Vision Research 143 (2018) 66–81

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Perceptual mechanisms underlying amodal surface integration of 3-D stereoscopic stimuli

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ARTICLE INFO

Keywords:
Amodal surface completion
Binocular disparity
Luminance contrast-polarity
Occlusion
Surface representation

ABSTRACT

The visual system can represent a partially occluded 3-D surface from images of separated surface segments. The underlying amodal surface integration process accomplishes this by amodally extending each surface segment behind the occluder (amodal surface extension) and integrating the extended surfaces to form a whole surface representation. We conducted five experiments to investigate how depth cues, such as binocular disparity, half-occlusion, and monocular depth cues (T-junctions and L-junctions), contribute to amodal surface extension, and how the geometrical relationship and image similarity among the surface segments affect surface integration. This was achieved by having observers adjust the stereoscopic depth and slant of a comparison stimulus to match those of the tested 3-D stimulus. We found that both binocular disparity and half-occlusion cues are used to determine border-ownership assignment of surface segments and for amodal surface extension. We also found that separated surface segments need to have the same luminance contrast-polarity for them to be integrated as a whole surface. Finally, we found that having the same motion direction, minimum misalignment between boundary contours, and proximity among separated segments facilitate their integration. Overall, our findings reveal a set of "perceptual factors" for amodal surface integration, which arguably reflects our visual system's built-in knowledge of the regularities in natural scenes.

1. Introduction

Perception of 3-D visual surfaces and surface layouts is essential for reliably recognizing objects and guiding actions in the natural environment (Gibson, 1950; Grossberg & Mingolla, 1985; Kanizsa, 1979; Marr, 1982; Nakayama, He, & Shimojo, 1995; Sinai, Ooi, & He, 1998). But how the visual system successfully mediates our perception of 3-D surfaces and surface layouts remains the subject of much research. This is because 3-D objects and surfaces in the real world are often imaged on our retinas as 2-D images with some parts missing due to occlusion. It has thus been proposed that to form 3-D representations of surfaces from 2-D retinal images, the visual system needs to sort out surface layouts by using depth information and to either extrapolate the projected image segments, or to interpolate the occluded surface segments that are not projected onto the retinas (e.g., Kanizsa, 1979; Kellman & Shipley, 1991; Michotte, Thinès, & Crabbé, 1967; Nakayama, Shimojo, & Silverman, 1989; Nakayama et al., 1995; Zhou, Friedman, & von der Heydt, 2000). Fig. 1a depicts an occluded surface scenario where an observer views a white horizontal rectangle that is partially occluded by two black vertical bars. The resultant retinal image due to the occlusion by the vertical bars is that of three separated image segments of the horizontal rectangle (Fig. 1b). Thus, to support our 3-D perception, the visual system needs to "decide" whether the three image segments are parts of a single surface in the back or three independent surface entities (Marr, 1982). If it is the former, the visual system will have to fill in the (two) occluded surface segments and integrate them with the three visible image segments to form a single surface representation (amodal surface integration).

The question is how the visual system accomplishes the operation of amodal surface integration. A number of studies have shown that the visual system capitalizes on its internal knowledge of the regularities of the natural 3-D visual surfaces, with respect to surface color, surface shape, spatial relations, projection geometry, etc., to construct representations of surfaces, including occluded surfaces (Anderson & Schmid, 2012; Anderson, Singh, & Fleming, 2002; Fantoni, Bertamini, & Gerbino, 2005; Gerbino & Fantoni, 2006; He & Ooi, 1998; Kanizsa, 1979; Kellman, Garrigan, & Shipley, 2005a; Kellman, Garrigan, Shipley, Yin, & Machado, 2005b; Kellman, Yin, & Shipley, 1998; Nakayama & Shimojo, 1990a, 1990b; Nakayama et al., 1989; Rubin, 2001; Sekuler, 1994; Sekuler, Palmer, & Flynn, 1994; Spehar & Clifford, 2003; Su, He,

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https://doi.org/10.1016/j.visres.2017.10.005
Received 2 June 2017; Received in revised form 25 September 2017; Accepted 3 October 2017

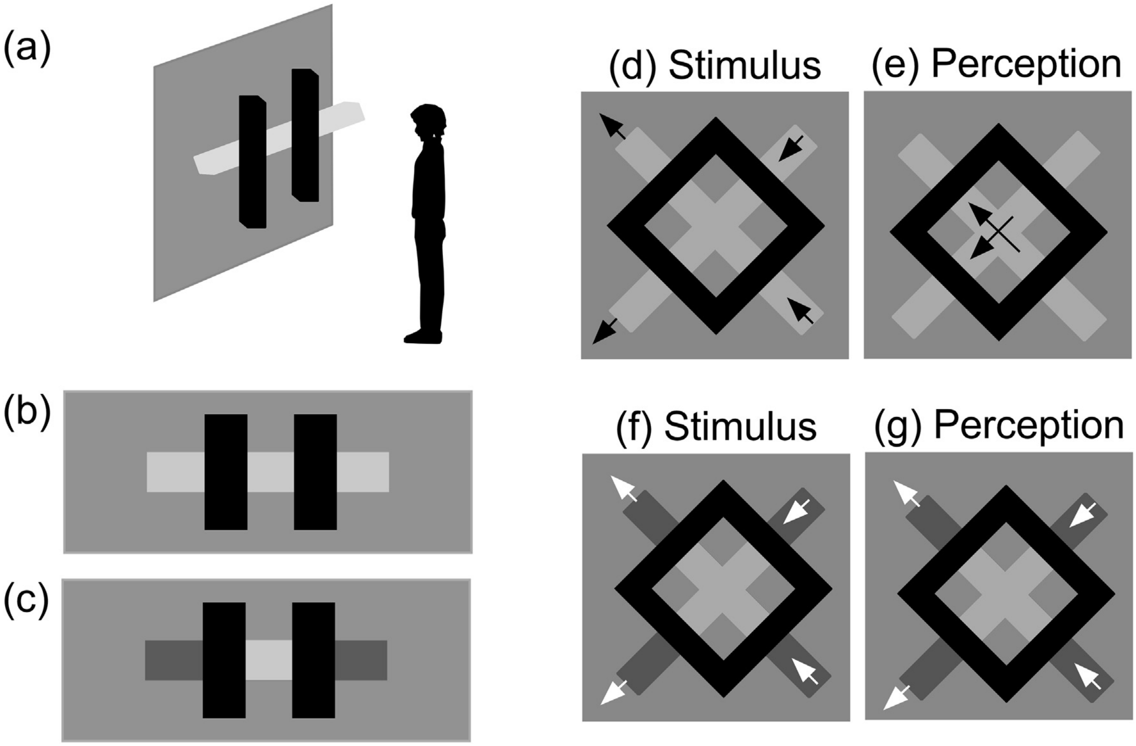

Fig. 1. Amodal surface integration. (a) Illustration of an observer viewing a white horizontal rectangle that is partially occluded by two black vertical bars. (b) The resultant retinal image of viewing the display in (a). The three separated image segments belong to the white horizontal rectangle. (c) An opposite contrast-polarity stimulus. Note the two flanking rectangle are darker than the background (negative luminance contrast-polarity) while the middle rectangle is lighter than the background (positive luminance contrast-polarity). (d) A test stimulus with the same contrast-polarity used by Su et al. (2010a). In the experiment, the black diamond frame and the gray rectangular elements arranged in an X-formation within the diamond frame were kept stationary, while the outer rectangles moved in the direction indicated by the arrows. (e) Observers tended to perceive the rectangular elements within the diamond frame as part of the outer oblique rectangles that slid over one another. This is because the amodal surface integration process represents each adjacent pair of outer and inner rectangles as a single moving surface that is occluded by the diamond frame. (f) A test stimulus from Su et al. (2010a) with opposite contrast-polarity in which the outer and inner rectangles have opposite contrast-polarity. (g) Observers tended to perceive the inner rectangles as stationary while the outer rectangles expanded and contracted.

& Ooi, 2010a, 2010b; Tse & Albert, 1998; van Bogaert, Ooi, & He, 2008; Van Lier, Van der Helm, & Leeuwenberg, 1995; von der Heydt, Peterhans, & Baumgartner, 1984; Watanabe, 1995; Watanabe & Cavanagh, 1993; Yin, Kellman, & Shipley, 1997; Yin, Kellman, & Shipley, 2000). For example, surface components from the same object/surface found present in the natural environment tend to have a higher statistical probability of having the same luminance contrast-polarity (Geisler & Perry, 2009). This empirical observation is consistent with our earlier phenomenological observation where we found that the visual system prefers to amodally integrate image segments with the same contrast-polarity over those with opposite contrast-polarity (He & Ooi, 1998; Su et al., 2010a, 2010b). Therefore, if one applies the same contrast polarity rule to the scenarios in Fig. 1b and c, it is predictable that the visual system has a larger bias to amodally integrate the three rectangular segments with the same contrast-polarity in Fig. 1b, than the ones in Fig. 1c where the middle rectangle (lighter than the background) and the two flanking rectangular segments (darker than the background) have opposite contrast polarity (Su et al., 2010a, 2010b).

An objective way to study amodal surface completion is by measuring its effect on a specific perceptual task (e.g., Gerbino & Fantoni, 2006; Kellman et al., 2005a; Marr, 1982; Ringach & Shapley, 1996; Rubin, 2001; Sekuler et al., 1994; Shimojo & Nakayama, 1990a, 1990b; Su et al., 2010a, 2010b; van Bogaert, Ooi, & He, 2008; Yin et al., 2000). For example, when spatially separated images are amodally integrated into a single surface entity, all separated components of the surface will exhibit similar surface properties (e.g., Su et al., 2010a). Consider the display in Fig. 1b again. Now, imagine that both the flanking rectangles carry leftward horizontal motion signals while the middle rectangle has no motion signal. According to our reasoning so far, the three rectangular segments, having the same contrast polarity, will be amodally integrated as a common surface. Therefore, we should then expect the entire surface including the static middle rectangle to be perceived as rigidly moving leftward. However, if amodal surface integration does not occur, the middle rectangle will remain stationary while the left flanking rectangle expands and the right flanking rectangle contracts. Therefore, by measuring whether motion is perceived in the middle rectangle, we can objectively reveal whether amodal surface integration takes place.

We took the objective approach in a previous study using a stimulus similar to that in Fig. 1d (Su et al., 2010a). The black diamond frame (physical occluder) and the gray X-shaped elements within the diamond frame were rendered stationary while the outer oblique rectangles carried the local motion signals depicted by the arrows. According to our prediction, the stationary X-shaped elements and the outer oblique rectangles would amodally integrate behind the black diamond frame as long single bars. Confirming this, we found that the observer perceived the stimulus as two longer oblique rectangles *sliding* over one another (global motion) (Fig. 1e). We then modified the stimulus in Fig. 1d to that in Fig. 1f so that the outer oblique rectangles were darker than the background while the X-shaped elements (inner oblique rectangles) remained lighter than the background. This set up a condition where the outer rectangles had opposite contrast-polarity relative to the background compared to the inner rectangles. With this opposite contrast-polarity condition, the inner rectangles within the black diamond frame were seen as stationary while the outer rectangles along each oblique axis simply compressed and expanded (arrows), i.e., no motion integration occurred (Fig. 1g). These two distinct motion percepts allowed us to determine whether the observer experienced amodal surface integration. Furthermore, by varying the width of the black diamond frame (occlusion gap size) in the same contrast-polarity condition