Occlusion cues resolve sudden onsets into morphing or line motion, disocclusion, and sudden materialization

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Abstract
An abrupt appearance of a new stimulus, or sudden onset, has several possible perceptual interpretations. The change may reflect an object new to the scene or instead be caused by disocclusion of a pre-existing object. Alternatively, the sudden onset may be interpreted as the morphing of a pre-existing figure (as in “line motion”). Previous work has focused on the morphing percept to the exclusion of other interpretations of sudden onsets. This paper supports the idea that morphing, and the other interpretations of sudden onsets, reflect occlusion cues indicating the most likely cause of the stimulus. Consider a line segment that appears abruptly. The data herein show that when the segment has already been represented as present in the scene (via amodal completion), its onset is likely to be perceived as a disocclusion event, with no appearance of morphing. Even when individual frames do not support amodal completion, dynamic (although motionless) cues can favor the disocclusion interpretation, again vetoing the perception of line motion. Some final demonstrations address sudden materialization, in which previously unseen objects suddenly appear. Again there is ambiguity in that sudden materialization and disocclusion can be caused by image changes that are locally identical. Remote cues to occlusion are shown to give these stimuli distinct appearances. The existence of these ambiguities, and the role of occlusion cues in resolving them, has implications for theories of motion perception and attentional capture.

Keywords: occlusion, sudden onset, attentional capture, line motion, depth, transformational apparent motion, prior entry

Introduction

A stimulus on a computer screen that becomes visible instantly rather than gradually is said to have a “sudden onset”. A sudden onset is sometimes interpreted perceptually as an outgrowth or morphing of a pre-existing object. This phenomenon, perhaps first noted by Kant (1951), was termed "line motion" by Hikosaka, Miyauchi, and Shimojo (1993). The broader terms "transformational apparent motion" and "morphing" have been introduced to include the experience of motion in the change of other figures in addition to lines (Tse, Cavanagh, & Nakayama 1998; Baloch & Grossberg 1997). “Morphing” will be used to refer to all these phenomena in the present paper.

In the study of perception, showing that visual mechanisms determine the most likely interpretation of the retinal stimulus is a venerable tradition (von Helmholtz 1867). For example, stereovision research elucidates how perceptual interpretation of retinal disparities match likely corresponding 3-D scenes (e.g. Gillam, Blackburn, & Nakayama 1999).

This, however, has not been the predominant tradition for research into the phenomenon of morphing motion. Instead, morphing motion has been explained by a putative effect of attention on perceptual latency (Hikosaka, Miyauchi, & Shimojo 1993; Faubert & von Grunau 1995), as the result of brain oscillations (Holt-Hansen, 1970), or by the responses of elementary motion detectors (Zanker 1994). For example, the attentional theory posits that attention reduces the perceptual latency of the attended end of the sudden onset. Subsequently, this would be expected to cause motion detectors selective for motion originating at the attentional locus to respond, yielding the percept of motion.

More recently, Tse, Cavanagh, & Nakayama (1998) instead advocated the most-likely-interpretation explanation of morphing motion, and Baloch & Grossberg (1997) presented a model which instantiates aspects of this idea. The argument is that segmentation mechanisms designed to determine the objects and their changes in the scene produce the perception of morphing motion, and that this segmentation operates on a space-time representation rather than operating on each frame separately. The evidence is a qualitative correspondence between percepts and what is intuitively expected of a rational segmentation mechanism. The purpose of this paper is to validate this correspondence with additional qualitative evidence and extend it to other perceptual interpretations of sudden onsets. Note, however, that this framework is not incompatible with an additional effect of attention by priming or by reducing perceptual latency.

In their examination of the morphing, Tse et al. (1998) explored the effects of figural continuity between stimuli in two-frame displays. Building on Faubert & von Grunau (1995), Tse et al. (1998) noted that when a stimulus appears suddenly and is spatially continuous with a pre-existing stimulus, it appears to grow out of the static stimulus. When the sudden onset is adjacent to two static stimuli rather than just one, the sudden onset appears to grow out of the static stimulus that is more smoothly continuous with it, even when the responses of...
simple motion detectors would favor the other direction (see Figure 8.7 in Tse et al. 1998). The putative effect of attention on perceptual latency cannot explain these results. Instead, in these cases the visual system seems to use segmentation cues to determine the origin of the sudden-onset stimulus.

Indeed, in a subsequent paper Tse & Logothetis (2002) found that the direction of morphing motion reflects correspondence of textures and colors in addition to luminance-defined continuity. In addition, their results suggested that the perception of morphing motion reflects a full 3-D, cue-invariant representation of the stimulus. This evidence provided some validation for Tse et al (1998)’s proposal that the full sophistication of human image segmentation machinery is brought to bear to determine the motion perceived.

Tse et al (1998) suggest that morphing motion is a manifestation of the same parsing processes that yield the phenomenon of spatial amodal completion — the perception that an object part behind an occluder joins together a partially occluded object. An intriguing prediction of this idea is that the same image cues that affect spatial amodal completion will also affect morphing motion. This paper presents decisive evidence for this. Indeed, the perception of morphing reflects amodal completion cues in a way consistent with a process designed to determine the most likely interpretation of the stimulus. Further demonstrations show that another stimulus ambiguity – whether sudden onsets are caused by disocclusion or by sudden materialization – are also resolved by cues to occlusion. Hence the interpretation of image cues to occlusion explains not only the perception of sudden onsets as morphing motion, but also the perception of onsets as disocclusion and materialization.

Previous, Poor Evidence that Amodal Completion can Affect the Perception of a Sudden Onset

This section argues that previous work provides only weak support for the hypothesis that amodal completion can affect whether morphing motion is perceived. In contrast, experiments reported in this paper will provide strong support for the hypothesis.

In a classic display of morphing motion, a filled rectangle suddenly appears, and is coterminous with an adjacent stable shape. Typically one perceives the rectangle to shoot out from the stable shape as if it were an extension of it. To explain the claim that the matching process in morphing motion can operate on an amodally completed representation, Tse et al offered the stimuli in Figure 1 (adapted from their Fig 8.5a). The right half of the display is similar to previous line motion displays by Hikosaka et al (1993). Thus it is unsurprising that the right line segment is perceived to shoot to the left. But Tse et al reported that the leftmost segment of the grey line in Figure 1 is also perceived to shoot to the left. To them, this indicated a role for the perceived continuity via amodal completion of the two line segments. Tse et al’s (1998) idea is that morphing motion mechanisms can operate on an amodally completed representation. However, the evidence in this case is quite weak. If the part of the stimulus which facilitates the amodal completion (the right half of Figure 1) is deleted, one would still expect to perceive the remaining line segment as shooting to the left, for the reason described below.

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Figure 1. According to Tse et al. (1998), the grey rectangles are perceived to shoot to the left, which they considered evidence that morphing motion reflects an amodally-completed representation.

The expectation that this percept might occur even without amodal completion is based on the strong similarity the display to those of Figure 2 (adapted from Tse et al’s Figure 8.2 and 8.4). In each case in Figure 2, Tse et al report that the line segment is perceived to shoot to the left. For these displays, the authors posit that the contiguity between the line segment and the shape on its right results in interpretation of the line segment as an extension of the shape on the right, yielding the perception of shooting to the left. However, these demonstrations undermine their claim that amodal completion causes the perception of motion in Figure 1, as the continuity factor documented in Figure 2 could be used to explain the morphing motion of both line

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Figure 2. A display adapted from Tse et al. (1998). The arrows in the static version indicate the percept and were not present in the experimental display. Reportedly, observers perceived morphing motion to the left in each case.
segments of Figure 1, without reference to amodal completion. Indeed, Tse et al provide additional examples to show that good continuity alone can determine the line motion percept (their Figure 8.3). Whether this continuity effect has anything to do with amodal completion remains an open question.

Inspired by a preliminary report of Tse et al’s work, Baloch & Grossberg (1997) also claimed that amodal completion plays a role in morphing motion. As evidence, they pointed to the display depicted by Figure 3 and reported that the rectangular red ring is perceived to shoot to the right, whereas the green line is perceived to shoot to the left.

Figure 3. A reproduction of Figure 10b from Baloch & Grossberg (1997). On some display devices there may appear to be a small gap between the red and green shape, but the experimental display contained no gap, only crisp T-junctions.

Baloch & Grossberg (1997) suggested that perception of the green line as shooting to the left implies an effect of amodal completion on morphing motion. But consider what the simple continuity factor would predict, irrespective of the occurrence of amodal completion. The physical continuity of the leftmost green line segment with the red rectangle on the first frame might cause it to be perceived as shooting to the left. In contrast, the continuity of the central green line segment with frame 1’s red rectangle might cause the central segment to be perceived as shooting to the right. Baloch & Grossberg (1997) report that instead, both green line segments are perceived to shoot to the left. This is consistent with their hypothesis of a role for amodal completion. However, they do not provide control displays to insure that the leftward motion does not result from another factor. This is a concern because the simple continuity factor predicts the presence of leftward motion in one part of the green line, and in this complex display it is possible that another factor might cause it to win out over the rightward motion also predicted by contiguity. For example, Steinman et al. (1995) provided evidence that line motion cues cause a center-surround opponent effect, which might favor perceiving the green line to move in the opposite direction than the red ring.

Further reason for uncertainty came from the present author’s subjective experience, in which the green line seems to appear all at once without any shooting sensation. It is unclear whether this informal observation constitutes inferior data to that of Baloch & Grossberg, since they did not report data in their paper nor say what sort of experiment they conducted with the display.

In the following experiment, a modified version of this display as well as some novel control displays were used to provide a better test of the possibility that amodal completion is a factor in the perception of morphing motion.

New Evidence for a Role for Amodal Completion: Modification of Baloch & Grossberg

The Baloch & Grossberg (1997) display was modified (one of the breaks in the green bar was eliminated) to create Figure 4A. The modification helped to clarify the question asked of the observers, by avoiding a potential need to distinguish between differing percepts in different parts of the green bar. If most observers perceive leftward motion of the green bar in A, then the data from the control displays (see Figure 4B, C, and D) should reveal whether this is due to amodal completion of the flashing green bar with the static green bar.

Subjects

A total of 31 subjects participated. All reported normal or corrected-to-normal vision. Of these, 28 were completely naive undergraduate and graduate students and 3 were experienced psychophysical observers.

Figure 4. Observers were more likely to perceive the green line as shooting to the left in the critical display A than in control displays B, C, and D. Apparently, the perceived continuity of the green segment with the preexisting segment via amodal completion increases the likelihood of perceiving motion. However, the movie version of this figure may result in a different experience than in the experiment, for various reasons, including perceptual interactions among animations simultaneously presented. Also, some display devices may introduce thin lines between the red and green shapes. These were not present in the experiment.
Stimuli and Procedures

To familiarize the observers with the morphing motion percept, each person was provided with a few examples. In one of these fairly unambiguous example displays, a rectangle flashed on and off next to a smoothly contiguous rectangle, yielding a morphing percept. In a second example, the flashing rectangle was contiguous with stable rectangles on both sides. Here, all observers reported experiencing motion from both sides at once, toward the center. As an example of nonmotion, observers were shown a flashing rectangle which was flanked by shapes contiguous with the flashing shape. But in this case the point of contact between the shapes was tiny and as expected, no observers reported perceiving motion.

After becoming familiar with morphing motion, each observer was shown the displays in pseudorandom order. After each display, they were asked to report whether they perceived any motion of the red and the green figures and, if they did perceive motion, the direction of motion perceived for each. The first 11 observers viewed only displays 4A, 4B, and 4C, as 4D was added after it was suggested by a reviewer.

Results and Conclusions

The theory that morphing motion is adaptively affected by cues to amodal completion made specific predictions for the displays of this experiment. Specifically, when cues to amodal completion indicate that the suddenly-appearing green line is an extension of the formerly present green line, observers should experience motion to the left. Indeed this was the claim made by Baloch & Grossberg (1997), although they did not report any data.

Contrary to what would be expected from Baloch & Grossberg (1997), in the present experiment the majority of observers (52%) did not perceive the green bar to shoot to the left in the display depicted in Figure 4A. Nevertheless, a closer look at the data does indicate some role for amodal completion. Specifically, compare the number of observers who perceived leftward motion in 4A with the number of observers who perceived leftward motion in the control displays (Figure 4B, C, and D).

In the case of the display of Figure 4A, 48% of the 31 observers reported that the green part shot to the left when it appeared, 35% reported no motion, and 16% reported that it shot to the right.

In the control display of Figure 4B, zero observers reported that the green shot to the left, for 4C only 13% did, and for the display of 4D, only 11% did. Hence significantly more perceived leftward green motion in 4A than in any of the control displays (pooled test t(60)=5.30, p<0.0001, t(60)=3.23, p=0.0002, and t(60)=4.13, p=0.0001, respectively). The complete results are provided in Table 1.

Table 1. Results for Displays Depicted in Figure 1.

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<tr>
<td></td>
<td>Green</td>
<td>Red</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Left</td>
<td>48%</td>
<td>3%</td>
<td>0%</td>
<td>13%</td>
</tr>
<tr>
<td>Right</td>
<td>35%</td>
<td>29%</td>
<td>100%</td>
<td>61%</td>
</tr>
<tr>
<td>None</td>
<td>16%</td>
<td>68%</td>
<td>0%</td>
<td>26%</td>
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The incidences of the perception of leftward, rightward, or no motion for the green and red shapes of the critical display A and the three control displays, B, C, and D of Figure 4. The incidences of the most critical percept, leftward motion of the green shape, are in the shaded cells.

This difference between the experimental and the control displays rules out several explanations of the perceived leftward motion of the green shape. That observers perceived the green shape of display B to shoot to the right instead of to the left implies that the presence of the static green rectangle on the right is not sufficient to cause leftward motion. The low incidence of leftward motion of the green shape in display C shows that the red figures of 4A also are not responsible for the prevalence of leftward motion in 4A. Finally, the low rate of leftward green motion in display D suggests that the mere presence of the red ring and the green bar, in combination, also cannot explain the leftward motion in A.

The factor responsible for the perception of leftward motion of the green shape in 4A, then, is the combination of the presence of the green rectangle on the right with the red ring in an occluding relationship. This indicates that the green line was perceived to shoot leftward because of its continuity with the green line on the right via an amodal representation. We can conclude that the continuity factor, which causes a shape to seem to shoot from one side, can be caused by continuity with amodal representations as well as visible representations.

Although 48% of observers perceived the predicted green leftward motion in display A, which was significantly more than in the control displays, still this means that less than 50% of the observers experienced the predicted percept. If continuity with an amodal representation is sufficient to cause morphing motion, then why did only a minority of observers perceive the morphing motion in Figure 4A? The motion of the nearby red shape, and other factors, may compete with amodal completion in determining the final percept. Other possible reasons for variability with these types of displays are discussed in the conclusions of the next section. In any case, since the evidence of this first experiment was not definitive, the next experiment used a different approach, which yielded stronger evidence for a role for amodal completion.
New Evidence for a Role for Amodal Completion: Novel Displays

The previous experiment provided tentative evidence for the idea that morphing motion is adaptively affected by image cues to amodal completion. Specifically, when a sudden onset appeared attached to a preexisting object through amodal completion, for many observers it appeared in motion, morphing from the side of the preexisting object.

But what if spatial amodal completion cues specified that a suddenly appearing figure had already been present, although occluded? If interpretation of sudden onsets intelligently incorporates amodal completion, the visual system should report that the sudden onset stimulus appeared by virtue of disocclusion rather than by morphing motion. Does our visual system do this? In the following experiment, we test this with pairs of displays that differ in whether cues to amodal completion are present.

If it turns out that morphing motion is indeed vetoed by cues to occlusion, a further question is whether the system makes this determination on the basis of individual frames, or whether it also integrates information from other frames. For continuous nonmorphing motion, it has already been shown that subsequent information is used to decide whether occlusion exists in a previous frame. For example, in the displays of Cicerone et al. (1995), an invisible, moving occluder is perceived when the movie is viewed, even though it is not perceived from individual static frames. Using some additional displays, we tested whether this would occur for two-frame morphing motion displays.

But, to start, the question was whether regions which appear suddenly would not be perceived to morph if they were previously represented amodally.

Subjects

20 subjects who reported normal or corrected-to-normal vision participated. Three were experienced psychophysical observers associated with the laboratory, and the remaining were undergraduates who participated for course credit or for pay. All were naive to the purposes of the experiment.

Stimuli and Procedures

Subjects viewed the stimuli through a mirror stereoscope which directed light from the left half of the CRT to the left eye and from the right half to the right eye, along a path from eye to screen of about 58 cm. Two copies of the stimulus, one for each eye, were displayed on the screen with an appropriate difference between the two copies when binocular disparity was desired.

Observers were screened for stereovision in a short test. First, observers reported the relative depth of several static targets which had relative disparity of ~0.2 deg. Subsequently they were tested on more targets for a total of 16 tests. These subsequent targets were presented only briefly, for ~250 msec (van Ee & Richards, 2002). Five of the 20 observers failed the screen by reporting the depth of more than 4 of the 16 targets incorrectly. Data of these observers was discarded.

After the stereovision screening procedure, observers were familiarized with morphing motion using the same procedure as that used in the previous experiment of this paper. Then each subject viewed in pseudorandom order a total of 18 displays, counting the multiple display speeds and the variations of stereodisparity (in front vs. behind) that were appropriate for a few stimuli. Each observer was asked to report whether the relevant dynamic part of the stimulus appeared to be in motion (“shooting”) or not. The two frames of each display were shown in alternation until the observer responded.

The displays most critical to the main hypothesis are schematized in Figure 5. The red shape of frame 2 was 8.5 deg wide and 2.42 deg high, and each of the red shapes was textured to include disparity signals from the shape’s interior.

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<tr>
<th>frame 1</th>
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<th>% saw motion red closer</th>
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Figure 5. The numbers indicate the percentage of the 15 observers who experienced morphing motion for displays A and B at the slowest alternation rate. Observers were more likely to experience motion when disparity indicated that the red was closer than the green than when the red was farther than the green. The implication is that when the red flankers are joined by an amodal representation, the sudden appearance of the central portion is interpreted as disocclusion rather than as morphing motion.

Observers viewed each of the two displays of Figure 5 at three different speeds: 360, 260, and 175 msec per frame, using Macromedia Flash MX™, which does not provide precise timing. Hence the displays were not synchronized with the screen refresh and presentation rate could vary by up to 70 msec per frame.

For each rate, observers viewed one version of each display in which the relative binocular disparity indicated that the red shapes were in front of the green, and another version in which the red shapes were behind the green, by 0.42 deg of disparity.
To determine whether other cues to occlusion could also play a role, the displays of Figure 6 were presented. The displays of Figure 6A, B, C, and D were shown at a rate of 635 msec/frame and those of 6E and 6F were presented at 450 msec/frame. These durations provided enough time for form analysis to exert its full effects (according to Tse & Logothetis, 2002).

![Figure 6](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/933596/)  
Figure 6. The numbers indicate the percentage of the 15 observers who reported motion for each of 6 displays. Fewer perceived motion when pictorial cues favored a preexisting amodal representation of the suddenly-appearing figure than when such cues were not present. This was true for the comparison of A to control displays B, C, and D, and also for E compared to control display F.

**Results and Discussion**

The results show that when a suddenly appearing stimulus was already represented amodally, observers are less likely to experience motion. As tabulated in Figure 5, observers were significantly less likely to experience motion when the red flanks were behind the green shape than when they were closer than the green shape. An ANOVA with subject, depth of the red flanks, display variant, and speed of the alternation as factors indicates that the depth of the flanks has a significant effect, $F(1,14)=28.7$, $p<.0001$, whereas none of the interactions is significant. There is also a main effect of display variant, with subjects significantly less likely to experience line motion in variant B, $F(1,14)=5.7$, $p=.031$. This was expected. The irregular contour of variant B was designed to make the stimulus more amenable to interpretation as green occluding the red. Specifically, in B it is easier to perceive the intersection of the red and green shapes as being intrinsic to the green shape rather than caused by the red occluding the green. A pilot experiment had prompted concern that observers would interpret variant A as the red shape occluding the green even when the stereo disparity specified otherwise, due to the strength of the T-junction as an occlusion cue. Display B was devised to counter this possible tendency towards a ceiling effect.

Presentation rate was also varied in case any particular speed significantly favored one interpretation, but no significant effect obtained. Overall, we have a clear result indicating that amodal completion can determine whether morphing motion is perceived. The sudden appearance of a figure that was already represented, albeit previously invisible, was not experienced as motion.

There were two purposes of including the displays of Figure 6 in the experiment. First, to determine whether displays even without stereo disparity could nonetheless change from morphing motion to disocclusion on the basis of a viable occlusion interpretation. A second question was whether sudden onsets could be interpreted as disocclusion even without an amodal representation prompted by the static display. This possibility arose because in the displays of Figure 6A and Figure 6E, the individual frames were not sufficient to induce the perception of occlusion.

The first frame of 6A is typically perceived as a red rectangle adjacent to a green rectangle, and in 6E the blue rectangle is perceived as flanked by a coplanar reddish shape and orange shape. However, the second frame of these displays suggests that, in the case of 6A, the red shape was but the visible portion of a larger bar, and in the case of 6E, that the orange and reddish shapes were in fact part of one shape behind a blue rectangle. This constitutes a dynamic cue to occlusion, as it requires the comparison of two frames. The question was whether this dynamic occlusion cue will reduce, compared to control displays, the perception of morphing motion of the red rectangle in 6A and of the orange/red shapes in 6E.

Indeed the data indicate that the dynamic occlusion cue was effective. The probability of perceiving morphing motion was much lower in the display of Figure 6A than in the control displays of Figure 6B ($t(28)=-4.91$, $p<.0001$) and 6C ($t(28)=-3.35$, $p=.0012$). This result was predicted, as the display of Figure 6A is more consistent with disocclusion of the extension of the red than are displays 6B and 6C. The cue to disocclusion is the coincident disappearance of the green shape when the extension of the red appeared. Still, a critic might attribute the difference in number of subjects reporting motion to
some general disruption of motion signals caused by the transient of the green shape's disappearance. The result with control display 6D counters that criticism. In display 6D the green rectangle disappeared just as it did in 6A, but the display in 6D was less consistent with the red being amodally completed behind and indeed motion was more likely to be perceived ($t(28)=-1.89$, $p=.035$).

Comparison of display E with control display F further supports the hypothesis that a motionless dynamic pictorial occlusion cue can cause the perception of disocclusion instead of morphing motion. When the first frame of display E is viewed alone, typically three aligned shapes are perceived rather than any occluding relationships. This is consistent with an interpretation of morphing motion when the next frame appears – the orange shapes morph together, closing like curtains over the blue rectangle. However, only 47% of observers perceived motion in this display. In this experiment observers did not report the nature of the occlusion perceived, so we cannot be sure of their interpretation, but in an unpublished experiment all those who reported motion described it as the curtain-closing percept. In the present experiment, instead of perceiving motion in display E, most reported that the blue shape appeared to dematerialize with the appearance of the second frame, revealing the center of the longer shape that previously had been occluded. Hence disocclusion was perceived despite the lack of any clue to the existence of the hidden material in the first frame. This suggests that the dynamic covering and uncovering itself can sometimes result in a disocclusion percept, effectively vetoing a morphing motion percept.

Once again, in display E, approximately half of observers perceived dematerialization of the blue, revealing an orange shape behind. None of the observers ever reported this in the case of display F, even though the center strip of display F was identical to display E. Instead, in display F observers reported morphing motion (100% vs. 47% of display E, $t(28)=-4.0$, $p=.0002$). The addition of the contiguous blue context to E, creating display F, resulted in interpretation of blue as the background. With the orange pattern seen in front, then, appearance of the orange could not be attributed to disocclusion and thus morphing motion of the orange was perceived.

Together these displays show that the perception of occlusion vs. dematerialization can occur even when no single frame yields amodal completion. Interestingly, the dynamic occlusion cues of these displays are dynamic but do not involve motion, despite the emphasis in the literature on motion as the dynamic occlusion cue.

A final point is that none of the observers perceived the blue shape of display 6E to transform or morph into the visible material of the second display. When one stimulus replaces another, how does the system decide whether to consider it a transformation of the old object instead of a new object? In the present case, the decision clearly has something to do with whether an occlusion relationship is plausible, but this question remains mostly unexplored.

Although in display F the prediction that morphing would be perceived was fulfilled without exception, most of the manipulations resulted in more modest increases in the likelihood of the predicted outcome. One reason is that the cues manipulated in the displays did not always result in a change in the perceived depth. For example, in the case of the displays in which stereo disparity was manipulated (Figure 5), a preliminary experiment showed that despite stereodisparity’s reputation as a potent depth cue, for many naïve subjects it did not overcome the interpretation they favored when the stimulus had no stereodisparity. Such dominance by non-stereo cues is not unprecedented (for a review, see Howard & Rogers 2002).

The other displays were also sometimes seen in ways unanticipated by the author. Furthermore, it seemed that attention could be used to perceive motion where at first glance motion was not perceived. This is consistent with previous results that, at least with some stimuli, attention can determine the motion perceived (Verstraten, Cavanagh, & Labianca, 2000; Cavanagh 1992). Conflicts between motion energy and ecological cues in some displays probably were another contributor to the variability of the results. Because of this variability, and especially because attention allows observer expectations to influence the results, collecting data from naïve subjects is quite important. In some previous reports in the literature, the methods were unfortunately not described, making the number of naïve observers used unknown.

### (Dis)occlusion vs. (De)materialization

The previous experiments suggest that the perception of morphing reflects segmentation mechanisms designed to determine the cause of a dynamic visual stimulus. Cues to amodal completion were shown to adjudicate between an interpretation of morphing and other interpretations.

In the remainder of this paper it is shown that sudden onsets contain yet another ambiguity: between disocclusion and sudden materialization. Further, a demonstration shows that the ambiguity can be resolved by image cues to occlusion. A larger point is that the ecological cue account of morphing motion not only explains many aspects of morphing motion, but also explains other interpretations of sudden onsets. By contrast, other theories of morphing motion do not have this generality.

A sudden onset of one stimulus also results in a sudden offset of the stimulus that was on the screen immediately before, be it a blank background or a figural pattern. An attendant ambiguity (Gibson, 1966) is that
the new stimulus could be a new object or it could instead have always been present in the scene and appeared simply by disocclusion. When a lone stimulus suddenly disappears from the screen, the new stimulus (a portion of the background) is interpreted as appearing due to disocclusion rather than sudden materialization. The interpretations of disocclusion and sudden materialization can be quite distinct in one's phenomenology. On the left side of Figure 7, the bright central bars seem to appear by virtue of sudden materialization, whereas on the right side they seem to appear due to disocclusion.

But does the differing experience of the two parts of the display depicted in Figure 7 show that disocclusion and sudden materialization always correspond to distinct percepts? A skeptic might argue that the predominant difference between the two parts of the display is a difference in salience, with the appearance of the background appearing much less salient than the disappearance of the figure. The salience difference is unsurprising due to the difference in contrast from the surround, with the appearance of the background having no difference from the surround and the smaller stimulus is very different from its surround. Higher surround contrast results in higher salience (Nothdurft, 1993). Would two-frame materialization and disocclusion look different even when contrast with the surround were equated, or is the perceptual difference in Figure 7 caused by nothing more than the contrast difference?

J.J. Gibson (1966) believed that there is more to the perceptual difference than a salience difference caused by contrast. He supported this with displays of temporally extended events, in which a gradual deletion cue can signal occlusion. However, he apparently did not control for local surround contrast. The display schematized in Figure 8 shows that even without a difference in local contrast, materialization and disocclusion look quite different.

Figure 8. In this movie, an illusory square is seen to occlude the red square in the occlusion display. When the red rectangle disappears, it seems to continue to exist behind the illusory square. By contrast, in the animation on the right the red rectangle appears to vanish from the scene, as if it dematerialized. Binocular disparity strengthens the effect but is not necessary for some observers.

The phenomenology of the appearance of the red square in the displays of Figure 8 differs. In the left hand display of Figure 8 dematerialization, without perceived motion, of the illusory square leads to the perception of disocclusion of the red square.

In both displays, the local images changes around the red square are identical. Nevertheless, the remote spatial context of frame 1 (which determines whether an illusory contour is created) causes the phenomenal appearance of the red square to be quite different in the two cases. In the disocclusion display, the notched circles yield the sense that a large grey square is present in frame 1. The filling-in of the circles in frame 2 causes the visual system to interpret the large illusory square as dematerializing, revealing by disocclusion the smaller red square. In the movie, stereo disparity is added to the large illusory square to increase the evidence for this perceptual interpretation.

In "materialization", the addition of arc to complete the blue circles, eliminating the illusory contour, plus the reversed stereo disparity causes the large square to be perceived behind the red square instead of in front.
Conclusions

This paper has documented the influence of occlusion cues on several perceptual interpretations of sudden onsets. First, strong experimental support was provided for the idea of Tse et al. (1998) that parsing and segmentation cues for amodal completion can determine the perceptual interpretation of morphing motion displays. Second, this idea was extended to the interpretations of sudden materialization and disocclusion. It was shown that these last two interpretations yield a distinction in observers' phenomenology, above and beyond differences in salience from local contrast. That the same occlusion cues can arbitrate between these varied interpretations hints at a common mechanism underlying the different interpretation of sudden onsets. The morphing or line motion interpretation is but one outcome of this process.

Previous literature has concentrated on the single distinction of the perception of motion vs. non-motion, and moreover has not fractionated non-motion into materialization and disocclusion. This additional distinction provides a challenge to models of the perception of dynamic scenes. After an identified object is no longer at a particular location, computational models typically only attempt to determine whether there is subsequently a corresponding match in another location (which would indicate motion) (Jovic & Frey 2001). If there is no correspondence match, models ought to also determine whether the object has simply disappeared or is instead still present but occluded.

Another challenge to models arises because previous studies of dynamic occlusion have focused on motion, usually progressive appearance and disappearance, as a critical cue. Sigman & Rock (1974) already showed that progressive change is not needed. The displays here show that motion itself is also not necessary to perceive dynamic occlusion.

Given the infrequency of sudden materialization and dematerialization in the natural world, one may wonder how the visual system came to distinguish between sudden dematerialization and sudden occlusion. The pioneering developmentalist Jean Piaget (1929) believed that young children fail to represent objects as continuing to exist when they disappear due to occlusion. This amounts to the notion that children represent disappeared objects as dematerialized, at least implicitly. Subsequent research showed that Piaget's notion is wrong — children continue to represent objects which have been fully occluded (Kellman & Spelke, 1983; Johnson, Bremner, Slater, Mason, & Foster 2002; Aguiar & Baillargeon 2002). Many dozens of experiments have now probed children's representation of occlusion events. Nevertheless, it seems that research has not been directed at the cues that might cause a child to perceive dematerialization rather than occlusion. Such an investigation could yield some surprising results, taking us even farther from Piaget's original belief. Specifically, if our perception of a distinction between occlusion and dematerialization comes from experience with dematerialization events, it may be that the young and inexperienced will perceive as occlusion many events that adults perceive as dematerialization.

The perception of sudden onsets is affected not only by the occlusion cues investigated here, but also by other factors (e.g. von Grunau, Dubé, & Kwas 1996; Eagleman & Sejnowski, in press). A major focus of previous work has been the influence of spatial attention on morphing motion. Attending to one end of a suddenly appearing bar can cause the experience of motion originating from the attended end (Hikosaka et al. 1993). Several researchers have concluded that attention reduces perceptual latency, causing the attended part of the figure to appear first. In their focus on mechanism, however, they seem to have overlooked functional consequences of this phenomenon. A typical real-world scene evokes a large number of low-level motion responses, many of which are spurious or otherwise not of interest to the observer. To speculate, this may be one reason for the role of attention in resolving motion ambiguity (Cavanagh 1992). In particular, one consequence of reducing the perceptual latency of an attended item may be to bias motion detectors to respond to the movement of the attended item rather than, for example, other items moving into the attended location. Attended figures with shorter latencies should reach motion detectors before figures in unattended areas. Since motion detectors are activated when receiving stimulation from one location shortly before another location, this will create a bias to perceive motion originating in the attended location. Hence rather than being an entirely non-adaptive byproduct of the circuitry of attention, reduction in perceptual latency may help to track items of interest.

Another line of research which heavily utilizes sudden onsets is the investigation of attentional capture. Research in this area has distinguished between sudden onsets that are "new objects" (Yantis, 1993), those that are object disappearances (Samuel & Weiner, 2001), and those that
are only a brightness or color change (Enns, Austen, di Lollo, Rauschenberg, & Yantis, 2001), and found evidence that “new objects” (which roughly seems to mean suddenly-materializing figures) are the most potent for attracting attention. But note that this classification does not differentiate between objects that appear by disocclusion, by materialization, or by morphing motion. The cues documented here should allow future work to determine the relative attention-summoning potency of these various interpretations of sudden onsets.

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