Amodal completion is modulated by lightness similarity

Juno Kim · Kelly Jeng · Barton L. Anderson

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Abstract The strength of amodal completion is known to be modulated by contour relationships and global shape. Some researchers have shown that amodal completion also depends on surface similarity, but they have not distinguished the relative importance of similarity in surface representations either pre or post lightness constancy. In the experiments reported here, we aimed to determine whether amodal completion depends on processes that occur either before or after the establishment of lightness constancy. We used computer rendering techniques to vary the consistency of a cast shadow with a decrement in luminance on one side of a partially occluded surface. We found that perceived completion depended on the consistency of the decrement in surface luminance with the orientation of a cast shadow (Exp. 1). In Experiment 2, we generated occluded surface fragments that could be either luminance-matched or lightness-matched to surface fragments on the opposite side of the occluder, and we found that the strength of amodal completion depended primarily on similarity in the perceived surface reflectance. In Experiments 3 and 4, we performed apparent-motion tasks to obtain converging evidence for grouping on the basis of perceived similarity in lightness. We found that matching surfaces in lightness significantly improved the apparent motion of surfaces behind an occluder, as compared with surfaces that were matched in contrast alone. These results suggest that amodal completion depends on the perceived similarity in lightness of partially occluded surface fragments.

Keywords 2-D shape and form · Apparent motion · Scene perception · Amodal completion

Our visual system provides rich information about the surface properties of objects across a wide variety of environmental conditions. Many objects tend to be partially obstructed from plain view by other objects in the foreground, but still appear as unified objects rather than independent image fragments. Amodal completion refers to the process by which the visual system integrates partially occluded image fragments into a percept of a unified surface. Much of the previous research on amodal completion has focused on the role of edge contours in determining when completion does and does not occur. The consideration of surface or material properties has been largely limited to manipulating the similarity in texture or color of surfaces in the image (Anderson, 2007a, b, c; Anderson, Singh, & Fleming, 2002; Kellman, Garrigan, & Shipley, 2005; Kellman, Garrigan, Shipley, & Keane, 2007a, b). Here, we explore the extent to which amodal completion depends on processes that occur before or after processes involved in establishing lightness constancy.

The material properties of surfaces can vary along a variety of dimensions, including color and lightness. Previous research has shown that the perceived strength of surface completion was sensitive to the similarity in luminance of solid and textured surfaces (Yin, Kellman, & Shipley, 1997, 2000). These studies revealed that the perceived path of tangent extensions depended not only on good continuation of their edges, but also on similarity in the color and textural detail of surface fragments. Although the findings support the view that amodal completion depends on the similarity in color or lightness of the image fragments, surface fragments that were matched in solid color were also matched in physical luminance and/or chromaticity in the image. It is therefore unclear whether amodal completion was mediated by low-level similarity in surface luminance or color, or by postconstancy representations of surface color and lightness.

Other researchers have obtained evidence suggesting that postconstancy processes play a strong role in the perceptual
grouping of disjoint objects under conditions of transparency. Rock, Nijhawan, Palmer, and Tudor (1992) investigated whether similarity in surface luminance or perceived lightness had greater influence on grouping in conditions of transparency. They tested whether a central column in 2-D squares would perceptually group with adjacent squares that were either reflectance- or luminance-matched to a central column of squares that were covered by a semiopaque sheet or shadow. Rock et al. found that the central squares grouped with the reflectance-matched rather than the luminance-matched squares. This result demonstrated that perceptual grouping depends on a postconstancy visual process that considers the similarity in perceived lightness of surfaces, rather than the similarity in image luminance. However, other researchers have provided evidence that low-level similarity in the contrast polarity of surface fragments contributes to grouping and amodal completion. Su, He, and Ooi (2010) manipulated the contrast polarity of image fragments separated by a number of different foreground occluding surfaces. The displays were arranged such that the central segments of each display generated no motion signal, but the flanking fragments moved in a manner consistent with a single object translating under the occluding segments. Su et al. found that global motion was only perceived when the inner and outer image fragments possessed the same luminance polarity relative to their background. The perception of global motion also occurred when the image fragments had different absolute luminance levels. This finding was interpreted as demonstrating the importance of low-level information about contrast polarity in modulating the strength of amodal completion. However, it still remains unclear whether simple image-based computations can generalize to more complex scenes with variations in shadow and illumination. In the experiments reported here, we aimed to determine whether postconstancy perceptual information—specifically, perceived lightness—contributes to amodal completion.

Experiment 1

Experiment 1 was designed to test whether amodal completion depends more on similarity in perceived reflectance or similarity in image luminance. The luminance of surfaces depends not only on their reflectance, but also on the structure and intensity of the surrounding illumination field. Shadows introduce an additional source of luminance variation in images of a surface. Since variations in the luminance across a surface that are caused by the distribution of lighting and shadows do not alter the surface’s physical reflectance, they should not alter perceived reflectance, to the extent that the visual system effectively discounts the contribution of the illuminant. We used 3-D rendering techniques to modulate the extent to which a decrement in surface luminance was consistent with a shadow cast across the scene. If similarity in perceived surface lightness is used to group surface fragments amodally into unified structures, then luminance variations attributed to a cast shadow should still promote strong amodal completion, as compared with surfaces containing luminance variations that are more consistent with pigmentation.

Method

Participants A group of 36 first-year psychology students at the University of Sydney voluntarily participated in this study for partial course credit. Written informed consent was attained from each participant prior to commencement of the experiment. All participants reported normal or corrected-to-normal vision. The participants were naïve as to the specific purpose of the experiment, and the procedures were approved by the Human Research Ethics Committee (HREC) at the University of Sydney.

Stimuli Experiment 1 consisted of a $2 \times 3 \times 2$ (Shadow × Misalignment × Edge Type) within-subjects experimental design. Shadow indicates the condition in which a luminance variation on an image fragment could be attributed to shadow (two levels: consistent or inconsistent) and was the main factor of interest in this experiment. We included three levels of misalignment between image fragments (aligned, intermediate misalignment, and greater misalignment). The last independent variable was the edge type of the shadow (two levels: sharp or penumbra edge). This variable was included in order to consider whether amodal completion depends on the shadow’s realism.

As is shown in Fig. 1, a pole is positioned in the foreground of a textured occluder and a partially occluded object with serrated edges. We added serrated edges to our surfaces to enhance the appearance of their occlusion by the foreground occluder. The two surfaces with serrated edges were placed between the occluding block and the background surface plane. The serrations limited observers from using simple edge alignment as the primary cue for their completion judgments. The quasiparallel edges retained much of the regularity across the edge in order to support subjective completion between the occluded surface fragments. The dimensions of the visible surface fragments formed rectangular surfaces in the image that were slightly less narrow on the left (approximately $24 \times 22$ cm) than on the right (approximately $36 \times 22$ cm). The horizontal dimension of the left fragment was reduced due to a pole that was situated in front of the end of the occluded surface. A collimated light source illuminated the scene, so that the effect of the light source on the luminance of both surface fragments was equated before the influence of shadow. The luminance of the fragments was uniform across the image of each surface (approximately 38.0 cd/m$^2$), except
for the image region in which the shadow was cast over the surface fragments on the right (approximately 0.5 cd/m²).

In the inconsistent condition, the pole’s cast shadow fell not only on the surface of the partially occluded object, but also on the occluder, in order to control for the width of the luminance difference across shadow conditions. The pole’s shadow was rendered to extend slightly left of the pole, as can be seen in Fig. 1, such that the luminance change on the partially occluded object could not be due to a shadow cast by the occluder.

The stimuli were presented on a Compaq P1220 CRT monitor set to a resolution of 1,024 × 768 pixels. The monitor was calibrated to a luminance range spanning 0.48 to 103.42 cd/m². The stimuli were presented using the upper luminance range of the monitor, which we verified to be approximately linear. The viewing area was enclosed by black curtains, and the monitor was the only light source within that space. Stimuli were displayed against a gray background of mean luminance 22.56 cd/m². Participants viewed the display from a distance of approximately 55 cm.

Procedure Data were collected using a two-alternative forced choice method of paired comparisons. Presentations were counterbalanced across the two sides of the display, requiring a total of 132 trials per session (12 × 12–12). The distance between the inner edges of the images on the display was 2.2 cm.

Observers were instructed to study the visible surface fragments on either side of the occluding block and to select the image in which the fragments appeared to more strongly complete behind the occluder. To verify that the data were acyclic, a test for weak stochastic transitivity (WST) was performed on the paired-comparisons data, on the basis of the total number of times a stimulus was selected by all observers (Tversky, 1969; see also Iverson & Falmagne, 1985). Paired-comparisons data were transformed for each observer into probability estimates of the likelihood that the occluded surface could not be due to a shadow cast by the occluder. The probability estimate was calculated as \( \frac{N}{T} \), where \( N \) is the number of times that a given display was selected to be more strongly completed than other displays, and \( T \) is the total number of trials within which the display was compared. This probability estimate was taken as the measure of amodal completion strength. An arcsine transformation of the probabilities was performed, so as to normalize the data before a repeated measures analysis of variance (ANOVA) tested for any main or interaction effects. A follow-up test for linear trends was also performed on the three levels of alignment.

Results and discussion

As is shown in Fig. 2, increasing the level of misalignment between surface fragments monotonically decreased the strength of amodal completion. The test for WST revealed no violations of transitivity (error ratio of 0.0, based on 220 tests among the 12 stimulus conditions). The repeated measures ANOVA showed a significant main effect of misalignment on the strength of amodal completion \( F(2, 70) = 263.4, p < .0001 \). A follow-up test for linear trends in misalignment and completion strength was also found to be significant across the two levels of shadow consistency \( F(1, 35) = 352.02, p < .001 \).

A significant main effect emerged of shadow orientation (consistent or inconsistent) on the perceived strength of completion \( F(1, 35) = 6.981, p < .05 \). At the same level of misalignment and edge type, the fragments in the consistent condition were judged as being more strongly completed than the fragments in the inconsistent condition. This can be seen in Fig. 2a, in which consistent shadow results in significantly stronger completion overall than the inconsistent shadow. We also found a main effect of edge type \( F(1, 35) = 4.44, p < .05 \), whereby observers judged amodal completion in images containing shadows with a penumbra edge as being significantly more completed than images containing shadows with a sharp edge (Fig. 2b).

A significant two-way interaction was revealed between shadow and misalignment \( F(2, 70) = 3.713, p < .05 \), suggesting that the effect of misalignment on completion was greater for the shadow-inconsistent than for the shadow-consistent condition. However, the remaining two- or three-way interactions were not statistically significant: We observed no significant interaction between shadow and edge type \( F(1, 35) = 1.37, p = .251 \), no significant interaction between misalignment and edge type \( F(2, 70) = 1.843, p = .166 \), and no significant interaction between shadow, misalignment, and edge type \( F(2, 70) = 2.67, p = .077 \).

These results suggest that the perceived strength of amodal completion is modulated by the consistency of a decline in surface luminance with the orientation of a cast shadow. This suggests that, whereas local cues to similarity in perceived lightness are used to infer amodal surface completion, they appear to be supplemented by global scene information. In the consistent condition, the decrement in luminance may have been attributed to shadow, and the surface region in shadow may have been perceived as being more similar in lightness to the surface regions in direct illumination. In the inconsistent condition, the decrement in luminance may have been perceived as a change in surface lightness. Following the experiment, two of the observers were asked which of two images (consistent vs. inconsistent shadow) appeared to contain a change in surface reflectance. Both observers indicated that the shadow-inconsistent surface appeared to contain a small region of dark surface albedo immediately adjacent to the occluder. These results are consistent with the view that amodal completion depends on postconstancy processes that decompose the image of the scene in order to discount the effects of shadow and lighting on a surface’s luminance.
Experiment 1 showed that amodal completion was modulated by changing the orientation of a cast shadow relative to a decrement in surface luminance that could have been attributed to either shadow or a change in surface albedo. This finding suggests that amodal completion is modulated by computations that extract information about surface lightness. However, the rendering used in Experiment 1 was performed without any ambient illumination, which caused surface regions in shadow to appear completely black in the image. In principle, the visual system cannot accurately determine the lightness of the surface region in shadow without some ambient illumination, so it is unclear whether lightness computations per se were responsible for the observed pattern of results.

To assess the role of lightness more directly, we used raytracing to simulate the ambient illumination provided by the light reflected by other surfaces in the scene. These displays produce more compelling experiences of lightness constancy to determine whether amodal completion depends on postconstancy processes. Previous studies have suggested that a similarity in surface color can modulate the effects of alignment on the strength of amodal completion (Yin et al., 1997). However, these studies used surfaces that were matched in image luminance, rather than color or reflectance. In Experiment 2, the scene was rearranged so that the luminance of surface fragments would be reduced by a cast shadow, while preserving their contrast ratios relative to the background. We reasoned that if similarity in surface lightness contributes to amodal completion, then a decrement in image luminance that was consistent with a cast shadow should nonetheless support amodal completion. In contradistinction, if amodal completion occurs prior to lightness constancy computations, then stronger amodal completion should be experienced when image luminance is matched. We further expected greater amodal completion in conditions in which the shadow covered only a portion of one surface fragment (as in Exp. 1), as compared with fully covering the fragment on one side of the occluder. This is because more information (such as X-junctions) would be available for the visual system to discount the effect of shadow on the surface’s luminance profile when it was only half covered in shadow.

Method

Participants A total of 16 first-year psychology students at the University of Sydney voluntarily participated in this study for partial course credit. Written informed consent was attained from each participant prior to commencement of the experiment. All participants reported normal or corrected-to-normal vision and were naive as to the purpose of the experiment.

Stimuli We used computer rendering to vary the image luminance of surfaces. Stimulus images of surfaces were rendered with simulated ambient reflectance using Blender 2.49b. Blender is an open-source 3-D graphical package (http://blender.org). As can be seen in Fig. 3, a blue block serving as an occluder was positioned against a textured or untextured
background plane. A blue block was used to ensure that any perceptual completion of surfaces would occur amodally behind the central structure, and not modally in front of the surface, which can occur when surfaces are matched in gray level in some achromatic lighting scenarios. A collimated light source was positioned to the right of the scene, which initially pointed straight down. The light source was rotated around the vertical axis of the image plane toward the occluder by an angle of 17.5°. The light source was then rotated around the zenith by 45.0° in order to illuminate the occluder from the upper right of the image. Shadows were generated by the occluded figures and the background in the simulated scene, which were configured to receive shadows by the ray-tracing software.

An orthographic projection was used to render 12 stimulus images according to a 3 × 2 × 2 within-subjects design. The vertical offset in the coalignment of the right occluded surface was adjusted relative to the left surface, ranging over three levels (0°, 0.25°, 0.50°). The height of the blue block in depth was also adjusted, so as to cause its shadow to cover either half of or the entire occluded surface on the left (two levels). The orthographic projection ensured that changes in the height of the block did not change the size of the occluder in the image. The right surface fragment had either an identical or a darker reflectance than the corresponding surface fragment on the left of the occluder (two levels). Separate sets of 12 stimulus images were generated for the three texture conditions (no texture, textured background, or textured fragments).

The luminance configuration of the display was identical to that in Experiment 1. However, the contrast ratio of the light and the dark texture components of the visible surface fragments was held at a constant of 1.3 between the surface regions in plain view or in shadow. At the viewing distance of 55 cm, the partially occluded visible surface fragments had an optical width of 6.65° and an optical height of 1.9°.

Procedure Data were collected using the same paired-comparisons method and treated in the same way as we described for Experiment 1. In Experiment 2, however, a total of 132 (12 × 12 – 12) counterbalanced image pairs were presented in a complete block of trials. Three full blocks of stimuli were presented, each with one of the three texture conditions. The order of the paired presentations was fully randomized, and the side of the screen on which each stimulus appeared was counterbalanced across trials. Following a test for WST, probability estimates for each stimulus were computed and arcsine transformed for normality. A repeated measures ANOVA was used to test for any main and interaction effects.

Results and discussion

No violations of WST were found for the 220 tests performed on the 12 stimulus groups in all three texture conditions. Figure 4 (top) plots the probabilities that the occluded figure appeared completed as a function of the vertical misalignment between surface fragments for the no-texture condition. A repeated measures ANOVA performed on the arcsine-transformed probability estimates revealed a significant main effect of misalignment [F(2, 30)= 196.4, p < .0001]. As is shown in Fig. 4, increasing the misalignment between surface fragments decreased the strength of perceived completion across both the lightness-matched and luminance-matched conditions and the half-shadow and full-shadow coverage conditions. Perceived completion was stronger when the fragments were matched on the basis of lightness (dark points and solid lines) rather than luminance (dashed lines). The ANOVA revealed significant main effects of lightness across all three levels of misalignment [F(1, 15) = 10.01, p < .01]. The main effect of shadow coverage was not significant [F(1, 15) = 1.612, p = .223]. However, a significant interaction was apparent between the effect of shadow coverage on perceived completion and whether the fragments were matched in lightness or luminance [F(1, 15) = 11.93, p < .005]; full shadows generated stronger completion than did half shadow for surfaces that were luminance matched. This is shown in Fig. 4 by the larger difference in amodal completion between the dashed lines of the full-shadow conditions (and gray/red points), as compared with the solid lines of the half-shadow conditions (and dark points).

One likely explanation for the interaction effect between shadow coverage and surface reflectance on completion is that the lack of contrast variation in luminance-matched fragments in full shadow (i.e., the lack of X-junctions) may have generated some ambiguity as to whether or not the surface fragments were reflectance matched. Surfaces that differed in physical reflectance appeared similar in lightness under full as compared with half shadow (Fig. 5). This ambiguity may occur because it is harder to discount the effects of shadow on surface luminance when the shadow covers the entire surface. The half-shadow condition provides additional information about the lightness of the surface regions receiving direct illumination. This information may be used to determine the lightness of the adjacent shadowed region, which is missing in the full-shadow condition.

Similar results were obtained with surfaces that were textured or presented on textured surrounds. Figure 4 (center) shows perceived completion estimates for the stimuli with textured backgrounds. A repeated measures ANOVA again indicated main effects of lightness [F(1, 15) = 13.2, p < .005] and misalignment [F(2, 30) = 94.88, p < .0001] on perceived completion. The interaction between lightness and shadow remained significant [F(1, 15) = 8.703, p < .001]. However, no other interaction terms were significant. Note that the graph is overall very similar to the results for images without texture, suggesting that increased textural detail on the background does not substantially affect judgments of amodal completion.
Figure 4 (bottom) displays the results of the repeated measures ANOVA for the stimuli with textured image fragments. Main effects of lightness \( F(1, 15) = 24.5, p < .0005 \) and misalignment \( F(2, 30) = 109.9, p < .0001 \) on perceived completion were again observed. The interaction between lightness and shadow was significant \( F(1, 15) = 13.54, p < .005 \), as was the interaction between lightness and misalignment \( F(2, 30) = 6.802, p < .005 \). The results are again very similar to those for the images without texture and with the textured background.

We found that the effects of the offset between surface fragments on amodal completion were directly modulated by similarity in the reflectances of the surface fragments: When the local luminance variation was consistent with a shadow cast from the occluding block (upper row of Fig. 3), the surfaces appeared more completed than when they had the same luminance but different reflectances (lower row of Fig. 3). The relative decline in perceived completion when the surfaces were matched in luminance (and not physical reflectance) may have occurred because the local contrast variations in surface luminance were consistent with a change in the surface’s physical reflectance. However, if simple computations of image contrast were used to estimate surface lightness, amodal completion should have been similar in the full-shadow and half-shadow conditions that were matched in luminance. The increase in amodal completion observed in luminance-matched surfaces in full shadow may be explained by postconstancy processes that may only incompletely recover information about surface lightness.

**Experiment 3**

In Experiment 2, we found that surfaces matched in physical reflectance appeared to be more strongly completed than surfaces of different reflectances that were physically matched in luminance. This finding supports the view that postconstancy information about the similarity in the perceived reflectance of surface patches modulates the strength of amodal completion. In Experiment 3, we sought to use a new method to provide converging evidence that perceived lightness influences amodal completion, without explicitly requiring observers to judge amodal completion directly. Shimojo and Nakayama (1990) had previously shown that apparent motion can be used to assess “amodal leakage,” or the continuation of partially occluded surfaces behind a foreground occluder. We used a similar apparent-motion task to present surfaces within the same image that were matched in either luminance or lightness. This had the added advantage of ensuring that the contrast of lightness-matched and luminance-matched surfaces could be compared within the same illumination context. As a control measure, we also matched the image luminance of surfaces with different reflectances by illuminating the darker surface fragment with a...
directional spotlight. This was performed to determine whether amodal completion depends on postconstancy processes that attempt to generically discount the effects of variations in the prevailing illumination on surface luminance.

Method

Participants A group of 16 first-year psychology students participated in the present experiment; all of them had normal or corrected-to-normal vision, as indicated on their consent to participation.

Stimuli The surface fragments were the same as the textured surfaces used in Experiment 2. Apparent motion was automated by the custom stimulus presentation software, which repetitively toggled between two frames every second: one frame showing the occluder and left fragment only, and a frame showing the occluder and two fragments on the right that differed in their mean levels of surface reflectance. Example stills of the frames can be seen in Fig. 6a.

Fourteen stimulus images were generated according to a 7 × 2 within-subjects design for each of the shadow and spotlight conditions, totaling 28 images. The mean reflectance for the fragments on the right of the occluder ranged from 0.2 to 0.8, with increments of 0.1 (seven levels; see Fig. 6b); each fragment lighter than the mean reflectance of 0.5 was paired with a fragment that was darker than 0.5 by the same magnitude. The seven upper–lower pairings in simulated reflectance were (0.2, 0.8), (0.3, 0.7), (0.4, 0.6), (0.5, 0.5), (0.6, 0.4), (0.7, 0.3), and (0.8, 0.2). The level of mean reflectance of the target (left) fragment was fixed at 0.8.

As in Experiment 2, the position of the occluding block in depth was adjusted so as to cause its shadow to either half cover or fully cover the left surface (two levels). To avoid hysteresis or adaptation effects, the orientation of the entire image was varied over a ± 15° range, but the orientation of the surface relative to the occluder was held constant at 90°. In addition to the images in the shadow condition, a set of images
in another condition were rendered in which a spotlight was positioned and oriented in order to increase the luminance of the darkest surface in one region. Thus, if the observers matched the surface fragments on the basis of similarity in perceived reflectance rather than luminance, they should select the surface fragment with a lower contrast relative to the background (Fig. 7).

Procedure The data were collected using a two-alternative forced choice paradigm. Observers were instructed to indicate, using the “up” and “down” arrow keys on a standard 101-key keyboard, whether the top or the bottom surface to the right of the occluder in the latter frame appeared to complete more strongly with the surface target displayed on the left of the occluder in the earlier frame. A total of 70 selections were required in order to complete five repeat blocks of trials (2 × 7 × 5). The order of reflectance pairings was fully randomized and counterbalanced across trials. Additionally, the order of conditions for the shadow and spotlight manipulations was counterbalanced across observers, with a short rest being provided between these conditions.

Paired-comparisons data were transformed for each observer into estimates of the probability that the surface at the top right of the screen would be selected as grouping more strongly with the target fragment on the left in the earlier frame. A repeated measures ANOVA was performed on the arcsine-transformed probability estimates of perceived amodal completion in order to test for main and interaction effects in the data.

Results and discussion

Figure 8 (top) plots the probabilities that the top fragment was selected as being more strongly grouped with the target fragment, as a function of its mean reflectance level. Probabilities for images in the full-shadow condition are shown as gray points, whereas probabilities for images in the half-shadow condition are shown as white points. As expected, both curves show that as the mean reflectance of the top fragment increased to approach the mean reflectance of the left fragment (held constant at 0.8), the probability that the top fragment was experienced as the motion pair with the left segment increased. A repeated measures ANOVA revealed a significant main effect of the reflectance of the top fragment on perceived motion [F(6, 90) = 36.8, p < .0001]. The preference for apparent motion based on similar surface reflectance, rather than surface luminance, occurred to equivalent extents, regardless of whether the left fragment was half or fully covered by shadow. Figure 8 (bottom) plots the probabilities that the patch with the lightest reflectance (regardless of whether it appeared as the top or the bottom response option) was selected as grouping more strongly with the left surface fragment. Single-sample t tests showed that the estimated probability of grouping on the basis of reflectance matching was greater than 50% chance for both the full-shadow condition [t(15) = 6.47, p < .0001] and half-shadow condition [t(15) = 16.49, p < .00001]. A repeated measures t test revealed that the probabilities of grouping were statistically equal between the half-shadow and full-shadow conditions [t(15) = 2.05, p = .06]. These results suggest that observers responded in a way that was consistent with grouping on the basis of similarity in lightness.

Figure 9 (top) depicts the probabilities that the top right fragment was chosen as forming an apparent-motion pair with the left fragment under full or half spotlight illumination. The general shape of the curve resembles the inverse of the curve depicting the results of the shadow manipulation in Fig. 8 (top). An ANOVA indicated a significant main effect of reflectance on perceptual grouping [F(6, 90) = 20.3, p < .0001]. Since the reflectance of the left fragment was held constant at 0.2 in this set of stimuli, our results show that the lower the mean reflectance of the top right fragment, the more likely the observer was to indicate the top fragment as having a stronger grouping with the left fragment.

The effect of similarity in surface reflectance on perceived grouping was still present in our apparent-motion displays when the spotlight covered the whole of the target fragment on the left. However the effect was much less in the full-spotlight than in the half-spotlight condition (the gray points and dark line of Fig. 9, top). Figure 9 (bottom) plots the probabilities that the patch with the darkest reflectance (regardless of whether it appeared as the top or bottom response option) was selected as grouping more strongly with the dark
surface fragment on the left. A repeated measures $t$ test showed that perceived grouping was stronger with the fragments under half spotlight illumination than with those under full spotlight illumination [$t(15) = 3.61, p < .005$]. Single-sample $t$ tests showed that grouping surfaces on the basis of reflectance matching was significantly greater than 50% chance for both the full-spotlight condition [$t(15) = 5.12, p < .05$] and the half-spotlight condition [$t(15) = 11.68, p < .0001$]. These results show that observers were more likely to select surfaces with darker reflectance as grouping more strongly with the target fragment under spotlight illumination, even though the fragments differed in image luminance.

**Experiment 4**

In the previous experiments, we found converging evidence to suggest that the grouping of surface fragments behind a central occluder is enhanced by similarity in surface lightness. Although the apparent-motion task used in Experiment 3 did not require observers to make explicit judgments about the strength of amodal completion, it only provided indirect support for the hypothesis that amodal completion depends on similarity in surface properties. Although the strengths of amodal completion and apparent motion appear to depend on similarity in surface reflectance, the findings of the previous experiments could also be explained by similarity in the contrast ratios of local surface fragments relative to the background on either side of the occluder.

To assess the potential role of image contrast in explaining the effects that we observed, we performed a new apparent-motion task in Experiment 4, inspired by the ambiguous motion displays used in a previous study on amodal completion (Shimojo & Nakayama, 1990). Shimojo and Nakayama presented two square tiles of the same luminance at the diagonal corners of an invisible square. The tiles were repositioned at the alternate diagonal corners on a second frame. Shimojo and Nakayama showed that increasing the horizontal-to-vertical (H/V) aspect of ratio of the invisible square increased the probability of vertical apparent motion, as the tiles on successive frames were closer in proximity in the vertical, rather than the horizontal, direction. They also found that in the condition in which perceived horizontal and vertical motions were equally probable, the direction could be biased in favor of motion across a centrally placed occluder as a result of “amodal leakage.” In Experiment 4, we replaced the tiles with our surface fragments, which were matched...
according to four different configurations: lightness matched; contrast matched; fully matched in contrast, lightness, and luminance; or not matched in any of these attributes. The observer responded according to whether he or she perceived grouping between surface fragments on the same side of the occluder or across the occluder. This provided a way to estimate the strength of apparent motion behind the foreground occluder in contrast-matched and lightness-matched fragments, again without requiring observers to make explicit judgments about the alignment of surface fragments.

Method

Participants A group of 19 adult observers participated in the study, all of whom had normal or corrected-to-normal vision, as indicated on their consent to participate. All participants were naive to the purposes of the study and had not participated in any of the previous experiments.

Stimuli The stimuli were based on the displays used by Shimojo and Nakayama (1990), except that we replaced their squares with our irregular oblong occluded surface fragments. The left and right sides of each fragment were removed in order to produce straight vertical edges that could be aligned with the edges of the central occluder (Fig. 10). The horizontal and vertical dimensions of the occluder (h = 13.5 cm × w = 2.0 cm) were altered from the previous experiments in order to allow larger variations in aspect ratio to be imposed between the positions of the surface fragments as they were displaced vertically along the length of the occluder. The surface fragments were adjusted in height to match approximately the width of the occluder (h = 2.0 cm × w = 3.0 cm).

As is shown in Fig. 10, the relationships between the surface fragments on opposite sides of the occluder were altered according to four main conditions: matched in luminance, lightness, and contrast ratio (A); matched in lightness and contrast ratio, but not luminance (B); matched in contrast, but not luminance and lightness (C); and not matched in luminance, lightness, or contrast ratio (D). We also rendered sets of images either with or without the central occluder: In some frames, the lightness-matched surfaces were rendered with the occluder placed to the left of the display, and the light source was rotated around the visual axis to cast a shadow over the left fragment (inset overlaying panel B). Thus, we created eight unique conditions. Each apparent-motion stimulus consisted of two frames, with the fragments positioned at diagonal corners of an invisible rectangle on one frame, and the opposite corners on the alternate frame. Each frame lasted for 260 ms, with the animation looping continuously for up to 60 frames. The distance (delta) between the inner edges of the surface fragments was variable and ranged between 1.1 and 7.7 cm on the display, relative to the 2.0-cm-wide occluder.

Procedure The observer systematically varied the vertical offset between the surface fragments along the occluder, which modulated grouping across the occluder due to changes in relative proximity between fragments presented on either side of the occluder. We instructed the observers to attend to whether they perceived the fragments as alternating in position back and forth across the occluder (horizontal motion) or flip-flopping up and down on one side of the occluder (vertical motion). They pressed one of two keys on the keyboard every second while viewing the displays, pressing the “V” key when vertical motion was perceived and the “H” key when horizontal motion was perceived.

Observer responses dynamically changed the H/V ratio of the display by small increments in favor of the alternative percept. Pressing the “H” key had the consequence of reducing the vertical distance between the fragments presented on
the same side of the occluder, which increased the probability of vertical motion (as in Shimojo & Nakayama, 1990). Pressing the “V” key had the consequence of increasing the vertical distance between the fragments presented on the same side of the occluder, which increased the probability of horizontal motion. This adjustment technique rapidly converged on the perceptual threshold at which perceived horizontal and vertical motions were equiprobable. Each observer made keyboard entries until three perceptual reversals were recorded, at which time the trial ended and the mean distance between the surface fragments along the occluder was taken as the point of subjective equality (PSE). A 2-s rest period was provided between trials, during which the scene was cleared except for the completely gray background (luminance = 22.56 cd/m²). Each trial took an observer no longer than 60 s to complete. The eight different test conditions were presented in random order with five repeat blocks of presentations, for a total of 40 trials per session.

We performed a repeated measures ANOVA to compare PSEs across the conditions with and without the presence of the occluder, and with systematically varied matching of the surface/image properties between the left and right sides of the display. The mean PSE of lightness-matched fragments was compared separately with the mean PSEs of the surface-matched and contrast-matched fragments. These planned comparisons were performed using repeated measures t tests.

Results and discussion

Figure 11 shows the mean PSEs for the threshold of vertical displacement between the surface fragments. The eight scene conditions that we examined in Experiment 4 are shown as separate bars along the horizontal axis. The repeated measures ANOVA indicated a significant main effect of the presence/
The results of Experiment 4 suggest that similarity in perceived lightness serves as a robust grouping cue for perceiving apparent motion. The presence of a foreground occluder increased the overall strength of perceived horizontal apparent motion across the occluder, consistent with “amodal leakage.” The role of surface similarity in perceptions of apparent motion and amodal completion is discussed further in the “General Discussion.”

General discussion

In the experiments presented herein, we sought to determine whether human vision uses postconstancy information about surface reflectance to perceive amodally completed surfaces. We found that a surface fragment with a decrement in luminance generated stronger amodal completion when it was consistent with the orientation of a cast shadow in the scene (Exp.1). In Experiment 2, we presented a partially occluded surface with a shadow either fully or half covering one of the visible surface fragments. We found that the effects of contour alignment on amodal completion were modulated by similarity in the physical reflectances of the visible portions of the partially occluded surface. In Experiment 3, we used an apparent-motion task to assess amodal completion indirectly, and found that the probability of perceived apparent motion also appeared to depend on postconstancy information about the similarity in surface lightness. A further control experiment revealed that the apparent motion behind the occluder was comparatively stronger for surfaces matched in reflectance, as compared with surfaces that differed in reflectance and matched in contrast (Exp.4). The results of these experiments provide converging evidence to suggest that the processes underlying amodal completion are sensitive to information about the similarity in the material properties of surfaces, such as their texture and albedo.

The effect of misalignment on completion strength observed in Experiment 1 was consistent with prior reports that increased misalignment of parallel edges decreases the strength of amodal completion (Albert & Tse, 2000; Kellman & Shipley, 1991; Shipley & Kellman, 1992; Tse, 1999a, b). These observations have been interpreted by some researchers as evidence suggesting that the perceived completion of partially occluded background surfaces depends on the image-based continuity of visible edge contours (Kellman & Shipley, 1991), although these authors subsequently abandoned this view when considering the role of stereoscopic information (Kellman et al., 2005). This revised account of completion is more in line with Tse’s “internal representation” account (Albert & Tse, 2000; Tse, 1999a, b), which asserts that completion is computed over intermediate perceptual representations of “mergeable,” unbounded volume extensions derived from global image cues. We used surfaces with
serrated edges in the first experiment to limit the role of image contour alignment. Our results suggest that the completion observed in our experiments occurs at a representational level that takes lightness constancy into account. We also found that perceived completion was modulated by the consistency of a luminance decrement on the surface that was more easily attributed to shadow. The increase in the strength of perceived completion when image fragments had similar surface reflectances, despite differences in surface luminance, suggests that amodal completion depends on postconstancy internal representations that discount the effects of scene illumination in order to estimate both the lightness and amodal completion of surfaces.

The findings from Experiments 2 and 3 were also consistent with an alternative view that amodal completion depends on the perceptual grouping of surface fragments that are similar in contrast level relative to the background (Su et al., 2010). However, it would seem that amodal completion may not generally depend on the image luminance or image contrast of the surface fragments per se, but rather, on the similarity in their recovered lightness, which may require more realistic display properties than had been used in previous studies emphasizing low-level image cues. This view is supported by the finding that amodal completion was influenced by the orientation of a cast shadow (Exp. 1).

Additional evidence for this account was provided in Experiment 4, which showed that apparent motion behind an occluder depends on similarity in perceived lightness. Consistent with Shimojo and Nakayama’s (1990) theory of “amodal leakage,” apparent motion was also significantly modulated in favor of the direction that crossed behind a centrally positioned occluder. This is because amodal leakage would have caused the perceived distance between the inner edges of the surface fragments behind the occluder to be smaller. Critically, however, we found that matching surfaces in lightness improved the strength of horizontal apparent motion behind the occluder above and beyond that produced by surfaces matched in contrast alone. It is worth noting that the size of these effects might be enhanced further by instructing participants to perform many practice trials, in order to minimize any potential hysteresis effects observed in an earlier study (Shimojo & Nakayama, 1990). On the basis of the present data, our findings suggest that amodal completion is modulated by the grouping of perceptually derived information about the material properties of surfaces. These findings further suggest that theories utilizing postconstancy internal representations may be best suited to account for the completion phenomena observed in displays depicting surfaces and volumes embedded in complex scenes.

One potential caveat on this interpretation is that it remains unclear whether amodal completion depends directly on similarity in surface lightness or is enhanced indirectly by the involvement of a supplementary grouping process that is sensitive to similarity in lightness. One thing that is clear, however, is that the process involved appears to estimate the similarity in surface lightness of occluded fragments before inferring surface continuity. Further work could help determine whether the dependence of amodal completion on similarity in lightness generalizes to other surface attributes, including 3-D shape and gloss.

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