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PHENOMENAL REPORT

Learning a surfaces' shape from binocular disparity and perceiving it from shading

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Abstract

Some special images are known to produce a learning effect in 3D perception. This image represents a 3D scene but it has been degraded so that the 3D information of the scene can be perceived from the image only after the learning has taken place. This study presents a new type of image that is not degraded but can produce a learning effect in 3D perception. This image has a luminance gradient of shading that represents a saddle (hyperbolic) shape that is perceived on the basis of the gradient only after the saddle shape has been learnt on the basis of binocular disparity. This learning effect suggests that the 3D information can be transferred across depth cues in the visual system.

Keywords: *Eureka effect; depth perception; perceptual learning; shape from shading*

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Our 3D perception of a 3D scene from a 2D image is usually veridical and it is usually not affected by prior experience (e.g. Firestone & Scholl, 2016; Mischenko et al., 2020, see also Adams et al., 2004; Maltz et al., 2021). But, there are a few special images whose perception changes when an observer has had some prior learning experience, for example, the Gestalt completion task (Street, 1931), the Dalmatian by R. C. James (see Gregory, 1970), and the Mooney faces (Giovannelli et al., 2010; Mooney, 1957; Moore & Cavanaugh, 1998). Images like these are usually generated by degrading images of 3D scenes so that an observer cannot usually see anything meaningful in the images when they are first seen but they can be seen from the degraded images after the original undegraded images have been seen by the observer.[1] The visual system could learn either (1) the relationship between the degraded images and the undegraded images that can induce the perception of the 3D scenes, or (2) the relationship between the degraded images and the perception of the 3D scenes by bypassing the undegraded images.

Here, we present a new type of image that is not degraded but that can produce a learning effect in 3D perception. Look at Fig. 1a. A convex, or a concave shape usually can be perceived on the basis of the shading around the center of the image. Next, look at the images in Fig. 1b after fusing them stereoscopically. You should perceive a saddle (hyperbolic, see Erens et al., 1993) shape (Fig. 2, see https://osf.io/rnf59/ for more details) that is based on the binocular disparity around the center of the fused image. Once this has been done, the saddle shape will be perceived entirely on the basis of the shading in Fig. 1a and b.[2] This learning effect on the perceived depth

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[1] Such a quick effect of a short experience may also be referred to as perceptual priming. The difference between priming and learning can depend on the procedure of studies testing these phenomena but the difference is not considered in this study (see Wiggs & Martin, 1998 for a discussion about a common neural mechanism behind them).

[2] This learning effect in Fig. 1 was tested in two sessions with four observers in Russia, six observers in Armenia, and 30 observers in Japan. All of the observers were naïve. They were not informed about the purpose of the study or the process of generating visual stimuli. The viewing duration was not limited and the observer could report their perception without any time pressure. The learning effect was considered to be observed by an observer (1) if the observer did not perceive the saddle shape in their

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in Fig. 1a was induced by the 3D information that was based on the binocular disparity.

The luminance gradient is Lambertian shading (Lambert, 1760/2001) of the shape that is represented by the binocular disparity and the Lambertian law of shading can be an important condition for obtaining the learning effect. The Lambertian law of shading can be violated by inverting the luminance gradient of shading of a 3D shape. The learning effect was not clearly observed from an image of the saddle shape with inverted shading (Fig. 3).[2] This difference of the learning effect between Lambertian shading and inverted shading suggests that the Lambertian law of shading is important for the learning effect. Note that it is also difficult to perceive a 3D shape from its image with inverted shading (Johnston et al., 1992). This common trend between the learning effect and 3D shape perception from shading suggests that the learning effect is perceptual rather than entirely a response bias.

Some individual differences were observed in this study (see Mollon et al., 2017 for a review of individual differences in visual perception). There were observers who could not perceive the saddle shape in their binocular observations of the stimuli in Fig. 1. It is worth pointing out that perceiving such a complex shape from a random dot stereogram is difficult and can involve a different learning process (Frisby & Clatworthy, 1975; Ramachandran, 1976). A few observers could see the saddle shape in their initial monocular observations of the stimuli. It is reasonable to consider that the perceived shape in the initial observations could also be affected by the observers' prior experience before their participation in the study because the reported phenomenon itself is the effect of the experience of seeing the saddle shape. There can also be an individual difference in the long-lasting effect of the learning. The authors of this study tested themselves in a pilot study around 20 years ago, in which both learned the saddle shape perception. The first author has seen the stimuli intermittently after the pilot study and he can always see the saddle shape. The second author could not see the saddle shape after 20 years but he re-learned it. These individual differences can be attributed to the experience of the individual observers but also to genetic factors.

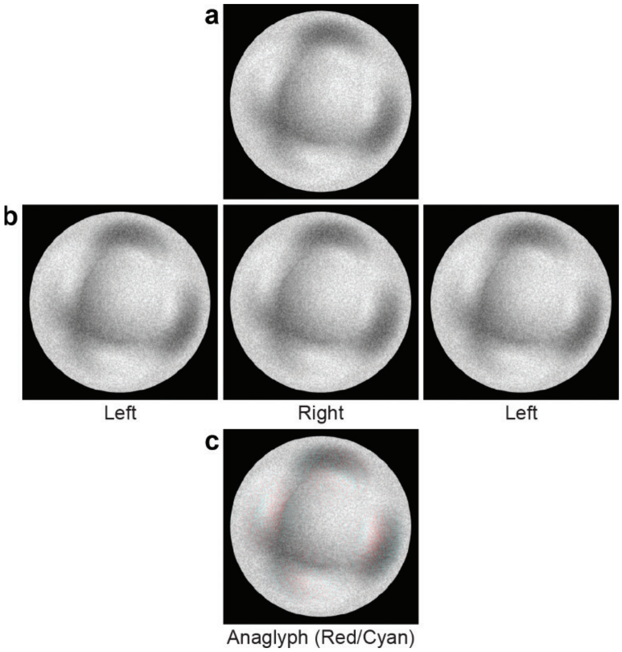

Fig. 1. Set of images that can produce a learning effect in 3D perception. (a) The central part of this image is usually perceived as a convex or a concave shape before learning and as a saddle (hyperbolic) shape after learning. A noise pattern was also added to the image in (a) for consistency with the images in (b) and (c). (b) Stereoscopic images with the luminance gradient of (a) from which a saddle shape (Fig. 2) is perceived on the basis of the binocular disparity. The left and central images are used for an un-crossed fusion and the central and right image are used for a crossed fusion.[3] A noise pattern was added to enhance the stereo correspondence between the images. The noise patterns in (a) and (b) were different from one another to avoid the learning effect based on the noise patterns alone (see O'toole & Kersten, 1992; Ramachandran, 1976). (c) An anaglyph image of the saddle shape (Fig. 2) with the luminance gradient of (a). The left eye of an observer sees the image through a red filter and the right eye sees the image through a cyan filter.

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initial monocular observation of the stimuli, (2) if the observer perceived the saddle shape in their binocular observation, and (3) if the observer perceived the saddle shape in their second monocular observation after the binocular observation. Three out of the 30 observers in Japan reported that they perceived the saddle shape in their initial monocular observations of the stimuli. Twenty-two (3 in Russia, 6 in Armenia, and 13 in Japan) out of the remaining 37 observers perceived the saddle shape in their binocular observations. After the binocular observations, 15 (3 in Russia, 3 in Armenia, and 9 in Japan) out of these 22 observers (68%) showed the learning effect. Any of the observers who did not perceive the saddle shape in their binocular observations did not perceive the saddle shape in their second monocular observations.

The same 40 observers were also tested with Fig. 3. The learning effect was observed from six (one in Armenia and five in Japan) observers out of 24 (three in Russia, six in Armenia, and 15 in Japan) observers (25%) who satisfied conditions that they did not perceive the saddle shape in their initial monocular observations and that they perceived the saddle shape in their binocular observations. Any of the observers who did not perceive the saddle shape in their binocular observations did not perceive the saddle shape in their second monocular observations. There were 21 common observers who satisfied these conditions for both Figs. 1 and 3. The learning effect was observed more frequently (the McNemar exact test, $\chi^2(1) = 9$, $p = 0.0027$) from Fig. 1 (14/21) than from Fig. 3 (5/21). These tests were conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

[3] The depth reversal (red areas are further and blue areas are closer) of the saddle shape in Fig. 2 could be perceived on the basis of binocular disparity when the right and central images in Fig. 1b are used for an un-crossed fusion and the central and left images in Fig. 1b are used for a crossed fusion. This depth-reversed shape is also consistent with the shading of Fig. 1a when the shape is illuminated from a direction that was slanted by 30° from the normal to the frontoparallel plane and that was tilted by 30° to the right of the vertical plane from below. So, it is possible to learn the relationship between the shading of Fig. 1a and the depth-reversed shape.

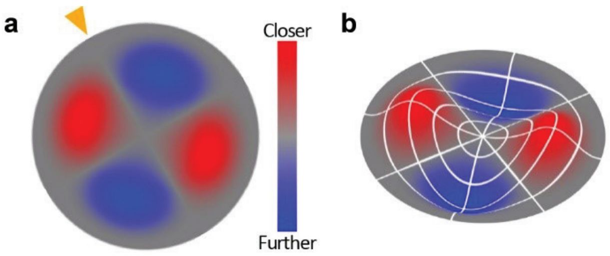

Fig. 2. (a) A distribution of the simulated depth of an object that was used to generate images in Fig. 1 (see https://osf.io/rnf59/ for more details). The depth is represented by color. The central part of the object's surface is saddle-shaped (hyperbolic). The images in Fig. 1 were generated by simulating that this object was being illuminated from above-left (Ramachandran, 1988; Sun & Perona, 1998), a direction that was slanted by 30° from the normal to the frontoparallel plane and that was tilted by 30° to the left of the vertical plane from above. The luminance polarity is consistent with the simulated saddle shape under the light from above (or above-left) assumption (Ramachandran, 1988; Sun & Perona, 1998) and the luminance gradient of the resulted image represents Lambertian shading (Lambert, 1760/2001) of the simulated saddle shape. (b) A diagonal view of the object.

Both the empirical and genetic factors can affect depth perception in the visual system, such as stereo acuity (Li et al., 2024) and cue combination (Cesanek & Domini, 2019; Ernst et al., 2000). These factors of the individual differences are not contradictory to one another and they can coexist. There can be multiple mechanisms behind the individual differences of the learning (see Dosher & Lu, 1998 for a discussion about multiple mechanisms of perceptual learning). These mechanisms behind the individual differences can also be relevant with other visual phenomena. Then, the mechanisms can be discussed by finding its correlation with other perceptual phenomena (Yang et al., 2020, see also Coren & Porac, 1987; Grzeczkowski et al., 2017; Kobayashi & Shapiro, 2025; Makowski et al., 2023; Tulver, 2019 for relevant discussions). Note also that Cognitive and social factors may also contribute to the individual differences of the learning (Dale et al., 2021).

The observed learning effect suggests that the visual system learned the relationship between the 2D image and the 3D information. This would mean that the visual system can memorize the 3D information. It could also be interpreted to mean that the visual system learned about the organization of the luminance gradient of the shading in the image. There are multiple local extrema in the luminance gradient shown in Fig. 1a so the visual system would need to segment the gradient for perceiving the surface shape from the shading (Nefs et al., 2005). This organizing process in the gradient could be influenced by the 3D information contained in the binocular disparity. This would mean that the visual system transfers the 3D information across these depth cues and that the cues can interact with one another.

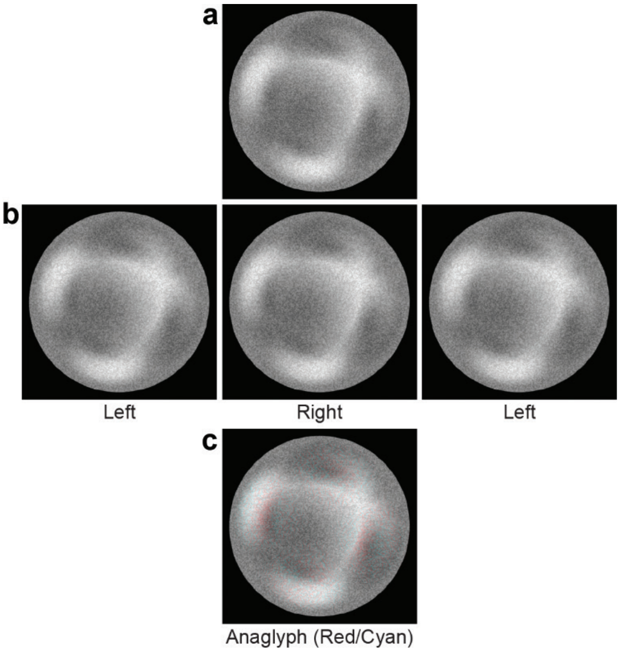

Fig. 3. Set of images that can hardly produce any learning effect in 3D perception. (a) This image has the same luminance polarity as the image in Fig. 1a but its luminance gradient is different from the luminance gradient of the image in Fig. 1a. The image was generated by simulating that the saddle shape (Fig. 2) was being illuminated from below-right and by inverting the luminance gradient in the image (see Johnston et al., 1992 for another study using the same image generation process). The luminance polarity of the resulted image is consistent with the simulated saddle shape under the light-from-above (or -above-left) assumption (Ramachandran, 1988; Sun & Perona, 1998) but the luminance gradient of the image cannot be Lambertian shading of the saddle shape (Lambert, 1760/2001). A noise pattern was also added to the image in (a) for consistency with the images in (b) and (c). (b) Stereoscopic images with the luminance gradient of (a) from which a saddle shape is perceived on the basis of the binocular disparity. (c) An anaglyph image of the saddle shape (Fig. 2) with the luminance gradient of (a). The left eye of an observer sees the image through a red filter and the right eye sees the image through a cyan filter.

Conflict of interest and funding

The Authors declare no conflict of interest.

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