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The neural correlates of vertical disparity gradient and cue conflict in Panum's limiting case

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A B S T R A C T

Although Panum's limiting case has been extensively researched, only recently has it been discovered that in addition to horizontal disparity, the final perception of depth is influenced by (i) the vertical disparity gradient and (ii) the degree of cue conflict between 2D and 3D shapes. The present study examines the neural correlates of the two factors, using EEG while observers viewed several versions of stereoscopic stimuli, which depicted Panum's limiting case. In these patterns the vertical disparity gradient was varied from 0.1 to 0.6, while the degree of cue conflict was manipulated from low to high. The ERP data showed that the amplitude of the N170 component (exogenous) was modulated by the vertical disparity gradient and cue conflict. In contrast, the N270 component (endogenous) was modulated by cue conflict only. Such findings demonstrate that both factors affect the perception of depth in Panum's limiting case, but at different stages: the vertical disparity gradient at an early stage of processing (N170) and cue conflict at two stages (N170 and N270). Hence, vertical disparity gradient is related to low-level visual stimulus parameters and can modulate exogenous component, while cue conflict is related to both exogenous and endogenous components.

1. Introduction

One of the most intriguing characteristics of the human visual system is stereopsis. The factors that influence stereopsis are important to examine in binocular depth perception. Since Julesz's (1971) random dot stereograms, research on stereoscopic vision focused heavily on horizontal disparity. It is generally believed that the depth in stereopsis is specified by the binocular disparity (Wheatstone, 1838). Recently, however, there has been a growing realization that this may be too narrow a view and the disparity can't explain many phenomena in stereopsis (Harris & Wilcox, 2009; Wardle & Gillam, 2013). Therefore, researchers try to investigate the other factors that impact depth perception.

Panum's limiting case is the most basic and typical stimulus configuration examined in the field of binocular stereopsis (Shimono, Tam, & Nakamizo, 1999). It generally refers to the stereogram which presents one feature to one eye and two features to the other producing a three-dimensional percept (Ono, Shimono, & Shibuta, 1992; Panum, 1858). However, there is a long contrary to the depth perception of Panum's limiting case. Even under the same disparity, some results explained by double fusion theory, but some was supported by single fusion hypothesis (Frisby, 2001; Gillam, Blackburn, & Cook, 1995; Wang, Wu, Ni, & Wang, 2001). The researchers have gradually begun to investigate the other factors which affect the depth perception in Panum's limiting case, besides the disparity. Until recently, Li et al. (2012) showed that this discrepancy could be explained by the fact that there are at least two additional factors contributing to the percept of depth in Panum's configurations. The results showed that in addition to horizontal disparity, the final percept of depth is influenced by two important factors: (i) the vertical disparity gradient along the stimulus; (ii) the degree of cue conflict between 2D and 3D shape.

The vertical disparity gradient can be defined as the ratio between relative disparity difference (i.e., absolute difference between the minimum and maximum disparity) along any pair of dichoptic features and their vertical separation (see the details in Burt & Julesz, 1980; Bülthoff, Fahle, & Wegman, 1991). Those studies have shown that binocular fusion is not only limited by the absolute disparity values, but also by the disparity gradient separating image points (Burt & Julesz, 1980; Devisme, Drobe, Monot, & Droulez, 2008). Moreover, the cue conflict refers to the

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2D retinal images cues which is inconsistent with the 3D interpretation cues, for example, shape and motion (Allison & Howard, 2000). Note that cue conflict between 2D vs 3D shapes refers to the inconsistency between the 2D shape signaled by monocular shape information and 3D shape signaled by binocular disparity (see the details in Li et al., 2012).

However, the aforementioned investigations of Panum's limiting case have focused primarily on behavioral results which can only provide the final 3D percepts of the participants, but have not provided insight into the underlying neural processes (i.e., time-course) associated with both factors impacting Panum's limiting case. Moreover, most of previous ERP studies focused primarily on the time-course of disparity processing (Cottereau, McKee, & Norcia, 2014). To our knowledge, no study to date has examined the electrophysiological correlates associated with both vertical disparity gradient and cue conflict in the depth processing of Panum's limiting case. The strength for using event-related potential (ERP) technique is that it can provide a direct and 'real time' index of neuronal activities at a millisecond scale of resolution and is ideally suited to examine the rapidly changing patterns of brain activities that underlie human binocular perception (Dima, Dillo, Bonnemann, Emrich, & Dietrich, 2011). Therefore, the purpose of the present study was to investigate whether the relatively early ERP components are related to these two determinants (vertical disparity gradient and cue conflict) of depth perception in Panum's limiting case.

Previous literatures have shown that at least two ERP components are related to stereopsis, the N170 and N270 (Fahle, Quenzer, Braun, & Spang, 2003; Spang, Gillam, & Fahle, 2012). It has been established that early visual ERP components are strongly modulated by low-level stimulus properties, such as size, contrast, luminance and spatial frequencies (Busch, Debener, Kranczioch, Engel, & Herrmann, 2004; Rossion & Jacques, 2008). The visual N170 is a negative waveform with an occipital-temporal scalp distribution that peaks between 150–200 ms post-stimulus (Jacques & Rossion, 2006). It is thought to be in the family of exogenous components which is driven by bottom-up physical features of the stimulus (Csibra, Kushnerenko, & Grossmann, 2008). Not only is the N170 elicited by faces, it is also associated with certain cognitive processes, such as attention and cognitive processes of Gestalt perception (Conci, Tollner, Leszczynski, & Muller, 2011; Sadeh & Yovel, 2010). However, it remains unknown whether other cognitive processes, such as the identification of the vertical gradient disparity and cue conflict, can also modulate the N170 amplitude.

Another event-related potential component that has been investigated in stereopsis research is the N2. Within the N2 family of ERP components, the N270 has been shown to be elicited with stimuli that lead to fusion and the perception of depth (Spang et al., 2012). The N270 has also been demonstrated to be related to the conflict processing system and the evaluation of information discrepancy (Mao & Wang, 2008; Wang, Kong, Tang, Zhuang, & Li, 2000). For example, Wang et al. (2000) showed that an ERP component N270 is elicited on the human scalp post-stimulus onset when the stimulus attributes conflicted with the preceded one. But no electrophysiological study has investigated if N270 is modified by the cue conflict between 2D and 3D shape.

For the present study, event-related potentials (ERPs) were employed to explore the underlying neural processing associated with vertical disparity gradient and cue conflict in the perception of depth in Panum's limiting case configurations. In these patterns the vertical disparity gradient was varied between 0.1, 0.3, and 0.6, while the degree of cue conflict was manipulated between low, medium, and high. Based on the existing literature (Mao & Wang, 2008; Spang et al., 2012), we hypothesize that vertical disparity gradient, which mainly reflects low-level physical stimulus properties, will be most salient in the amplitude of N170. Moreover, the N270, which reflects conflict processing, will be modulated by the cue conflict between the 2D and 3D shape information.

2. Methods

2.1. Participants

Observers were recruited from Southeast University and paid for their participation. Prior to testing, all participants' stereopsis was assessed using the Stereo Titmus test (Stereo Optical, Chicago, IL). Observers were included in the study only if their stereoscopic acuity was at least 20 arc sec. Of 34 potential observers, 8 did not meet this criterion, resulting in a final sample of 26 participants, aged 21–33 years (14 females, 12 males). All had normal or corrected-to-normal vision and right-handed. Participants had no previous history of brain injuries, neurological or ophthalmologic problems and they were not under any medical treatment. Written informed consent was obtained from each participant once the study had been fully explained. This research followed the tenants of the Declaration of Helsinki.

2.2. Apparatus

Stereoscopic stimuli were generated on a G5 Macintosh computer with Matlab (MathWorks, Natick, MA) and the Psychtoolbox (Brainard, 1997; Pelli, 1997). Stimuli were presented on a pair of CRT monitors (ViewSonic G225f) arranged in a mirror stereoscope at a viewing distance of 48 cm. The resolution of the monitors was 1280×1024 pixels and the refresh rate was 100 Hz. At this resolution and viewing distance, each pixel subtended 1.89 arcmin. Observers used a chin and forehead rest to stabilize head position during testing. A keyboard was used to record responses. The EEG signals were recorded from 64 tin electrodes mounted on an elastic cap using the Neuroscan system (NeuroScan Inc., Herndon, VA, USA).

2.3. Stimuli

The stimuli used in this study were the similar three series of configurations used by Li et al. (2012), which they named the Frisby, Gilliam, and Wang configurations. Take the Gillam configuration series (shown in Fig. 1) as an example, two factors were varied based on the original Gilliam's arc stimuli: vertical disparity gradient and cue conflict. The stimuli in Frisby and Wang configurations series were similar to the Gilliam stimulus series except that the arc was replaced by wavy and oblique lines, respectively. The three series, which depicted Panum's limiting case, all included 9 (3 vertical disparity gradient $\times$ 3 cue conflict) experimental conditions.

Three values of vertical disparity gradient were used 0.1, 0.3, and 0.6, which were measured according to the definition of the vertical disparity gradient (Burt & Julesz, 1980). The manipulation of cue conflict between 2D and 3D shape was low, medium and high based on the results of Li et al. (2012). This study has shown that, from columns A to C depicted in Fig. 1, the degree of cue conflict increases from low to high (see the details in Part 1 of Supplementary Material).

2.4. Procedure

In the preliminary session, the observers viewed a series of the Panum's limiting case stimuli and were asked to report their percepts. During this training session, observers were given instructions which allowed them to classify their percepts as either