Topographical representation of binocular depth in the human visual cortex using fMRI

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We used binocular stimuli to define how the visual location of stereoscopic depth structure maps topographically onto the human visual cortex. The main stimulus consisted of a circular disk of dots, most at zero-disparity, against which a single quadrant was defined with changing disparity (‘correlated’ disparity), and moved around the visual field. The second stimulus had exactly the same structure, except that the disparity in the quadrant was ‘anticorrelated,’ that is black dots in one eye were paired with white dots in the other. Unlike the correlated stimulus, this ‘anticorrelated’ stimulus did not lead to a perception of depth. The activation maps to these disparity stimuli are very similar to those produced using stimuli defined by luminance or motion. The lateral area of the occipital lobe showed the largest difference in response to correlated, as opposed to anticorrelated, disparity. This region included human MT/V5 and two areas, LO-1 and LO-2, recently defined as retinotopically distinct areas within area KO. All these areas, plus V3 and hV4, showed a significantly larger response to the correlated stimulus, compared to the anticorrelated stimulus. No other visual areas showed a significant difference in response. However, the responses to correlated disparity were significantly more reliable than those to anticorrelated in all areas, except V1. Although there are considerable differences in the experimental approach, our fMRI results are broadly consistent with primate neurophysiology showing responses to anticorrelated disparity in V1 neurons.

Keywords: functional magnetic resonance imaging, disparity, retinotopic mapping, depth perception, visual cortex


Introduction

The world around us appears in three dimensions despite the fact that our retinas are two-dimensional. One of the most consistent sources of information about the third dimension comes from the fact that our two eyes have slightly displaced viewpoints, leading to slightly different retinal images. While the neurophysiological evidence for neurons sensitive to these binocular disparities has been growing steadily since the 1960s, it was an area neglected for many years in the functional imaging literature. Over the past 5 or 6 years, however, fMRI studies of disparity processing in human subjects have begun to emerge.

The first study to systematically examine responses to stereoscopic depth was Backus, Fleet, Parker, and Heeger (2001), who parametrically varied the size of the disparity in the stimulus and related it to the change in BOLD activity. Comparing the response to a single depth plane with two transparent depth planes, Backus et al. found that area V3A showed the largest response of the early visual areas. This experiment was performed when identification of human visual cortical areas was at an early stage and, consequently, only areas V1, V2, V3, V3A, and MT+/V5 were considered for analysis.

Later studies identified other areas that appear to be particularly sensitive to stimuli defined by stereoscopic depth. Tsao et al. (2003) used a variety of depth stimuli to show that retinotopic areas V3A and V7, and two other areas, termed V4d-topo and caudal parietal disparity region (CPDR), gave the strongest activation in human subjects. Similarly, Tyler, Likova, Kontsevich, and Wade (2006) identified the kinetic occipital area (KO) as particularly responsive to disparity edges. This area appears to lie within the V4d-topo described by Tsao et al. Neri, Bridge, and Heeger (2004) found that while dorsal areas showed a large activation to absolute disparity, ventral areas were activated by both absolute and relative disparity, a result consistent with that of Gilaie-Dotan, Ullman, Kushnir, and Malach (2002) showing ventral stream activation to disparity-defined objects.

However, the study of Neri et al. (2004) used spatially unstructured stimuli, so depth edges were not present. Here we used a disparity-defined stimulus to produce a topographical map of activation to stereoscopic depth edges across the visual cortex. In retinotopic mapping, a large circular field is explored with a visual stimulus in the
shape of a wedge that rotates slowly and systematically over time about the center of the circle to new angular positions. Recording of the cortical activation as a function of time is used to map out the visual topography of cortical regions.

While there is general agreement about the retinotopic maps of early visual areas, based on their response to a wedge containing high luminance contrast (Dougherty et al., 2003), the determination of visual topography becomes more difficult in visual association areas. The labeling of an area as ‘retinotopic’ may depend critically on the stimulus used for mapping the area. Areas selective for more sophisticated features may require more sophisticated mapping stimuli. For example, the retinotopic map in MT/V5 is clearer if the stimulus used to map the region is moving rather than flashing. Similarly, several groups have shown that retinotopy can be observed in the intraparietal sulcus (IPS) when a task related to saccades or attention is used (Schluppeck, Glimcher, & Heeger, 2005; Sereno, Pitzalis, & Martinez, 2001; Silver, Ress, & Heeger, 2005; Swisher, Halko, Merabet, McMains, & Somers, 2007).

The topographic organization of visual cortex was measured with two binocular stimuli. The first stimulus was ‘correlated’: Here a circular field was filled with binocularly correlated dots of zero disparity, except for a wedge in which the disparity was non-zero and modulated between near and far over time. This stimulus generated distinct depth edges that defined the boundaries of the wedge. We compared the cortical maps generated with depth edges defined by binocular disparity against the maps generated with other visual stimuli, including the recently reported visual topography in some regions of the lateral occipital cortex (Larsson & Heeger, 2006).

We also used a second type of binocular stimulus, an ‘anticorrelated’ condition: Here the circular field contained binocularly correlated zero disparity dots as before, but the wedge contained binocularly anticorrelated dots. This stimulus has two useful attributes for our experiments. First, it does not produce a percept of a depth edge at the boundary of the wedge. Nonetheless, the perceptual segregation of the wedge is readily visible in the anticorrelated stimulus, so it can be used to test for a response to the visibility of the wedge, separate from the visibility of stereoscopic depth edges. Second, the statistics of the local retinal distributions of dots are identical for both correlated and anticorrelated stimuli.

The aims of this study were threefold: (1) to compare the cortical topography mapped using binocular depth against the topography from the longer-established luminance contrast and visual motion maps; (2) to investigate whether the topography is driven by the perception of depth (the correlated stimulus), or more basic disparity signals (the anticorrelated stimulus); and (3) to discover whether there are areas that are difficult to map with flashing checkerboard stimuli but are more evident with a disparity-defined stimulus.

Methods

Magnetic resonance data were acquired on a 3T whole body scanner (Varian Unity Inova, Palo Alto, CA), with a head insert gradient coil (Magnex, Oxford, UK) giving a maximum gradient strength of 34 mT/m. Five subjects aged 20–32 (all female) with normal or corrected-to-normal vision each participated in 4 scanning sessions: (1) to map the visual areas using a luminance stimulus (Retinotopic mapping), (2) mapping with a motion stimulus (Motion mapping), (3 and 4) mapping with a correlated stereoscopic stimulus (×5 scans) and with an anticorrelated stereoscopic stimulus (×5 scans).

Stimuli

Stimuli were presented on a VSG 2/5 graphics card (Cambridge Research Systems, Cambridge, UK) using an XGA projector (Sanyo, Watford, UK). Subjects viewed the stimuli using mirrors above their head to view a screen at their feet, giving a viewing distance of 300 cm. The resulting visual field measured 10.4° × 13.9°. Padding was placed around the head to reduce the amount of subject movement during the scanning session.

Luminance mapping

A black–white checkerboard (diameter 10°), contrast reversing at 8 Hz, was used to produce a retinotopic map using well established methods (DeYoe et al., 1996; Engel, Glover, & Wandell, 1997; Engel et al., 1994; Sereno et al., 1995). At any time, a 45° wedge of the checkerboard was visible, while the remainder of the screen was mid-gray with a small red fixation marker. After 4 s, the wedge position was incremented by 30°. Thus, a complete cycle consisted of 12 wedge positions and lasted 48 s. Six cycles were presented in a single run (288 s), and 4 runs were used to produce the activation map. Owing to small differences in stimulus parameters, we were unable to make a direct quantitative comparison of the BOLD responses to luminance checkerboards against those for motion and disparity. A pictorial representation of this stimulus is shown in Figure 1A.

Motion mapping

The motion stimulus consisted of a circular patch of diameter 8° filled with 500 black dots of size 5 × 5 pixels (0.09° × 0.09°) on a white background. A 90° wedge of dots was moving at any time. The movement of the dots in the wedge lasted for 4 s and alternated between inward and outward radial motion every second. After 4 s, the wedge position was moved by 45°, giving 8 stimulus positions in a single cycle lasting 32 s. Six cycles were presented in a run...
(192 s) and 5 scans were used to generate the map. An illustration of this stimulus is shown in Figure 1B.

Disparity mapping

Two images (5.4° diameter) were presented on the screen, each consisting of 200 white, and 200 black random dots of 4 × 4 pixels (0.07° × 0.07°). The exact pattern of dots changed every frame (60 Hz). Subjects free-fused the two images to produce a single stereoscopic patch of dots. For one subject, a baffle was used to block the monocular images. However, the other 4 subjects found this made fusion too difficult. At any one time a disparity of 0.07° was added to a 90° segment of dots. The disparity was such that the dots in that region appeared in front of the main pattern for 1 s, and then it was inverted to appear behind for 1 s. This was repeated such that the region was ‘active’ for a total of 4 s. After this time, the active region moved on 45° such that a complete cycle took 32 s. Six cycles were presented in each 192-s scan. When the stimulus was ‘correlated’, all black dots in the left eye were matched with black dots in the right eye. White dots were also matched in the two eyes. In the ‘anticorrelated’ case, each black dot (in the active quadrant) was paired with a white dot in the other eye, while the rest of the stimulus had correlated dots (black paired with black, white with white) of zero disparity. The lower row of Figure 1 illustrates these two different stimuli. Panels D and E can be free-fused to illustrate an example of the correlated case, while fusing panels E and F demonstrates the anticorrelated stimulus.

There are some important functional differences between the disparity stimulus and the flashing checkerboard used for luminance mapping. The wedge containing the active checkerboard is presented against a mean gray background. The contourless gray background is unlikely to excite many visual cortical neurons. In contrast, the wedge containing the active disparity stimulus is presented against a background of binocularly correlated dots of zero disparity. This stimulus is known to activate a large population of neurons, particularly in early visual cortex (Cumming & DeAngelis, 2001). However, fMRI studies using adaptation have demonstrated that a greater response is generated by a changing stimulus than a uniform one. Therefore, an ‘active’ quadrant that changes its disparity from near to far every second for 4 s should produce a larger BOLD signal than a disparity that is unchanged at zero disparity for 28 s.

fMRI data collection and analysis

Echo planar images (EPI) oriented perpendicular to the calcarine sulcus were acquired with an RF surface coil (NOVA medical, Wakefield, MA) using typical fMRI BOLD imaging parameters (TR = 4 s, TE = 30 ms, 2.0 × 2.0 mm² in-plane resolution, 32 2 mm slices). Each scan consisted of 6 blocks, giving a total scan length of either 288 s (luminance stimulus) or 192 s. Either 4 or 5 runs of a given stimulus type were performed. At the end of each session, a T1-weighted image with the same slices as the functional data was collected to aid alignment to the whole brain anatomical image.

The first stimulus cycle of each scan was discarded to minimize transient effects of signal saturation. The linear trend in the time series at each voxel was removed to compensate for slow signal drift (Smith et al., 1999). Motion correction was performed on each scan (Jenkinson,
Coherence measures

For the disparity experiments, data were collected in 2 sessions, aligned to the high resolution T1 whole brain scan (see Anatomical data analysis section), and the functional activation was transformed into that space. The data from the 2 sessions were then averaged. A Fourier analysis was performed on the averaged data for all stimulus types to investigate the areas of cortex activated. The response coherence (amplitude at stimulus frequency divided by the summed amplitudes at all frequencies) was used as a threshold measure. A rough estimate of the statistical significance of the response coherence can be calculated using the following formula

\[
t = r \sqrt{\frac{n - 2}{1 - r^2}},
\]

where \( t \) is the \( t \)-statistic, \( r \) is the coherence value, and \( n \) is the number of data points (Sokal & Rohlf, 1995). From this \( t \)-statistic, a \( p \)-value can be generated to give an estimate of the significance of activation. It is, however, only an estimate because many of the assumptions associated with such statistics are known not to be true in fMRI data. The null hypothesis for this statistic is that there is no significant signal at the frequency of the stimulus, compared with the noise at the other frequencies. Since the noise associated with fMRI BOLD data is known to be correlated, it cannot meet the assumption that the noise is uncorrelated.

Visual area analysis

Two measures were taken in order to compare the response to correlated versus anticorrelated disparity stimuli. Firstly, the amplitude of the response at the stimulus frequency was calculated for the two disparity conditions to give a difference in response level. The second metric looked at how well the response was restricted to the stimulus frequency, measuring how many standard deviations the amplitude at this frequency differed from the distribution of other amplitudes. This was achieved by using the mean and standard deviation of the stimulus frequency amplitude and the non-stimulus frequency amplitudes to compute a \( z \)-statistic.

Anatomical data analysis

In addition to the fMRI data, a whole brain T1-weighted scan was collected using a brain volume coil (Varian, Palo Alto, CA). Sagittal slices, 1-mm thick, were acquired at a resolution of \( 1 \times 1 \text{ mm}^2 \) using a 3D FLASH sequence. Functional data from all sessions were aligned to the whole brain image using the T1-anatomical image collected in each fMRI session (Nestares & Heeger, 2000).

Gray and white matter were segmented using custom software (Larsson, 2001), and a surface corresponding to the gray–white matter boundary was extracted and computationally inflated. This surface was then flattened to produce ‘flat maps’ showing for each subject the pattern of sulci and gyri, onto which the functional data were then transformed.

Results

Maps generated by disparity

Correlated disparity produced activation maps with the predicted phase responses in all 10 hemispheres. Figure 2 shows maps for correlated disparity stimuli for the left hemisphere in 4 hemispheres. Visual areas, defined using retinotopic mapping with luminance stimuli, are superimposed on these flattened representations. All subjects, with the exception of Subject 4, show extensive activation across visual cortex, both in the areas defined as retinotopic with luminance or motion stimuli and beyond these areas.

Disparity maps compared to motion

In order to determine how well the disparity stimulus excites visual areas, the disparity activation map was compared with a map defined by motion. A retinotopic stimulus defined by motion is an effective stimulus for mapping human area MT/V5 (Huk, Dougherty, & Heeger, 2002), in addition to activating the early visual areas. Figure 3 shows 4 hemispheres, 2 left and 2 right for Subjects 1–4. The left side of the figure shows the maps produced by the motion stimulus, and the right side shows the correlated disparity maps.

Probably the most striking result here is that the main areas of activation are very similar for the two stimulus types. However, in spite of this similarity, for each visual area, significantly more voxels were activated by the motion stimulus than the correlated disparity stimulus (chi-square goodness of fit \( p < 10^{-5} \) for all visual areas). This discrepancy in total number of voxels activated may explain why the borders of the early visual areas do not appear to be as clear in the case of disparity compared to motion. In general, the maps for disparity are noisier, with some small areas of activation at ‘out-of-phase’ values.

There are two main differences in the way the data were collected. Firstly, the number of data samples is different. Since the main aim of this study was to examine disparity mapping, data for these stimuli were collected over two...
sessions and consist of a total of 10 scans of 5 cycles. However, the motion activations were produced by 5 scans of 5 cycles. Another difference is the size of the stimulus. Since the disparity stimuli were presented side by side in the visual field, it was necessary for them to be of smaller diameter. This should not necessarily degrade the map, but it may be less extensive. However, Figure 3 does not reveal much difference in the extent of activation between the different maps.

**Out-of-phase activity**

It is clear from Figure 2 that in at least 2 subjects there is activity that is not in the correct phase for the hemisphere shown. This ‘out-of-phase’ activity is located in the central region of the visual cortex, between the dorsal and ventral visual areas. The region of cortex represents foveal vision, for which it is often difficult to define the borders between different visual areas and for this reason these borders are not drawn in this cortical region. It is of note, however, that there is no evidence of any significant ‘out-of-phase’ activity in either the luminance or motion defined maps.

**Comparison of correlated with anticorrelated activation**

Next, we compared the activation resulting from binocularly anticorrelated with that from correlated stimuli. The use of an anticorrelated stimulus ensures that all aspects of the image, such as the dot position, are identical except for the luminance polarity of the dots in the active quadrant, which is swapped between left and right eyes. However, there is no visible depth edge that defines that active quadrant in the anticorrelated stimulus. Figure 4 shows the activation maps produced by anticorrelated stimuli in the same hemispheres as those shown in Figure 2. There is a clear retinotopic map in 4/5 subjects (again the activation for Subject 4 is considerably lower). Moreover, the phase of activation for anticorrelated stimulation is matched to that of the correlated condition. The activation phases in the two conditions were significantly correlated for each visual area, with mean correlation coefficients of 0.33, 0.39, 0.59, 0.48, 0.56, 0.44, and 0.48 for areas V1, V2, V3, hV4, V3A, MT, and V7. Figure 5 shows plots of the phase correlation in areas V1 and V3, the lowest and highest correlations, respectively.

In spite of the high correlations in phase for the two disparity conditions, significantly more voxels were activated in all visual areas to the correlated stimulus \( p < 10^{-5} \) in all visual areas). The voxels activated by the correlated, but not the anticorrelated, stimulus are shown in Figure 6, with details as Figure 2.

**Magnitude of activation**

Since the correlated condition produces a robust perception of depth, it might be predicted that the neural response would be greater to this condition. Figure 6
suggests that this may be the case. However, in many visual areas the amplitude of the BOLD signal change is not significantly different in the two conditions. The mean response amplitudes are shown in Figure 7 for each visual area, defined using retinotopic mapping. Error bars show standard errors. Figure 7A shows the magnitude of the % BOLD change to the correlated stimulus, and Figure 7B shows the response to the anticorrelated stimulus. Only 3 visual areas (indicated with an asterisk) show a significantly larger response to the correlated stimulus on a paired t-test, V3 ($t = 1.81; p < 0.05; df = 9$), hV4 ($t = 1.80; p < 0.05; df = 9$), and MT ($t = 2.90, p < 0.0005; df = 9$). As the assumptions associated with the parametric t-test are not necessarily satisfied in these data, a non-parametric rank sign test was also used: The same 3 areas showed a larger response for correlated stimuli. Across all visual areas, the response to correlated stimuli is significantly larger than anticorrelated (paired t-test, $t = 3.41; p < 0.0005; df = 68$).

However, the presence of out-of-phase activity in the activation maps may affect the estimates of response amplitude because the BOLD responses are averaged across all activation phases. If the out-of-phase activity were significantly higher for the anticorrelated stimulus rather than the correlated one, this could account for the similarity of response amplitudes. It was therefore
necessary to investigate further how the response differs between the two conditions.

Response correlation by visual area

We analyzed the responses according to the temporal correlation between the stimulus and the evoked BOLD response. Figure 8 illustrates a time series of the BOLD response to the stimulus. Figure 8A shows the time series for Subject 1 for area V7 for the correlated experiment, and Figure 8B shows the corresponding data for the anticorrelated experiment. Both conditions have the same response amplitude. In order to test the significance of the response modulation, a Fourier transformation was performed. Figures 8C and 8D show the peak of the response at 5 cycles/scan, the frequency of the stimulus, in red.

A suitable measure of how well the response is matched to the stimulus is the $z$-statistic of signal amplitude at the stimulus frequency compared with amplitudes at all other frequencies (for more details, see Methods). The mean $z$-statistic for each visual area is plotted for correlated (A) and anticorrelated (B) experiments in Figure 9. The $z$-statistic is significantly greater for correlated than anticorrelated stimuli in all visual areas except V1 ($V_2$, $t = 2.95, p < 0.005$; $V_3$, $t = 3.82, p < 10^{-4}$; $hV_4$, $t = 2.16, p < 0.05$; $V_3A$, $t = 3.06, p < 0.005$; $V_7$, $t = 2.71, p < 0.01$; $MT$, $t = 5.20, p < 10^{-4}$). When a non-parametric rank sign test is performed, the same areas show a significantly higher $z$-statistic to correlated stimuli. It is clear from the plots in Figure 9 that this is the case.

Activation at double stimulus frequency

Figure 8 indicates that there is significant change in BOLD signal at 10 cycles/scan for the example visual area shown. Since any voxel contains thousands of neurons, two different neuronal populations could contribute to the signal. One population responds preferentially to the changing disparity of the active quadrant, and another responds preferentially to the zero disparity region. Since
these two populations respond to features 180° apart, a signal at double the stimulus frequency would be predicted. To determine whether such a pattern is present, the amplitude of activation at 10 cycles/scan was compared between the correlated and anticorrelated conditions. A significantly greater response at double the stimulus frequency was found for the anticorrelated condition in all visual areas ($p < 0.05$), except hV4 and V7. However, there is also generally greater noise in the responses for the anticorrelated condition. To test whether the greater response at double the stimulus frequency was specific, we performed the same comparison but using 9 cycles/scan. In this case, no visual area showed any difference between the two disparity conditions. We conclude that

Figure 6. Voxels significantly activated by the correlated, but not the anticorrelated stimulus. The topography obvious in the correlated data is now absent, as much of the topography was also present in the anticorrelated condition.

Figure 7. The amplitude of the change in BOLD response in each visual area for the two stimulus types. Error bars show standard errors of the mean. Areas in which the correlated response is significantly greater than the anticorrelated are shown with *.

Figure 8. (A and B) The time series for area V7 of Subject 2 for the correlated and anticorrelated scans respectively. There were 5 stimulus cycles, and the modulation to this stimulus frequency is clear in both cases. (C and D) The Fourier transform of these data. Although the response amplitudes are matched at 5 cycles per scan, the anticorrelated response also has considerable modulation at other frequencies, noticeably at double the stimulus frequency (10 cycles per scan).
the response to the anticorrelated wedge genuinely contains a component at twice the stimulus frequency, i.e., $2f$. The amplitude ratios of $2ff$ are shown for all visual areas in Figure 10. The correlated ratios (A) are considerably smaller than the anticorrelated values (B).

We wanted to check whether this effect at $2f$ for the anticorrelated stimulus might be responsible for the difference in $z$-statistic between correlated and anticorrelated highlighted in Figure 9. When the $z$-statistic was recalculated, using frequencies other than $2f$, there was little difference to the outcome. Therefore, there is no reason to alter our earlier conclusion that the activation at the scan frequency $f$ is consistently greater for the correlated condition.

**Activation on the lateral surface of the occipital lobe**

There are several regions of the occipital cortex lying outside of the early visual areas (V1, V2, V3, V3A, hV4, V7, and MT) that appear to show a differential response to the correlated and anticorrelated stimuli (Figure 2). The region of cortex lying between V3A and MT on the flattened representation has been identified by both Tyler et al. (2006) and Tsao et al. (2003) as responding to stereoscopic depth. However, the former authors refer to a part of this area as kinetic occipital area (KO) and the latter to a larger area, V4d-topo. To define this area, Tyler et al. used a kinetic boundary stimulus, similar to that used by Dupont et al. (1997) in their PET study.

One important methodological issue in brain imaging is that the response in any data set that is used to determine a ‘region of interest’ (ROI) is likely to be greater than the responses in other data sets. This is because the ROI is defined as the set of all voxels that show an activation greater than a particular threshold. With all other stimuli, including a repeat presentation of the stimulus used to define the ROI, the activation of the voxels comprising the ROI is likely to be lower. We avoided this issue by using the motion stimulus to define ROIs for this region of cortex for which the luminance...
stimulus is less suitable. Fortunately, the motion stimulus used in this study effectively produces a kinetic boundary that moves around the visual field, so this sector of the disk should activate the topographically mapped cortical region in a phase-dependent way.

Furthermore, if a single area is to be defined, it should have a single hemifield representation. Most recently, Larsson and Heeger (2006) have clearly demonstrated 2 additional retinotopic areas, LO-1 and LO-2 in this region of cortex. They assert that both these areas lie within the designated area KO. Using the motion stimulus, we confirm their results by mapping these 2 areas retinotopically in all subjects. Examples of these definitions from the motion stimulus are in the 4 hemispheres in Figure 3. These same definitions are superimposed on the disparity maps, indicating significant activity in all cases.

Both LO-1 and LO-2 have a large response amplitude to the correlated disparity condition. Figure 3 shows that there is a substantial correspondence between the details of the topography revealed by correlated disparity and that revealed by visual motion. Figure 11A shows that both of these LO areas have a significantly larger response amplitude to correlated disparity than anticorrelated (t = 3.76; p < 0.005; df = 9 (LO-1) and t = 4.04; p < 0.005; df = 9 (LO-2)). Similarly, the difference in z-statistic is also highly significant (Figure 11B). Since these areas are most likely subdivisions of KO as defined by Tyler et al. (2006) and others, these results are consistent with previous data.

Discussion

When a wedge defined by binocular disparity moves around a circular disk of zero disparity dots, the cortical activation of many visual areas has the form of a retinotopic map. This is true for both correlated and anticorrelated binocular disparities. The active quadrant of the correlated stimulus was perceived as a plane that steps backwards and forwards in depth. The anticorrelated stimulus, on the other hand, was perceived as a cloud of dots, with no clearly defined plane.

Differences between responses to correlated and anticorrelated stimuli

The largest difference between correlated and anticorrelated stimuli occurs in the areas on the lateral surface of the occipital lobe, LO-1, LO-2, and area MT. Area MT was defined using the method of Huk et al. (2002), which requires that MT is defined as the motion-activated region with a defined retinotopic map confined to the contralateral visual field. We therefore conclude that the specific activation due to binocularly correlated stimuli was located in human MT, rather than the adjacent areas that constitute human MT+. There could be several reasons why these lateral occipital areas have the largest differences in response to correlated and anticorrelated stimuli. Apart from the obvious possibility that these areas are specialized in some way for stereoscopic vision, another possibility is that the correlated stimulus ‘jumps’ between two positions in depth and therefore can be perceived as moving in depth. For an area such as MT, known to be very sensitive to motion, this could be a more effective stimulus than dots forming the rest of the circular disk, as these dots simply appear to flicker.

Interestingly, neither of the two dorsal areas that have previously been implicated in disparity processing with fMRI, V3A, and V7 (Backus et al., 2001; Neri et al., 2004; Tsao et al., 2003) showed a larger response to correlated than anticorrelated stimuli. In contrast, ventral area hV4 did show a larger response, consistent with neurophysiological data from the non-human primate (Tanabe, Umeda, & Fujita, 2004) and with the finding that ventral visual areas appear to reflect perceived depth more than dorsal areas (Neri et al., 2004).

A more consistent difference between correlated and anticorrelated conditions was the finding that the response was more restricted to the stimulus frequency in the correlated conditions. This was true for all visual areas, except V1 for which there was no significant difference in response to correlated and anticorrelated stimuli. Again, this is broadly consistent with the neurophysiological studies of primate visual cortex that show V1 neurons respond to both correlated and anticorrelated RDS stimuli (Cumming & Parker, 1997).

Disparity sensitivity in lateral occipital cortex

It is clear from a number of fMRI studies that some regions of lateral occipital cortex have considerable sensitivity to disparity (Tsao et al., 2003; Tyler, 2004; Tyler et al., 2006). Although different terminology was used in these studies, the areas of activation were consistent, and both probably included the two retinotopically defined areas LO-1 and LO-2 used here (Larsson & Heeger, 2006). LO-1 showed the largest change in % BOLD signal to correlated disparity of any visual area. The response of LO-2 was comparable to the larger responses of the other retinotopic areas. In both cases, there was a significantly larger response to the correlated, than the anticorrelated condition. Previous studies have noted that areas of the lateral occipital cortex, such as KO, exhibit sensitivity to borders, either kinetic or otherwise (Dupont et al., 1997; Tyler et al., 2006; Van Oostende, Sunaert, Van Hecke, Marchal, & Orban, 1997; Zeki, Perry, & Bartels, 2003). One possible explanation of the greater response to correlated disparity is therefore that this stimulus defines the visual border more effectively.
An alternative interpretation is that neurons in these regions respond less well to anticorrelated disparity. Further investigation specifically targeting these alternative interpretations is necessary.

**Neural signals underlying topography**

Whilst the topographical maps are driven by disparity differences in the stimuli, it is clear that there are several potential mechanisms by which this response is generated. The first possibility is that the changing disparity, both correlated and anticorrelated, is driving the response. A less likely explanation is that the pattern is generated by a preference for non-zero rather than zero disparity. This is considered less likely because of the response to the anticorrelated stimulus. In this stimulus, the zero disparity region is correlated, but the ‘active’ region is anticorrelated at non-zero disparities. Since anticorrelated stimuli produce a consistently lower response than correlated ones (Cumming & Parker, 1997), it seems unlikely that the non-zero anticorrelated response would be greater than a zero disparity one. A further possibility that cannot be ruled out is that the response is to the border between the zero-disparity region and the ‘active’ region. This particular experiment cannot distinguish between the above options.

The finding that the anticorrelated stimulus generates a topographic map suggests that depth perception alone cannot be responsible for generating the topography. However, since the topography is clearer, and the number of voxels activated greater in the correlated case, the neural activity associated with depth perception appears to contribute to the topography.

**Differences in maps generated by disparity compared to luminance and motion**

One of the most striking observations is that, in most cases, the maps due to the 3 different stimulus types are actually very similar. Generally, the visual area boundaries are less distinct when the disparity, rather than the luminance or motion stimuli are used. This is in spite of the additional data collected using the disparity stimulus. This could be potentially due to details of the experimental design. For example, the stimulus size was smaller for the disparity stimuli, simply because the left and right eye images both needed to fit onto a single screen. However, there is no evidence that using a smaller stimulus (5°) should degrade the retinotopic map. A more likely explanation is that the disparity stimulus consistently activates a smaller pool of voxels, and the frame-by-frame change in spatial position of the random dots adds noise. This effect may be even more pronounced when the anticorrelated stimulus is used, since the size of the neuronal response is smaller (Cumming & Parker, 1997).

There does not appear to be any area that can be consistently mapped across subjects using disparity but not luminance or motion. However, it may be easier to obtain a reliable retinotopic map in areas such as V7 when a disparity stimulus is used, rather than luminance. Human subjects are sensitive to a large range of disparities, so the size of the disparities used for the experiment may have favored certain areas. In particular, it could be that the small disparities used here were particularly effective at stimulating the ventral visual system that may be used for fine object recognition. In contrast, the disparities that may be used for spatial localization by the dorsal visual areas may be considerably larger. Whether such a dichotomy exists is a question for further investigation. The evidence that exists is discussed in the next section.

**Out-of-phase activity**

In the correlated and to a greater extent in the anticorrelated activation maps, there is a region of out-of-phase activity clustered in the foveal region of areas V1, V2, and V3. The most likely explanation of this is a response to zero disparity. In both disparity stimuli, the ‘active’ region is contrasted with a zero disparity region. If a larger proportion of voxels in a given areas of cortex are sensitive to zero or near-zero disparity, a greater response may be evoked by the zero-disparity region than the active quadrant. Since neurons close to the fovea tend to be sensitive to disparities close to zero (Prince, Cumming, & Parker, 2002), it is not surprising that this out-of-phase activity is clustered in the foveal region of cortex. It is now widely accepted that disparity selective neurons show a continuum of tuning shape (Cumming & DeAngelis, 2001; DeAngelis & Newsome, 1999; LeVay & Voigt, 1988; Prince, Pointon, Cumming, & Parker, 2002) rather than the discrete classes originally proposed (Poggio & Fischer, 1977; Poggio, Gonzalez, & Krause, 1988). However, Cumming and DeAngelis (2001) have shown that the distribution of disparity tuning curves changes from striate to extrastriate visual areas. In V1, the tuning is clustered around symmetric tuning. V2 shows a fairly even distribution, while in extrastriate cortex (MT and MST) there is a greater preponderance of odd symmetric tuning, that is, near and far cells. Near and far cells are activated more by non-zero disparities, so the activation to the zero disparity background would be lower in extrastriate areas.

**Effects of attention**

In this study, we did not specifically control the attentional state of the subject. It is well established that...
attention can influence fMRI activity in visual cortex (Gandhi, Heeger, & Boynton, 1999; Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999; Silver, Ress, & Heeger, 2007).

Therefore, the cortical responses that we have studied here will include components related to the subjects’ attention to the stimuli as well as the purely stimulus-related components. It might be argued that the correlated stimulus is generally more capable of attracting attentional resources, in comparison with the anticorrelated stimulus. In spite of the absence of a task (except free fusion), the amplitude of response to the two stimulus types was not significantly different in many visual areas. This is different from cases where attention has been directed to a spatial location, where the enhancement due to attention is generally evident across almost all cortical visual areas. We have to acknowledge the possibility that the effects of attention and the amplitude of stimulus-related response to correlated and anticorrelated stimuli might covary inversely. This would produce the appearance of little change in overall response across cortical areas in our experiments. However, for this to be the case, the attentional signal would have to be small in areas where the stimulus-related signal is large and large where the stimulus-related signal is small and, as far as we are aware, there is no evidence to suggest such a variation of attentional signals across visual areas.

Comparison with neurophysiology

Several studies have investigated whether neurons respond to anticorrelated disparity patterns in addition to correlated. At the first level of binocular combination, V1, it is well established that single neurons respond to both correlated and anticorrelated random dot patterns (Cumming & Parker, 1997), and it has been shown that the behavior of these neurons can be accounted for by a simple model (Read, Parker, & Cumming, 2002). This is in agreement with our finding that only area V1 shows no difference between responses to the correlated and anticorrelated stimuli measured either by the amplitude of the change in BOLD response or the variability of the response to the two stimulus types.

Beyond V1, both V4 and inferotemporal cortex show reduced responses to anticorrelated, compared with correlated stimuli (Jansen, Vogels, Liu, & Orban, 2003; Tanabe et al., 2004). Comparisons between correlated and anticorrelated stimuli have not been made in dorsal regions of visual cortex. The results obtained here are consistent with neurophysiological data. hV4, the most ventral area that is defined retinotopically here, shows a significantly greater amplitude of response to correlated than anticorrelated stimuli.

The most significant differences between correlated and anticorrelated responses were found in the lateral occipital cortex, areas LO-1, LO-2, and MT. This appears in conflict with neurophysiological evidence that there are neurons tuned to anticorrelated disparities in area MT of the macaque (Krug, Cumming, & Parker, 2004). However, at least two factors could account for this difference. Firstly, the dominance of neurons in MT with odd-symmetric tuning profiles (noted in the Out-of-phase activity section) may be sufficient to favor the responsiveness of MT to the correlated form of disparity stimulus used here, which steps from near to far disparity. Secondly, the visual appearance of the correlated stimulus is a movement in depth from front to back during the ‘active cycle.’ For an area such as MT that is sensitive to motion, this visibility of this motion-in-depth may potentially evoke a larger response, in comparison with the anticorrelated condition that does not evoke any perception of motion.

Function of disparity and depth perception

One of the complications of investigating depth processing is that the computation of depth can serve many purposes. Tsao and Tootell (2004) suggest that the dorsal areas should predominant because the primary function of 3D perception is to define spatial location. However, while this may be true, this rapid 3D perception does not need to be computed using binocular disparity. In fact, the stereoscopic system is widely accepted to be sluggish relative to other visual processing (Nienborg, Bridge, Parker, & Cumming, 2005; Norcia & Tyler, 1984) and is often used predominantly for fine depth perception and/or visual segmentation. Indeed, Neri et al. (2004) showed that ventral visual areas respond to both absolute and relative disparity, whereas dorsal areas only respond to absolute disparity. Since disparity contributes to perception in many ways, it would not be surprising if it cannot be simplistically localized to any given area or visual stream.

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References


disparity in macaque V1. *Journal of Neurophysiology, 87*, 209–221. [PubMed] [Article]


