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Brain activation difference evoked by different binocular disparities of stereograms: An fMRI study

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ABSTRACT

The binocular disparity of two retina images is a main cue of stereoscopic vision. However, the global dependency between brain response and binocular disparity still remains unclear. Here, we used functional Magnetic Resonance Imaging (fMRI) to identify stereopsis-related brain regions with a modified Random Dot Stereogram (RDS) and plotted the activation variation curves under different disparity size. In order to eliminate the confounding shape difference between the stereogram and the plane, commonly seen in RDS, we modified the RDS to a checkerboard version. We found that V3A, V7 and MT+/V5 in dorsal visual stream were activated in stereoscopic experiment, while little activation was found in ventral visual regions. According to the activation trends, 13 subjects were divided into three groups: 5 subjects with turning points (a shift from increased to decreased activation), 5 subjects without turning points and 3 subjects with activation unrelated to disparity. We inferred that the dorsal visual stream primarily processes spatial depth information, rather than shape information.

1. Introduction

Binocular disparity, one of the most important cues of human stereopsis, refers to the difference between two retinal images seen by the left and right eyes [1]. It is important to understand the neural mechanisms of disparity-evoked stereopsis in both psychological research and ophthalmology clinical application [1,2]. Disparity size, which determines apparent depth, is an important entry point to reveal the mechanisms of stereoscopic vision.

Neuron-based studies on monkeys and cats provide some fundamental proofs that a large number of disparity-tuned cells exist in the visual cortex [3–11]. Their firing rates vary with disparities and different neurons generally have different preferred disparity ranges [5,12–17]. Some studies also found that regions such as the inferior temporal cortex (LOC) include neurons that respond to concave or convex surfaces selectively [18,19], which indicates a functional division for stereoscopic vision processing in the cortices exists.

Further, functional Magnetic Resonance Imaging (fMRI) studies have shown that dorsal visual cortices, particularly V3A, V5/MT and V7 [20–27], and some ventral visual regions, such as V4 and LOC [24,28,29], are important regions in stereoscopic vision processing. The dorsal and ventral visual streams are believed to play different roles in stereopsis processing. The dorsal visual regions process absolute disparity and stereoscopic depth identification, while the ventral visual regions process relative disparity and spatial shape recognition [28,30–34].

Several fMRI-based studies have specialized in the relationship between brain response and disparity size. Preston et al. and Minini et al., in 2008 and 2010, investigated this question respectively [24,25]. They found that the response of dorsal visual regions increased with the binocular disparity, while the response of ventral visual regions remained approximately unchanged. They inferred that stereoscopic vision was processed mainly in the

Abbreviations: fMRI, functional Magnetic Resonance Imaging; RDS, Random Dot Stereogram; LOC, Lateral Occipital Complex; LCD, Liquid Crystal Display; BOLD, Blood Oxygenation Level-dependent; EPI, Echo Planar Imaging; MNI, Montreal Neurological Institute and Hospital; FWHM, Full-width Half Maximum; GLM, General Linear Model; PARS, Population Average Landmark and Surface-based; ROI, Region of Interest.

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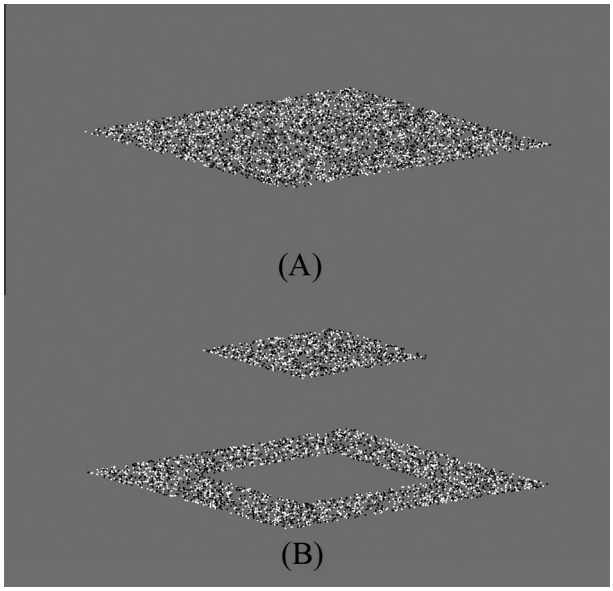

Fig. 1. The spatial structures of the general (A) zero binocular disparity Random Dots Stereogram (RDS) and (B) nonzero binocular disparity RDS are showed. There is an obvious square in (B) while not in (A).

dorsal visual stream, while the ventral visual stream extracts shape information from disparity images. However, the range of disparity they selected was both relatively small (smaller than 0.25° in Preston's experiment [24], smaller than 0.7° in Minini's experiment [25]). Therefore, the disparity-response curve in larger disparity remains unclear.

In light of this, we designed an fMRI-based experiment that included a more extensive binocular disparity range. Since there were additional shape differences between the Random Dots Stereograms (RDS) with zero disparity and nonzero disparity, cortical activations were not only from the designed stereoscopic depth differences but also from the confounding shape differences when comparing the two types of stimuli (Fig. 1). In order to verify further the functions of different regions, we modified the general RDS to eliminate confusion of shape (see Section 2). We hypothesized that cortical activity would not always increase with binocular disparity, and further, that the main cortices for processing stereoscopic depth were dorsal visual regions, rather than ventral visual regions consistent with Preston and Minini [24,25], so there would be no activation in the ventral visual stream. The results showed that most activated regions were localized in the dorsal visual stream and intensity of dorsal activations did not always increase with disparities.

2. Materials and methods

2.1. Subjects

Thirteen subjects (6 males and 7 females, 23–29 years) participated in the study. Experiments were approved by the local ethics committee and were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All subjects provided informed consent and received compensation for their participation. All subjects have normal or corrected-to-normal vision. No participant revealed any brain tissue abnormality on anatomical MRI. Before the main experiment all subjects passed a stereoscopic vision test (with a correct rate of 90% or better), in which they were instructed to watch a series of stereoscopic images and judge their types, concave or convex. All the materials were consistent with those used in fMRI experiment.

2.2. Stimuli

Based on the commonly used RDS, we developed a modified version, called checkerboard RDS. Each sub-image of the RDS was made up of interleaved black and white boxes ($3.12 \times 2.60°$) (similar to a checkerboard) which was constructed by random dots ($0.16 \times 0.13°$). All dots floated on the mid-gray background with 50% density (Fig. 2(A–C)). With this setting, both RDSs with zero disparity and nonzero disparity include a same shape which ensured that the only difference between them was stereoscopic depth. In order to fix the subject's eyes, a black cross ('+') was set in the center of RDS without disparity. All disparities were exerted to black boxes, while there were no disparities were applied for white boxes.

We employed a Liquid Crystal Display (LCD) monitor to present RDSs. The stimulus sequence was designed with E-prime 2.0 (Psychology Software Tools, Inc.). Subjects watched the screen through a mirror with a pair of red-blue glasses when lying in the MRI scanner. The color between the red-green glasses and the LCD monitor had been tested and calibrated.

2.3. Data acquisition

All MR images were acquired in a 3.0 T Philips (Philips Healthcare, Best, The Netherlands) Achieva MRI Scanner with a maximum gradient amplitude of 80 mT/m and a maximum slew rate of 200 mT/m/s. The Blood Oxygenation Level-dependent (BOLD) signals were obtained with Echo Planar Imaging (EPI) sequence (TE: 30 ms, TR: 2000 ms, Flip angle: 90°, voxel size: $3 \times 3 \times 3.5$ mm^3, 34 slices, no inter-slice skip, slice orientation: transverse, whole brain acquisition) was used to acquire functional images. A high resolution anatomical scan ($1 \times 1 \times 1$ mm^3) was also taken.

2.4. Experiment design

Seven conditions (six nonzero disparity conditions and one zero disparity condition) were set in our experiment. The six nonzero disparity conditions included 4 uncrossed (far) disparities (1.2, 0.9, 0.6, 0.3°) and 2 crossed (near) disparities (0.3, 0.6°). The crossed disparities larger than 0.6° were excluded as most subjects found it difficult to fuse the left and right images in this range.

The block design was used. A run contained five parts. Each part consisted of seven condition blocks and one control block. The seven conditions above were traversed randomly in the seven condition blocks, while the mid-gray background was displayed in the control block (rest block). Each block lasted for 20 s. The total duration was 800 s (400 volumes). In each condition block, six RDSs with the same binocular disparity but different box locations were presented randomly. In order to avoid the possibility of physiological noise, the presentation duration of each image was randomly selected from the time set (2200 ms, 2500 ms, 2900 ms, 3200 ms, 3400 ms and 4000 ms). Each image was followed by a 300 ms pause to buffer the sharp transition between two images.

The subject's task in the scanner was to perceive the disparity-defined depth of images shown on the screen. During the process, subjects were instructed to concentrate their attention and stare at the central cross to avoid eye motion. Soon after the scan, they were instructed to finish an inquiry on depth perception performance.

2.5. Data analysis

SPM8 (Functional Imaging Laboratory, Wellcome Trust Centre for Neuroimaging, Institute of Neurology, UCL) was used to preprocess and analyze the data. In preprocessing, the functional images of each subject were realigned to their mean image, followed by

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