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A computational model of perceptual grouping and 3D surface completion in the mime effect

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Abstract

We propose a computational model of perceptual grouping for explaining the 3D shape representation of an illusory percept called "mime effect." This effect is associated with the generation of an illusory, volumetric perception that can be induced by particular distributions of inducing stimuli such as cones, whose orientations affect the stability of illusory perception. The authors have attempted to explain the characteristics of the shape representation of the mime effect using a neural network model that consists of four types of cells–encoding (E), normalizing (N), energetic (EN), and geometric (G) cells. E cells represent both the positions and orientations of inducing stimuli and the mime-effect shape, and N cells regulate the activity of E cells. The interactions of E cells generate dynamics whose mode indicates the stability of illusory perception; a stable dynamics mode indicates a stable perception, whereas a chaotic dynamics mode indicates an unstable perception. EN cells compute the Liapunov energetic exponent (LEE) from an energy function of the system of E cells. The stable and chaotic dynamics modes are identified by strictly negative and strictly positive values of LEE, respectively. In case of stability, G cells perform a particular surface interpolation for completing the mime effect shape. The authors confirm the model behaviour by means of computer-simulated experiments. The relation between the model behaviour and the shape representation in the human brain is also discussed.

Keywords: Mime effect; Surface completion; Liapunov exponents; Bifurcation; Non-Classical Receptive Field

1. Introduction

The human visual system integrates bottom-up and top-down processes in order to analyse shapes. Bottom-up processes segment the observed scenes, while top-down processes optimize object representations (Li, Piech, & Gilbert, 2004). Perceptual grouping is a major feature of bottom-up/top-down interaction, involving the grouping of individual items into fewer coherent objects. In addition to the surface completion process (or filling-in), perceptual grouping yields illusory percepts (Mendola, 2003, Chap. 3); (Meyer & Petry, 1987, Chap. 1). Neurophysiologists have found evidences of the brain ability to group parallel lines into textures (Murray et al., 2002). Further, psychologists (Pragnanz laws) and computational theorists (Fiorentini, Baumgarther, Magnusson, Schriller, & Thomas, 1990, Chap. 7); (Marr, 1982); (Shapley, Caelli, Grossberg, Morgan, & Rentschler, 1990, Chap. 15) have also investigated the grouping process (Robertson, 2003).

The mime effect is one of the illusory phenomena induced by such grouping and completion processes (Zhang, Idesawa, & Sakaguchi, 1997, 1998). This effect is associated with the generation of an illusory, volumetric percept by proper distributions of elongated inducers such as cones and cylinders. Moreover, the stability of this effect depends on the orientations of the inducers (see the next section for details).

We hereby propose a computational model of perceptual grouping for explaining the shape representation of the mime effect. This model consists of four types of cells that interact to generate the dynamics associated with the stability of the mime effect and to form the surface representation of the induced shape. An indicator called Liapunov energetic exponent (LEE) can be used to determine the mime effect stability from the dynamics mode. We display the shape obtained through computer-simulated experiments and analyse the bifurcation of

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Mathematical Symbols

$\mathrm{E}_i(k)$	Activation of the ith encoding cell at time k
$\mathrm{N}_i(k)$	Activation of the ith normalizing cell at time k
$(C, \overrightarrow{O})$	Inducer with position C and orientation $\overrightarrow{O}$
$(S, \overrightarrow{O})$	Patch centred on S with normal vector $\overrightarrow{O}$
$\delta_i(C, \overrightarrow{O})$	1 if $(C, \overrightarrow{O}) = (C_i, \overrightarrow{O_i})$, otherwise, 0
$a_\mathrm{E}, b_\mathrm{E}, c_\mathrm{E}, d_\mathrm{E}, a_\mathrm{N}, b_\mathrm{N}, c_\mathrm{N}, d_\mathrm{N}$	Constants
β_{ij}	Connection weight between E_i and E_j
$\Psi(k)$	Energy function at time k
Ω	Bifurcation parameter
ρ	Parameter of shape form
$\widehat{B_1 S_0 A_1}$	Geometrical angle between lines $(S_0 B_1)$ and $(S_0 A_1)$
$(\widehat{\overrightarrow{O_i}, \overrightarrow{O_j}})$	Geometrical angle between vectors $\overrightarrow{O_i}$ and $\overrightarrow{O_j}$

the dynamics that is important for controlling the dynamics mode. We also discuss the biological plausibility of our model.

2. Problem with mime-effect shape representation

The mime effect was discovered by Idesawa and his colleagues (Zhang et al., 1997, 1998) (Fig. 1.a); in this effect, a three-dimensional (3D) illusory object can be perceived from a set of suitably arranged inducing stimuli. The most important feature of this effect is that people can perceive a volumetric object filled with a transparent medium that is characterized by its brightness and colour. The inducers should comprise elongated 3D objects (such as cones, cylinders and trapezoids) that are suitably arranged in their positions and orientations. In order to induce the mime effect, three classes of inducers specified by their positions – front, back and side – are required. The front inducers support the volume of the illusory object and the side inducers bound its space, while the back inducers help determine the transparency. When these three classes of inducers are employed, the distribution of inducer orientations affects the stability of illusory perception: the mime effect is stably perceived if the inducer orientations coincide with those of the normal vectors of the object surface formed by the mime effect, while the stability is deteriorated if the inducer orientations deviate from the normal vectors (see Fig. 1.a–c). It has also been reported that illusory perception is enhanced when the inducers move over the surface of the object (Uchida & Idesawa, 2002a, 2002b).

In this article, the authors focus on the following two questions;

1. How do inducer representations interact and determine the stability of the mime effect?
2. How is the shape of the mime effect completed?

The authors have constructed a neural network model to answer these questions. Before going into the details of the proposed model, we would like to define some symbols to represent the 3D structures.

The mime effect used in the present research is induced by a spherical distribution of fixed inducers (the centres of the

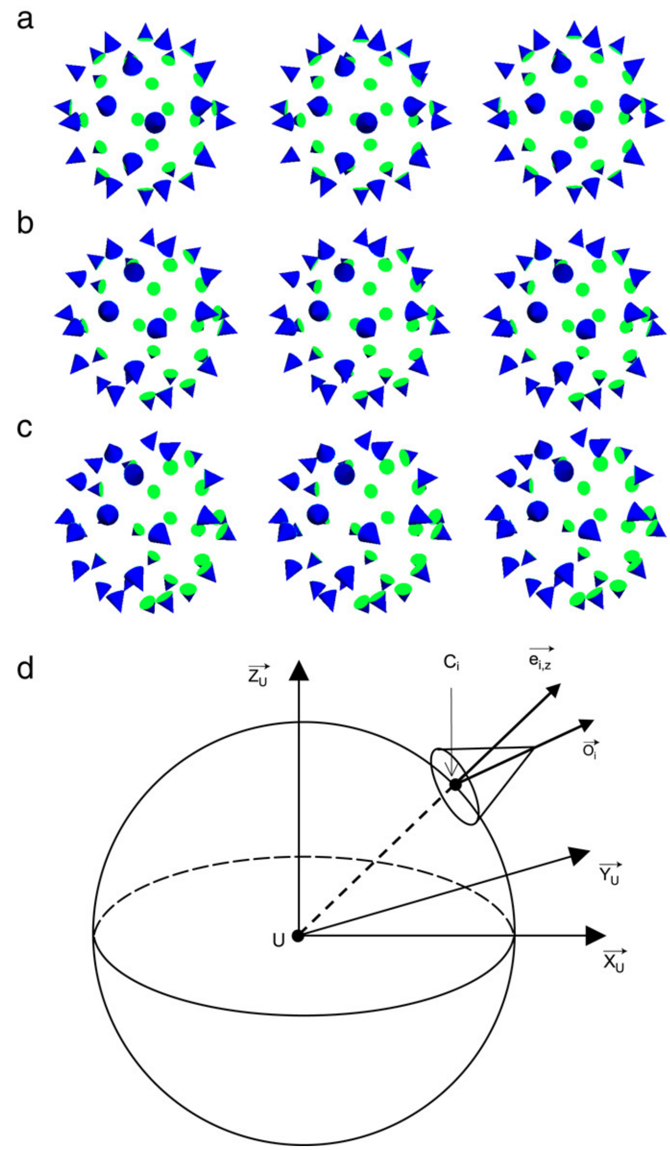

Fig. 1. Mime effect. Mime effect generated by a typical stereoscopic pair of spherical distribution of cones. The volume in scene (a) is bright. The inside of the sphere is filled with a transparent medium. The quality of perception decreases in (b) when cone orientations $\overrightarrow{O_i}$ are deviated from the vectors $\overrightarrow{e_{i,z}} = \frac{\overrightarrow{\mathrm{UC}_i}}{\mathrm{UC}_i}$, which are normal to the sphere at C_i (d), and the mime effect disappears beyond a deviation threshold (c). The positions C_i are relative to the object-centred referential $R(U, \overrightarrow{X_U}, \overrightarrow{Y_U}, \overrightarrow{Z_U})$, where U is the centre of the sphere.

inducer bases are located on a sphere). The shape of the mime effect is the illusory sphere that bounds the transparent volume. Each inducer can be specified by the position of its basis centre C_i and its orientation $\overrightarrow{O_i}$ ($\overrightarrow{O_i}$ is parallel to the inducer basis normal vector). The coordinates of C_i are relative to an orthonormal referential $R(U, \overrightarrow{X_U}, \overrightarrow{Y_U}, \overrightarrow{Z_U})$, where U is the center of the sphere, $\overrightarrow{Z_U}$ and $\overrightarrow{X_U}$ define the frontal plane, and $\overrightarrow{Y_U}$ is the normal to the frontal plane (inward). The deviation of the orientation $\overrightarrow{O_i}$ is expressed through the elevation θ and the azimuth φ, which are generally used to determine $\overrightarrow{O_i}\,(\theta_i, \varphi_i)$ in the orthonormal referential $R_i(C_i, \overrightarrow{e_{i,x}}, \overrightarrow{e_{i,y}}, \overrightarrow{e_{i,z}})$. Here,