relative reliability (Ernst & Bülthoff, 2004; Jacobs, 2002; Landy, Banks, & Knill, 2011). The major difference is that the perceptual representations of reliability or conclusiveness considered in cue integration models are supposed to exist and play a role in the perceptual system itself or at the interface between different perceptual modalities rather than at the interface between the perceptual system and our conscious experience.

Relation to the boundary extension effect

Both the static occlusion illusion and the dynamic version of it investigated in the present article are in some ways similar to the boundary extension effect—that is, to the finding that subjects tend to render partly occluded regions of the original scene as directly visible when asked to draw a visual scene from memory (Intraub & Bodamer, 1993; Intraub & Richardson, 1989). Different from the static occlusion illusion and the present dynamic version of it (which are most naturally regarded as purely perceptual effects), though, the boundary extension effect is conceived of as a memory effect. The two phenomena may, however, be more closely related than hitherto appreciated. According to Intraub (2010, p. 240), for instance, "viewers have no difficulty discriminating the currently present visual sensory input from the amodally perceived continuation of objects and surfaces beyond the view-boundaries" when the stimulus is visible but "falsely remember having seen beyond the edges of the view when the visible stimulus is interrupted for less than 1/20th of a second before reappearing at test (i.e., boundary extension; Intraub & Dickinson, 2008)." The findings of Palmer and colleagues (Palmer et al., 2007; Palmer & Schloss, 2009) as well as the present findings strongly suggest that the former assumption is unwarranted. Clearly, this does not in any way imply that boundary extension is not due to memory effects, but it does suggest that perceptual processes and memory processes can produce very similar effects. This is not surprising given the intimate relationship between memory and perceptual processing (e.g., Bartlett, 1932). One may argue that neither the static occlusion illusion nor the present dynamic illusion are immediate and purely perceptual effects and that they are in fact due to memory effects operating on a short time scale. It is difficult to see how this can be ruled out experimentally, but this issue appears rather moot given that most aspects of natural perceptual processing (e.g., motion perception or transsaccadic integration) must, by logical necessity, involve memory processes of one kind or another.

It is interesting to speculate whether the boundary extension effect may also involve a visibility paradox of the kind documented here. In typical experiments investigating the boundary extension effect, subjects are asked to draw from memory a picture of a previously viewed scene. The task of representing their percept pictorially on a piece of paper forces them to compensate the extensions of any regions of the visual field through corresponding reductions in their rendition of other regions of the field. Thus, even if the boundary extension effect also involves a visibility paradox, it is likely to go unnoticed in this kind of experimental investigation.

Relation to the shrinkage illusion

Beyond the theoretical challenges already mentioned, the static occlusion illusion raises an intriguing

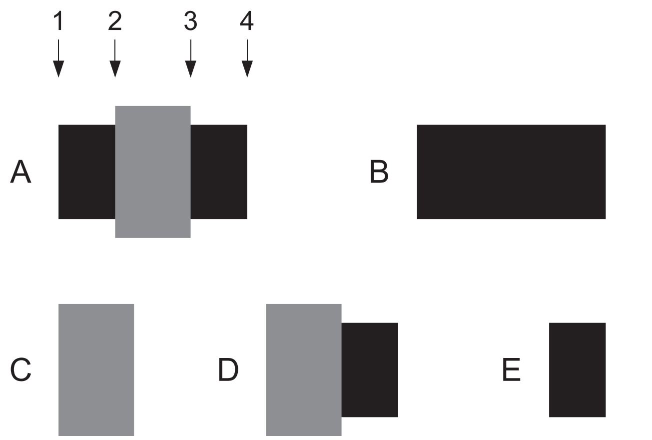

Figure 11. The partly occluded black rectangle in A appears to be less wide than the identical, unoccluded one in B. This effect is called the shrinkage illusion. The gray rectangle in C appears to be less wide than the identical one in D. This effect is called the configural shape illusion. The black rectangle in D appears to be wider than the one in E. This is a version of the static occlusion illusion. See the text for further explanation.

question when considered in conjunction with Kanizsa's shrinkage illusion (Kanizsa, 1972, 1979; Vezzani, 1999) and the configural shape illusion recently described by Schloss, Fortenbaugh, and Palmer (2014). The shrinkage illusion can be observed in a two-sided variant (Figure 11A) of a static occlusion illusion display (Figure 11D). The partly occluded horizontal bar in Figure 11A appears less wide than the identical, unoccluded horizontal bar in Figure 11B. At the same time, both visible parts of the black bar in Figure 11A appear slightly elongated along the horizontal axis when compared with the stimulus in Figure 11E, an effect very similar to that observed in the static occlusion illusion (Figure 11D vs. Figure 11E). This would seem to suggest that the occluded, central part of the horizontal bar must be perceived as significantly shortened in order for the shrinkage illusion to manifest itself despite the opposing tendency toward visible elongation of the unoccluded outer parts, which would be expected due to the partial modal completion known from the static occlusion illusion. However, Schloss et al.'s (2014) studies on the related configural shape illusion suggest that the vertical bar occluding the central region in Figure 11A should be perceived as wider rather than thinner. A version of the configural shape illusion can be seen in Figure 11: The gray rectangle in Figure 11D appears to be slightly wider than the identical one in Figure 11C.

It is presently unclear how these apparent contradictions can be resolved. But there is clear evidence that, in contrast to the occlusion illusions, neither the shrinkage illusion nor the configural shape illusion depend on the perception of occlusion in any way (Schloss et al., 2014; Vezzani, 1999). Palmer and Schloss (in press) recently proposed a common explanation for both illusions in terms of edge-based assimilation. According to this explanation, different perceptual estimates are being made of different distances in different contexts. When judging the length of the horizontal bar in Figure 11A, the observer judges the distance between edges 1 and 4, which are perceptually displaced toward edges 2 and 3 through assimilation. This produces the shrinkage illusion. When one judges the distance between inner edges 2 and 3, outer edges 1 and 4 become the relevant context, which pulls edges 2 and 3 outward. This makes the vertical occluder appear broader.

It may be interesting to consider whether this kind of principle can serve as an alternative explanation for the visibility paradox observed in our dynamic occlusion illusion. Maybe the perceptual estimates of the angular extents of the occluding disk sector and the unoccluded portions of the ring are made in different ways due to different contextual influences, such as the edge assimilation proposed to account for the shrinkage illusion and the configural shape illusion. In principle, we regard this as a possible hypothesis. However, due to the circular layout of our stimuli, judgments regarding the angular extents of the two elements should be based on estimates regarding the position of the very same pair of edges because the two radial edges of the occluding disk sector physically coincide with those of the visible part of the ring and because no further radial edges are present in the stimulus. Naively speaking, there do not seem to be different contexts available regardless of whether the extent of the disk sector or the extent of the ring is being estimated. Thus, for this kind of explanation to be viable, it would seem necessary to assume that the causally effective context change is a perceptual one that must somehow be induced by the difference in the perceptual tasks. Generally, we regard this as an interesting possibility that cannot be ruled out based on our present experiments. However, that the specific idea underlying Palmer and Schloss' (in press) explanation of the shrinkage illusion and the configural shape illusion can also explain the visibility paradox derived from our dynamic occlusion illusion seems unlikely given that the latter seems to be intimately linked to the perception of occlusion, which plays no role in the former illusions or in Palmer and Schloss' (in press) explanation of them.

Relation to da Vinci stereopsis

The curious observation that occluded regions may be experienced as modally visible is reminiscent of a well-known aspect of binocular vision, namely that certain parts of a visual scene that are occluded to one

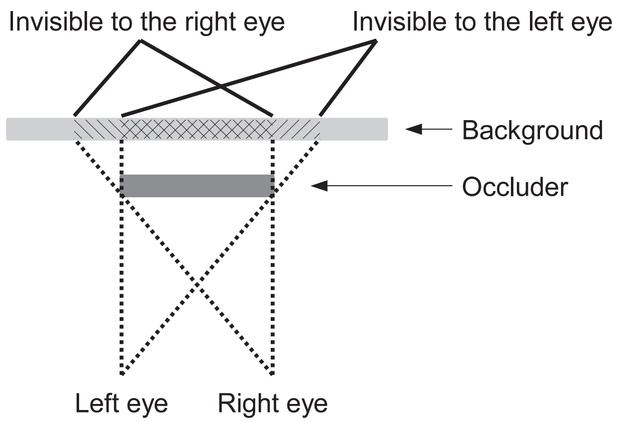

Figure 12. In occlusion situations as shown here, portions of the background are optically invisible to the left eye only, to both eyes, and to the right eye only, respectively. Whereas the background regions invisible to both eyes are typically perceived as amodally completed, regions visible to only one eye are experienced as modally visible.

eye are directly visible to the other and vice versa (Figure 12). These regions typically appear modally visible provided that the given interocular difference is consistent with real-world occlusion constraints ("da Vinci stereopsis"; Nakayama & Shimojo, 1990; Shimojo & Nakayama, 1990b). If, however, the interocular difference violates these constraints (i.e., when details are present in the right field of the left-eye image but not in the right-eye image), binocular rivalry or interocular suppression occurs.

As pointed out by Palmer et al. (2007), one may be tempted to link the static occlusion illusion to some filling-in mechanism or "da Vinci buffer" used for the region that is visible in only one eye. According to that, based on monocular occlusion cues the visual system may assume that a thin strip of the background is visible to one eye but not to the other, which might affect the partial modal completion of that strip. However, as Palmer et al. (2007) showed, da Vinci stereopsis cannot be a significant factor in the explanation of the static occlusion illusion because the modal expansion occurs not only along vertical occluder edges but also along horizontal occluder edges. The same argument applies to the dynamic occlusion illusion since the rotating occlusion edges are nonvertical most of the time. Nevertheless, Palmer et al.'s (2007) idea of a da Vinci buffer may still be interesting if considered in more general terms. Rather than a buffer specifically dedicated to the processing of binocular half-occlusions, one could conceive of a more general occlusion buffer used for storing previously visible regions or anticipating new visible regions in connection with motion parallax or relative motion of occluder and background.

Relation to visible persistence

The perceptual extension of the background ring observed in Experiment 1 (or, equivalently, the percept of more dots than are actually simultaneously visible through the open sector of the rotating disk in Experiment 2) can be conceived of as resulting from a kind of visible persistence (Coltheart, 1980): If visual impressions of stimulus elements corresponding to the background ring persist for some time after their objective disappearance (through occlusion or deletion), this should naturally lead to a perceptual elongation of the visible ring segment. It is clear that visible persistence cannot account for the static occlusion illusion, but it could in principle account for the degree to which the effect in our dynamic version of the occlusion illusion exceeds that in the static version. Several observations, however, make it difficult to link this phenomenal visible persistence to simple neural persistence (i.e., simple temporal integration, sluggish temporal responses of receptors, or positive afterimages). First, it is difficult to see why sluggish receptor responses should lead to a perceptual elongation of the background ring but not to a perceptual elongation of the occluder in the foreground. This asymmetry was even observed in the illusory occluder condition of Experiment 2 in which the colors of the occluder and the background were essentially identical. Second, since the percept of the occluder was essentially veridical, any elongation of the background ring (or, equivalently, any persistence of the dots in Experiment 2) due to persistent receptor responses would be expected to appear superimposed in front of the occluder. Informal observations indicate that this was not the case (see also the Supplementary Demonstration and Movie 1). Third, it is difficult to see how occlusion cues, which had a clear influence on the amount of phenomenal elongation (or, equivalently, phenomenal persistence) observed in our experiments, could have a causal influence on the sluggishness of receptor responses. Thus, the idea of simple neural persistence does not seem very useful for understanding the present observations.

Conversely, however, the present observations may potentially be useful for understanding the results of psychophysical experiments aiming to investigate visible persistence. Many investigations of visible persistence have used stimulus situations and tasks similar to those used in our experiments in order to estimate the duration of visible persistence (Coltheart, 1980). The influence of occlusion cues documented in the present study suggests that occlusion cues, even if they were implicit and unintended by the researchers, may have also influenced the results of the former studies. Our findings are in a way complementary to the observation that phenomenal visible persistence can be reduced by motion cues (Burr, 1980). Given the well-documented complementary relationship between motion and occlusion cues (Anderson & Sinha, 1997; Ekroll & Borzikowsky, 2010; Gibson, Kaplan, Reynolds, & Wheeler, 1969; Sigman & Rock, 1974; Yantis, 1995), it is perhaps not surprising that occlusion cues seem to have the converse effect on phenomenal visible persistence. When the objective disappearance of a stimulus element at a given location of the visual field occurs because it has moved somewhere else, it would make little sense for the visual system to maintain a persistent representation of it; however, when the disappearance is due to occlusion, this would surely be the case. As our findings suggest, this persistent representation may even be experienced as phenomenally specified and visible (i.e., modal in the traditional terminology), even though the represented stimulus element is experienced as occluded at the same time.

Relation to the anorthoscopic effect

In the present study we used a stationary background seen through a moving "slit" as a stimulus. Our first informal chance observations of the visibility paradox, however, which originally motivated this study, were made when viewing a demonstration of the anorthoscopic effect. Here, one may have the compelling impression of a complete moving stimulus even though only small parts of it are revealed successively, as it moves behind a stationary occluding screen with a thin slit in it (Anstis & Atkinson, 1967; Aydın, Herzog, & Öğmen, 2009; Fendrich, Rieger, & Heinze, 2005; Haber & Nathanson, 1968; Morgan, Findlay, & Watt, 1982; Wollschläger, 2006; Wollschläger & Faul, 2006). Our use of the converse arrangement in the present study was motivated by the fact that it tends to yield more stable percepts, but because our original observations were made using a stimulus moving behind a stationary slit, we believe that the visibility paradox also occurs in that case.

A major discussion in the literature on the anorthoscopic effect has been whether the effect can be simply explained in terms of "retinal painting" (i.e., a combination of eye movements bringing the successive views of the figure through the slit into spatial register on one hand and simple receptor persistence on the other) or whether more elaborate perceptual processing is involved. In light of the literature presently available, it seems safe to conclude that retinal painting sometimes indeed plays a role but that it cannot explain all the pertinent findings. Consequently, more elaborate perceptual processing seems to be involved. Our findings accord with this general conclusion. As already explained in the previous section, our findings cannot be attributed to retinal painting or simple neural persistence alone. On the other hand, though, manifestations of retinal painting can readily be observed in our stimuli at swifter rotation speeds. The choice of the relatively slow rotation speeds used in our study was motivated by the wish to avoid as much as possible the involvement of retinal painting.

On the retinal painting account of the anorthoscopic effect, one would expect a modal percept of the completed part of the background figure in front of the occluding disk (although it is actually located behind it) because an afterimage of it is projected onto the stimulus. On the hypothesis of more elaborate processing, on the other hand, one would be more prone to expect an amodal impression of the completed figure. If the visibility paradox, as we believe, also occurs in connection with the anorthoscopic effect, however, a part of the perceptual completion of the target stimulus may actually have a modal appearance, even when the latter hypothesis is true.

Relation to the "grand illusion of consciousness"

Referring to various phenomena such as the perception of the blind spot, transsaccadic memory, and change blindness, several authors have pointed out that much of the visual field is subjectively experienced to be apprehended much more clearly and directly than one would intuitively expect considering the sparse input actually available to or represented by the visual system (Blackmore, Brelstaff, Nelson, & Troscianko, 1995; Dennett, 1993; O'Regan, 1992). This counterintuitive but seemingly rather general feature of the phenomenology of vision is generally known as the "grand illusion of consciousness" (e.g., Noë, 2002). The phenomenon documented in the present study can be regarded as yet another example of this "grand illusion," and by virtue of being relatively simple and quantifiable it may prove useful for clarifying the debate on what visual awareness of a surface actually means.

Relation to general theories of perception

Most current theory and research on vision is based on the assumption that the visual system evolved to provide the organism with a representation of the outside world that is as veridical as possible given the many ambiguities of the sensory input. According to this general perspective, visual illusions arise because visual mechanisms aiming for veridicality have to rely on error-prone heuristics in order to resolve the many fundamental ambiguities of the sensory input. Thus, the study of visual illusions is regarded as an important tool for establishing what heuristics the visual system exploits toward the goal of achieving veridical perceptual representations of the outside world. While this perspective, in general principle, naturally accounts for visual illusions, it is less obvious how it can account for the existence of impossible figures such as, for instance, the Penrose triangle or the paintings of Escher and Reutersvärd (Cowan, 1977; Gregory, 1980; Hochberg, 2003; Huffman, 1971; Kulpa, 1983, 1987; Penrose & Penrose, 1958). Different from traditional visual illusions, which merely involve nonveridical percepts, these impossible figures involve percepts with an internal structure that is incompatible with any consistent real-world interpretation whatsoever. The visibility paradox documented in the present study is analogous to these impossible figures because it shares this property.

A further observation that also makes it difficult to account for the visibility paradox in terms of the standard perspective is the following: According to this perspective, illusions occur because the visual system cannot resolve the ambiguities of the visual input correctly in all cases. Thus, for instance, illusions of size occur because the size of distal objects is ambiguously specified by the size of their retinal projection. But there is no analogous ambiguity associated with the property of being occluded or not: If a region of a visual scene is unoccluded it projects onto the retina, and if it is occluded it does not. Thus, it is difficult to see why the visual system should produce an illusion in which "the target is perceived as though it were less occluded than it actually is" (Palmer & Schloss, 2009, p. 1083).

Recently, however, there has been an increased interest in alternative general perspectives on perception questioning the idea that perceptual systems evolved to maximize veridicality and its various implications (Hoffman, 2009; Hoffman, Singh, & Mark, 2013; Koenderink, 2010, 2011, 2013; Mark, Marion, & Hoffman, 2010; Singh & Hoffmann, 2012; von Uexküll, 1909). One key alternative idea is the notion that the visual system evolved to provide the organism with a user interface allowing for adaptive interaction with the environment rather than with a veridical representation of the physical properties of the outside world. From this perspective, the attributes of perceptual experience do not have to resemble physical aspects of the outside world any more than the desktop and icons of a computer resemble its internal physical states (Hoffman, 2009). Our perceptual world is not expected to have an internal structure mirroring the structure of the outside world. Hence, impossible figures such as the visibility paradox documented in the present study pose no challenge to this perspective. In fact, they may even be regarded as evidence in favor of it.

Our proposed resolution of the visibility paradox is concordant with such a perspective in several regards. First, the idea that the phenomenological variable "modal versus amodal" does not represent the seemingly corresponding physical variable "directly visible versus occluded" but rather the conclusiveness of the sensory evidence for the experienced percepts is more in line with the notion of percepts as icons than the notion of percepts as veridical perceptual representations of the outside world. Second, considering that the conclusiveness of the sensory evidence for a given perceptual interpretation can be understood as an index of perceptibility rather than mere optical visibility and that knowledge of the former is arguably more important to the organism, our proposal is also concordant with the idea that maximizing veridicality is not always the best way to ensure adaptive interaction with the environment.

As a final note, it may be worth pointing out that the idea that phenomenal visibility represents the conclusiveness of the underlying sensory evidence is similar to previous suggestions linking qualia to the reliability of perceptual inferences (Gregory, 1997; Hibbard, 2008; Ramachandran & Hirstein, 1997).

Conclusions

In this article, we present a dynamical display in which the background region is perceived as less occluded than it actually is. This is similar to what Palmer et al. (2007) observed with the static occlusion illusion. Our experimental findings lend further credence to Palmer and colleagues' partial-modal-occlusion hypothesis, which links the illusory extension of the background region to occlusion cues. These findings also confirm the existence of a seemingly paradoxical percept in which more than 360° of a circular stimulus display is experienced as directly visible (modal). In order to resolve this paradox, we propose that the phenomenological variable "modal versus amodal" represents the conclusiveness of the sensory evidence for the experienced percepts rather than optical visibility. In our view, this hypothesis is a promising candidate solution to the "perplexing" issue of "how to understand the nature of the partial-modal-completion hypothesis" (Palmer et al., 2007, p. 669). Functionally, the perceptual representation of conclusiveness of sensory evidence might be more useful than estimates about optical visibility.

Keywords: mental representation, phenomenal visibility, occlusion illusion, modal completion, amodal completion

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References

Anderson, B. L., Singh, M., & Fleming, R. (2002). The interpolation of object and surface structure. *Cognitive Psychology, 44*(2), 148–190, doi:http://dx.doi.org/10.1006/cogp.2001.0765.

Anderson, B. L., & Sinha, P. (1997). Reciprocal interactions between occlusion and motion computations. *Proceedings of the National Academy of Sciences, USA, 94*(7), 3477–3480.

Anstis, S. M., & Atkinson, J. (1967). Distortions in moving figures viewed through a stationary slit. *American Journal of Psychology, 80,* 572–585.

Aydın, M., Herzog, M. H., & Öğmen, H. (2009). Shape distortions and Gestalt grouping in anorthoscopic perception. *Journal of Vision, 9*(3):8, 1–8, http://www.journalofvision.org/content/9/3/8, doi:10.1167/9.3.8. [PubMed] [Article]

Bartlett, F. C. (1932). *Remembering: An experimental and social study*. Cambridge, United Kingdom: Cambridge University Press.

Blackmore, S. J., Brelstaff, G., Nelson, K., & Troscianko, T. (1995). Is the richness of our visual world an illusion? Transsaccadic memory for complex scenes. *Perception, 24,* 1075–1081.

Burr, D. (1980). Motion smear. *Nature, 284*(5752), 164–165.

Carlson, T. A., Alvarez, G., Wu, D., & Verstraten, F. A. (2010). Rapid assimilation of external objects into the body schema. *Psychological Science, 21*(7), 1000–1005.

Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics, 27*(3), 183–228, doi:http://dx.doi.org/10.3758/BF03204258.

Cowan, T. M. (1977). Organizing the properties of impossible figures. *Perception, 6*(1), 41–56.

Davies, P. (1973). Effects of movements upon the appearance and duration of a prolonged visual afterimage: 1. Changes arising from the movement of a portion of the body incorporated in the afterimaged scene. *Perception, 2,* 147–153.

Dennett, D. C. (1993). *Consciousness explained.* Boston, MA: Little Brown.

Dieter, K. C., Hu, B., Knill, D. C., Blake, R., & Tadin, D. (2014). Kinesthesis can make an invisible hand visible. *Psychological Science, 25*(1), 66–75.

Ekroll, V., & Borzikowsky, C. (2010). The role of occlusion cues in apparent motion. *Perception, 39*(12), 1606–1623, doi:http://dx.doi.org/10.1068/p6646.

Ekroll, V., Faul, F., & Golz, J. (2008). Classification of apparent motion percepts based on temporal factors. *Journal of Vision, 8*(4):31, 1–22, http://www.journalofvision.org/content/8/4/31, doi:10.1167/8.4.31. [PubMed] [Article]

Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences, 8*(4), 162–169.

Fendrich, R., Rieger, J. W., & Heinze, H.-J. (2005). The effect of retinal stabilization on anorthoscopic percepts under free-viewing conditions. *Vision Research, 45*(5), 567–582.

Foley, J., van Dam, A., Feiner, S., & Hughes, J. (1996). *Computer graphics: Principles and practice in C.* Boston, MA: Addison-Wesley.

Gibson, J. J., Kaplan, G., Reynolds, H., & Wheeler, K. (1969). The change from visible to invisible: A study of optical transitions. *Attention, Perception, & Psychophysics, 5*(2), 113–116, doi:http://dx.doi.org/10.3758/BF03210533.

Gregory, R. L. (1980). Perceptions as hypotheses. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 290*(1038), 181–197.

Gregory, R. L. (1997). Knowledge in perception and illusion. *Philosophical Transactions of the Royal Society of London B: Biological Sciences, 352*(1358), 1121–1127.

Gregory, R. L., Wallace, J. G., & Campbell, F. (1959). Changes in the size and shape of visual after-images observed in complete darkness during changes of position in space. *Quarterly Journal of Experimental Psychology, 11*(1), 54–55.

Haber, R. N., & Nathanson, L. S. (1968). Post-retinal storage? Some further observations on Parks' camel as seen through the eye of a needle. *Perception & Psychophysics, 3*(5), 349–355.

Hibbard, P. B. (2008). Can appearance be so deceptive? Representationalism and binocular vision. *Spatial Vision, 21*(6), 549–559.

Hochberg, J. (2003). Acts of perceptual inquiry: Problems for any stimulus-based simplicity theory. *Acta Psychologica, 114*(3), 215–228.

Hoffman, D. D. (2009). *The interface theory of perception: Natural selection drives true perception to swift extinction*. In S. Dickinson, M. Tarr, A. Leonardis, & B. Schiele (Eds.), *Object categorization: Computer and human vision perspectives* (pp. 148–165). Cambridge, United Kingdom: Cambridge University Press.

Hoffman, D. D., Singh, M., & Mark, J. (2013). Does evolution favor true perceptions? In B. E. Rogowitz, T. N. Pappas & H. De Ridder (Eds.), *SPIE Proceedings*, vol. 8651 (pp. 1–12, CID: 865104). Bellingham, WA: SPIE.

Hogendoorn, H., Kammers, M. P., Carlson, T. A., & Verstraten, F. A. (2009). Being in the dark about your hand: Resolution of visuo-proprioceptive conflict by disowning visible limbs. *Neuropsychologia, 47*(13), 2698–2703.

Huffman, D. A. (1971). Impossible objects as nonsense sentences. *Machine Intelligence, 6*(1), 295–323.

Intraub, H. (2010). Rethinking scene perception: A multisource model. In B. Ross (Ed.), *Psychology of learning and motivation*, vol. 52 (pp. 231–264). Burlington, VT: Academic Press.

Intraub, H., & Bodamer, J. L. (1993). Boundary extension: Fundamental aspect of pictorial representation or encoding artifact? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*(6), 1387–1397.

Intraub, H., & Dickinson, C. A. (2008). False memory 1/20th of a second later: What the early onset of boundary extension reveals about perception. *Psychological Science, 19*(10), 1007–1014.

Intraub, H., & Richardson, M. (1989). Wide-angle memories of close-up scenes. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(2), 179–187.

Jacobs, R. A. (2002). What determines visual cue reliability? *Trends in Cognitive Sciences, 6*(8), 345–350.

Kanizsa, G. (1972). Schrumpfung von visuellen Feldern bei amodaler Ergänzung. *Studia Psychologica, 14,* 208–210.

Kanizsa, G. (1979). *Organization in vision: Essays on Gestalt perception*. New York: Praeger.

Kanizsa, G. (1985). Seeing and thinking. *Acta Psychologica, 59*(1), 23–33.

Kanizsa, G. (1987). Quasi-perceptual margins in homogeneously stimulated fields. In S. Petry & G. E. Meyer (Eds.), *The perception of illusory contours* (pp. 40–49). New York: Springer.

Kaufman, E. L., Lord, M., Reese, T., & Volkmann, J. (1949). The discrimination of visual number. *The American Journal of Psychology, 62*(4), 498–525.

Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23,* 141–221.

Koenderink, J. J. (2010). Vision and information. In L. G. Albertazzi, J. van Tonder, & D. Vishwanath (Eds.), *Perception beyond inference: The information content of visual processes* (pp. 27–58). Cambridge, MA: MIT Press.

Koenderink, J. J. (2011). Vision as a user interface. In B. E. Rogowitz & T. N. Pappas (Eds.), *IS&T/SPIE Electronic Imaging*, vol. 7865 (pp. 1–12, CID: 786504). Bellingham, WA: SPIE-IS&T.

Koenderink, J. J. (2013). World, environment, Umwelt, and innerworld: A biological perspective on visual awareness. In B. E. Rogowitz, T. N. Pappas, & H. de Ridder (Eds.), *IS&T/SPIE Electronic Imaging*, vol. 8651 (pp. 1–9, CID: 865103). Bellingham, WA: SPIE-IS&T.

Koffka, K. (1935). *Principles of Gestalt psychology*. New York: Harcourt, Brace, & World.

Kulpa, Z. (1983). Are impossible figures possible? *Signal Processing, 5*(3), 201–220.

Kulpa, Z. (1987). Putting order in the impossible. *Perception, 16*(2), 201–214.

Landy, M. S., Banks, M. S., & Knill, D. C. (2011). Ideal-observer models of cue integration. In J. Trommershuser, M. Landy, & K. Koerding (Eds.), *Sensory cue integration* (pp. 5–29). New York: Oxford University Press.

Mark, J., Marion, B., & Hoffman, D. D. (2010). Natural selection and veridical perception. *Journal of Theoretical Biology, 266,* 504–515.

Metelli, F. (1970). An algebraic development of the theory of perceptual transparency. *Ergonomics, 13,* 59–66.

Metzger, W. (1975). *Gesetze des Sehens*. Frankfurt, Germany: Kramer.

Metzger, W., Spillmann, L. T., Lehar, S. T., Stromeyer, M. T., & Wertheimer, M. T. (2006). *Laws of seeing*. Cambridge, MA: MIT Press.

Michotte, A., Thinès, G., & Crabbé, G. (1991). Amodal completion of perceptual structures. In G. Thinès, A. Costall, & G. Butterworth (Eds.), *Michotte's* *experimental phenomenology of perception* (pp. 140–167). Hillsdale, NJ: Lawrence Erlbaum.

Morgan, M. J., Findlay, J. M., & Watt, R. J. (1982). Aperture viewing: A review and a synthesis. *Quarterly Journal of Experimental Psychology, 34A,* 211–233.

Nakayama, K., & Shimojo, S. (1990). Da Vinci stereopsis: Depth and subjective occluding contours from unpaired image points. *Vision Research, 30*(11), 1811–1825.

Noë, A. (2002). Is the visual world a grand illusion? *Journal of Consciousness Studies, 9*(5–6), 1–12.

O'Regan, J. K. (1992). Solving the "real" mysteries of visual perception: The world as an outside memory. *Canadian Journal of Psychology/Revue Canadienne de Psychologie, 46*(3), 461–488.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Palmer, S. E., Brooks, J. L., & Lai, K. S. (2007). The occlusion illusion: Partial modal completion or apparent distance? *Perception, 36*(5), 650–669.

Palmer, S. E., Davis, J., Nelson, R., & Rock, I. (2008). Figure-ground effects on shape memory for objects versus holes. *Perception, 37*(10), 1569–1586.

Palmer, S. E., & Schloss, K. B. (2009). Stereoscopic depth and the occlusion illusion. *Attention, Perception, & Psychophysics, 71*(5), 1083–1094.

Palmer, S. E., & Schloss, K. B. (in press). The occlusion, configural shape, and shrinkage illusions: Contextual influences on perceived size and shape. In A. G. Shapiro & D. Todorovic (Eds.), *Oxford compendium of visual illusions*. Oxford, United Kingdom: Oxford University Press.

Penrose, L. S., & Penrose, R. (1958). Impossible objects: A special type of visual illusion. *British Journal of Psychology, 49,* 31–33.

Petersik, J. T., & McDill, M. (1981). A new bistable motion illusion based upon "kinetic optical occlusion." *Perception, 10*(5), 563, doi:http://dx.doi.org/10.1068/p100563.

Ramachandran, V. S., & Hirstein, W. (1997). Three laws of qualia: What neurology tells us about the biological functions of consciousness. *Journal of Consciousness Studies, 4*(5–6), 5–6.

Ritchie, J. B., & Carlson, T. (2010). Mirror, mirror, on the wall, is that even my hand at all? Changes in the afterimage of one's reflection in a mirror in response to bodily movement. *Neuropsychologia, 48*(5), 1495–1500.

Rubin, E. (1915). *Synsoplevede figurer: Studier i psykologisk analyse* [Translation: *Visually experienced figures: Studies in psychological analysis*]. København og Kristiania: Gyldendalske Boghandel, Nordisk Forlag.

Rubin, N. (2001). Figure and ground in the brain. *Nature Neuroscience, 4*(9), 857–858.

Schloss, K. B., Fortenbaugh, F. C., & Palmer, S. E. (2014). The configural shape illusion. *Journal of Vision, 14*(8):23, 1–18, http://www.journalofvision.org/content/14/8/23, doi:10.1167/14.8.23. [PubMed] [Article]

Shimojo, S., & Nakayama, K. (1990a). Amodal representation of occluded surfaces: Role of invisible stimuli in apparent motion correspondence. *Perception, 19*(3), 285–299, doi:http://dx.doi.org/10.1068/p190285.

Shimojo, S., & Nakayama, K. (1990b). Real world occlusion constraints and binocular rivalry. *Vision Research, 30*(1), 69–80.

Sigman, E., & Rock, I. (1974). Stroboscopic movement based on perceptual intelligence. *Perception, 3*(1), 9–28, doi:http://dx.doi.org/10.1068/p020357.

Singh, M., & Hoffmann, D. D. (2013). Natural selection and shape perception: Shape as an effective code for fitness. In S. J. Dickinson & Z. Pizlo (Eds.), *Shape perception in human and computer vision — An interdisciplinary perspective* (pp. 171–185), book series *Advances in computer vision and pattern recognition*. London: Springer.

Steinman, R. M., Pizlo, Z., & Pizlo, F. J. (2000). Phi is not beta, and why Wertheimer's discovery launched the Gestalt revolution. *Vision Research, 40*(17), 2257–2264, doi:http://dx.doi.org/10.1016/S0042-6989(00)00086-9.

Vezzani, S. (1999). Shrinkage and expansion by amodal completion: A critical review. *Perception, 28,* 935–947.

von Uexküll, J. (1909). *Umwelt und Innenwelt der Tiere*. Berlin, Germany: Springer.

Wertheimer, M. (1912). Experimentelle Studien über das Sehen von Bewegung. *Zeitschrift Für Psychologie, 61,* 161–265.

Wollschläger, D. (2006). *Dynamic surface completion: The joint formation of color, texture, and shape* (Unpublished dissertation). Christian-Albrechts-Universität zu Kiel, Kiel, Germany.

Wollschläger, D., & Faul, F. (2006). Dynamic texture spreading. Probing the mechanisms of surface interpolation. *Spatial Vision, 19*(1–2), 193–218.

Yantis, S. (1995). Perceived continuity of occluded visual objects. *Psychological Science, 6*(3), 182–186, doi:http://dx.doi.org/10.1111/j.1467-9280.1995.tb00329.x.