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The Ebbinghaus illusion in contrast-defined and orientation-defined stimuli

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ABSTRACT

In the retinal image of the natural world, edges and shapes can be defined by first-order attributes, such as luminance, and second-order attributes, such as contrast and texture. Previous studies have suggested that, in the human visual system, these attributes are initially detected separately and integrated later. Thus, comparing the strength of different geometrical optical illusions in stimuli, in which different elements are defined by the same or different attributes, is helpful to investigate at which stage the underlying mechanism of the illusion is located. We investigated whether there is a single common mechanism underlying the Ebbinghaus illusion in stimuli defined by different attributes. We used the traditional Ebbinghaus (Titchener) illusion figure: a target disk surrounded by smaller or larger inducer disks. The background and stimuli consisted of sine-wave gratings. We manipulated the luminance, contrast, and grating orientations of the target disk and inducer disks to create stimuli defined by each of these attributes. We then examined whether the illusion occurred in stimuli defined by each single attribute and in compound stimuli, in which the target and inducers were defined by different attributes. We found that the Ebbinghaus illusion occurred with the same strength in stimuli defined by all three attributes. We also found an asymmetry, such as the second-order inducers affected the first-order target less than they affected the second-order targets, but the first-order inducers affected all targets similarly. Our findings suggest that different attributes are likely to be integrated into a cue-invariant shape representation prone to the Ebbinghaus illusion. However, first-order and second-order stimuli may differently contribute to the quantitative aspect of the illusion, resulting in the asymmetric illusion strength.

1. Introduction

In addition to first-order information, such as luminance variations, natural images contain abundant second-order information that can be detected by the human visual system (Schofield, 2000). Second-order information encompasses a wide range of stimulus attributes, including spatial variations not in mean luminance but in local contrast and texture, relative motion, and binocular disparity. While the first-order attributes can be conveyed by a single point of an image, detection of the second-order attributes requires comparing more than one point (Cavanagh & Mather, 1989). Also, the second-order attributes cannot be detected by linear Fourier analysis mechanisms, as opposed to the first-order attributes (Chubb & Sperling, 1988). The human visual system can detect and process both first- and second-order information. A conventional view supported by numerous neurophysiological studies is that these two types of information are detected by separate parallel channels and are, at least partly, integrated at a higher stage (Baker & Mareschal, 2001 for review).

Psychophysical studies also support the initial separate processes for first- and second-order information in both static and motion stimuli. Sensitivity to contrast-modulated gratings is lower than that to luminance-modulated ones, although the sensitivity curves for these two types of grating have similar dependencies on spatial frequency (Schofield & Georgeson, 1999). There is order-specific facilitation within each stimulus type, but no cross-facilitation between luminance and contrast modulations. Different types of second-order stimuli, such as contrast and orientation modulations, do not facilitate the detection of each other (Kingdom, Prins, & Hayes, 2003). For motion, alternating frames of luminance and contrast modulations do not integrate to enable motion correspondence across these frames, implying separate processing of first- and second-order motions (Ledgeway & Smith, 1994). On the contrary, alternating frames of different types of second-order modulations can integrate for motion detection. Thresholds of direction identification for luminance-modulated and contrast-modulated drifting gratings are elevated after adaptation to moving stimuli of the same order, but effects of adaptation scarcely transfer between first- and second-order stimuli, consistent with separate processing (Nishida, Ledgeway, & Edwards, 1997).

On the other hand, first- and second-order attributes can interact with each other at later stages. For example, in an orientation detection

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task, the first-order carrier and second-order envelope of a grating can interfere with each other (Dakin, Williams, & Hess, 1999). In some cases of such integrations, each attribute plays its own specific role, thus the identity of each should be preserved. Examples of such integrations come from studies on depth perception: an equiluminant color grating combined with a luminance grating enhances depth perception when they have different orientations, but suppresses it when they share the same orientation and phase (Kingdom, 2003; Kingdom, Rangwala, & Hammamji, 2005). A color grating can also yield phase-dependent depth enhancement when combined with a grating defined by both luminance and orientation modulations (Kingdom, Wong, Yoonessi, & Malkoc, 2006). Other second-order attributes can also help to construct depth. When contrast and luminance variations are positively correlated, they usually signal a shading cue, but when they are negatively correlated, they are more likely to signal a change in object material; accordingly, noise gratings modulated in both luminance and contrast, trigger a strong sense of depth when luminance and contrast share the same peak, but not when their peaks are misaligned (Schofield, Hesse, Rock, & Georgeson, 2006; Schofield, Rock, Sun, Jiang, & Georgeson, 2010).

These studies show that when different attributes (luminance, color, contrast, and orientation modulations) interact with each other, they can play distinct and unique roles, such as enhancing the sense of depth or signaling changes in material. However, in other cases, all types of attributes play the same role, e.g., defining an edge or a shape. In these cases, similar underlying mechanisms might exist separately for each attribute, or all attributes may be completely integrated and then processed by a single shared mechanism. It is conceivable that the former is relevant at early stages of processing while the latter at later stages. For example, Georgeson and Schofield (2002) showed complete transfer of the tilt aftereffect between first- and second-order stimuli. However, they also showed that the identity of each attribute was not lost, concluding that separate channels process the first- and second-order attributes at an earlier stage and by a common, or pooled, adaptation mechanism at a later stage. Transfer of the tilt aftereffect between different types of second-order stimuli also occurs but incompletely, suggesting only partial integration (Cruickshank & Schofield, 2005).

For luminance-defined (LD), contrast-defined (CD), and orientation-defined (OD) patterns, incomplete transfer of the motion aftereffect occurs from first- to second-order stimuli and from CD to OD patterns, but not from second- to first-order patterns and from OD to CD patterns (Schofield, Ledgeway, & Hutchinson, 2007). Given partial transfer, LD, CD, and OD stimuli may be processed within distinct mechanisms each adaptable to motion, but the existence of transfer implies that all three attributes may share a common adaptation mechanism with a hierarchy of processing in order from LD to CD to OD stimuli, where attributes extracted earlier affect attributes extracted later, but not vice versa.

On the other hand, some more intricate aspects of shape perception, such as the interpretation of occluding surfaces and the sense of depth in the figures such as the Necker cube, are similar among different attributes, namely luminance, color, and texture, suggesting that at processing stages pertinent to these aspects, some attributes are completely integrated into a single cue-invariant representation of shape and processed within a single shared mechanism (Cavanagh, 1987). To know whether shapes are processed by the same mechanism irrespective of defining attributes, a promising strategy is to examine whether a certain shape illusion arises in stimuli defined by different attributes. For example, Hamburger, Hansen, and Gegenfurtner (2007) showed that many geometrical optical illusions occurred in equiluminant color stimuli and had the same magnitude as in LD stimuli, claiming that stimuli defined by luminance and color are processed by a common underlying mechanism for these illusions. The illusions these researchers investigated include the Ebbinghaus (or Titchener) illusion, in which a central disk surrounded by smaller disks appears larger than the same central disk surrounded by larger disks—in our study, we took advantage of the very powerful effect of this illusion as a tool to investigate cross-attribute interactions in shape processing.

As for second-order attributes, in an early report by Ramachandran and Anstis (1990), who anecdotally mention that the Ebbinghaus illusion might occur in stimuli defined by relative motion, no measurement was made, let alone comparison with that seen in first-order stimuli. Cavanagh (1989) reported the Zöllner and horizontal-vertical illusions of comparable illusion strength in stimuli defined by such attributes as luminance, color, texture, relative motion, and binocular disparity. However, the Zöllner illusion, but not the horizontal-vertical illusion, became weaker in compound stimuli that comprised shape elements defined by a combination of different attributes. It was concluded that different attributes are processed within separate but similar underlying mechanisms for the Zöllner illusion to occur, but the horizontal-vertical illusion is likely to arise owing to the stage of cue-invariant shape processing. In another study by Papathomas, Feher, Julesz, and Zeevi (1996), the Ebbinghaus illusion was examined in stimuli defined by both luminance and binocular disparity (hence monocularly visible) and stimuli defined solely by binocular disparity (hence cyclopean). The illusion was weaker for the cyclopean stimuli than for the monocularly visible ones. Moreover, the illusion was weaker in compound stimuli, especially when the inducer disks were cyclopean, and the target disk was monocularly visible. These results are more consistent with distinct mechanisms in similar processing principles implemented within separate channels, rather than with a single shared mechanism working on an integrated cue-invariant shape representation. However, as the authors note, the monocularly visible stimuli had two components (with luminance and disparity corresponding to first-order and second-order attributes respectively), thus more information was available, which might have contributed to the difference in illusion strength. Furthermore, intrusion of first-order artifact from potential crosstalk cannot be completely denied, considering the specifications of the monitor and liquid-crystal shutters used to deliver binocular images.

Therefore, in this study, we aimed to clarify whether the Ebbinghaus illusion has the same magnitude in stimuli defined by a first-order attribute, stimuli defined only by a second-order attribute without any first-order cues, and compound stimuli in which the attribute of the target disk and those of the inducer disks differ. Contrast and orientation modulations are the easiest to isolate from luminance modulations, therefore we used LD, CD, and OD stimuli. Using two different second-order attributes, i.e., CD and OD also allowed us to test whether different second-order attributes are processed by single or separate mechanisms .

2. Methods

2.1. Observers

The first author (O1) and five naïve adults (three females and two males) participated. All had normal or corrected-to-normal visual acuity with no astigmatism. Our study followed the Declaration of Helsinki guidelines and was approved by the institutional ethics committee of the Graduate School of Humanities and Sociology at the University of Tokyo. We obtained written informed consent from all participants prior to the experiment.

2.2. Apparatus

Stimuli were generated by a computer (Apple Mac Pro) using MATLAB (The MathWorks) programming software and the Psychophysics Toolbox extensions (Brainard, 1997; Pelli, 1997) and presented on a 22-inch liquid crystal monitor (Eizo FlexScan SX2262W) with a resolution of 1920 × 1200 pixels and a refresh rate of 60 Hz that was driven by an ATI Radeon HD 5770 graphics card calibrated for gamma correction to linearize the luminance output as measured with a photometer (Cambridge Research Systems ColorCAL). The experiment