Dichoptic studies of instantaneous colour constancy in human vision

John L. Barbur[1], Darryl DeCunha[1] and Karoline Spang[2] Applied Vision Research Centre[1], City University, London, UK. Human Neurobiology[2], Bremen, Germany

Abstract

The relative contribution the primary visual cortex and extrastriate visual areas make to instantaneous colour constancy (ICC) in human vision was investigated using a number of visual psychophysical techniques and also fMRI. We wanted to establish whether the conscious perception of surround colour changes caused by changes of illuminant in the same eye is a necessary condition for the normal functioning of ICC mechanisms. The results reveal no statistically significant difference in ICC between monocular and binocular conditions. The ICC index is however much reduced when the test patch and the Mondrian surround are viewed dichoptically. The results also show that the perceived colour of the surround Mondrian patches in the test eye can be strongly influenced by the presence of a similar Mondrian in the conditioning eye. Surprisingly, the strength of ICC achieved in such dichoptic colour fusing experiments is completely independent of "perceived" changes of illuminant colour in the Mondrian surround and depends only on the monocular changes of surround illuminant. The fMRI studies compared levels of cortical activation elicited when viewing coloured Mondrians under a number of different conditions. Patch luminances and chromaticities were varied independently, either randomly or as dictated by changes of illuminant. The results show that spatial changes in chromatic context, either as a result of material or illuminant changes cause significant activation in the primary visual cortex and less so in other extra-striate areas. These findings point to the neural substrates in V1 that are rich in monocularly driven neurons, as the principal locus for instantaneous colour constancy in human vision.

Introduction

Colour constancy represents an important fundamental aspect of our visual experience and is achieved through a series of processes. Some of these are rapid, almost instantaneous with the change of illuminant (5) and rely on computation of changes in chromatic context. Longer time-course processes that involve chromatic adaptation can achieve almost perfect functional colour constancy, i.e., the colour of objects is recognized as belonging to the same category, even when the illuminants differ significantly in spectral composition. The latter processes also rely on the internal representation of different colour categories and the ability to match perceived object colours in context with remembered colours (6; 11). There are significant advantages in employing both rapid and slow processes to achieve colour constancy. A change of illuminant carries useful information that is easily detectable during the first few seconds, but less so, following a period of adaptation to the new illuminant. This information would not be available to the subject if the rapid colour constancy processes produced almost perfect constancy. Once chromatic adaptation is established the perception of object colours matches well our expectations of colour categories based on their internal representation.

When special viewing arrangements eliminate all chromatic context, the "instantaneous" colour constancy mechanisms become ineffective and the perceived colour of an isolated object viewed against a black background is determined almost entirely by its wavelength radiance distribution. This is again of advantage since under such conditions neither illuminant nor spectral reflectance can be estimated accurately and any assumptions about either of these two variables can lead to erroneous observations. Normal viewing conditions involve both static as well as changing chromatic context either as a result of material or illuminant changes. ICC mechanisms work well under such conditions and provide the very rapid processing needed to achieve some level of colour constancy. Several studies have attempted to localise neural mechanisms with the properties needed to achieve ICC. Although some investigations suggest that von Kries type transformations of cone photoreceptor signals (3; 8) can be achieved within the retina (4), the majority of studies investigated the large field chromatic organisation of neurons in extra-striate visual area V4 and beyond (12). More recent studies revealed the existence of colour sensitive neurons in the primary visual cortex with a continuum of preferred chromaticities. The output of such neurons can however be modulated by changing the colour of the immediate surround in a way that is consistent with colour induction as observed psychophysically (10). In this study we carried out a number of visual psychophysical and fMRI experiments to establish whether the primary visual cortex is the principal substrate for ICC computations. Changes in the perceived colour of a central test patch in response to surround illuminant changes in a variety of monocular, binocular and dichoptic experiments formed the basis for the main visual psychophysical studies. Only two of these experiments will be reported in this paper. The first experiment investigated the extent to which ICC depends on the adjacency of the immediate surround in monocular, binocular and dichoptic viewing of the test patch and surrounding Mondrian background (Fig. 1). The second experiment involved comparison of neural activity generated by two coloured Mondrians, selected to differ only in chromatic contrast changes as dictated by changes of illuminant.

Experiment 1

The psychophysical studies employed a dynamic colour matching (DCM) technique (2) that has several advantages over other methods developed for colour matching (1; 2). The Mondrian display can be illuminated with one of two illuminants (daylight (D_{65}) and tungsten (CIE illuminant A)). During the colour matching test, the illuminant changes sequentially every 0.8s, but the change of illuminant affects only the surround and not the test patch. The stimuli were generated using a 30bit per pixel graphics board (Elsa XXL stereo graphics card, frame rate 120Hz, spatial resolution 1024 x 768 pixels) and were displayed on a 17" Sony Trinitron G520 monitor. The chromaticities of display

phosphors and the luminance relationships were calibrated automatically using a Minolta CS-1000 telespectroradiometer and a LMT-1003 luminance meter, respectively. The stereo shuttle goggles supplied with the Elsa board were calibrated spectrally and allowed the subject to view the stimuli in stereo at 60Hz. The interleaved stimulus frames were programmed to produce either monocular, binocular or dichoptic stimuli. One of the Mondrian patches serves both as reference, when the Mondrian is illuminated with daylight, and as the matching test stimulus, when the Mondrian is illuminated with tungsten. The chromaticity of the reference stimulus remained unchanged throughout the test. The subject had complete control of matching stimulus chromaticity by moving the mouse on a surface that emulated the CIE-(u',v') diagram. The interval of matching stimulus presentation was also indicated to the subject by the presence of a small black dot at the centre of the test patch. The subject's task was to set the test target chromaticity so that its colour remained invariant with surround illuminant changes.

Figure 1. *Example of Mondrians illuminated with D65 and tungsten illuminants. By altering the left eye stimulus in different ways one can generate binocular viewing (i.e., identical left and right eye images), monocular viewing (i.e., the Mondrian is presented only to one eye) and dichoptic viewing (i.e., the test patch is presented to one eye and the changing Mondrian surround is presented to the other eye).*

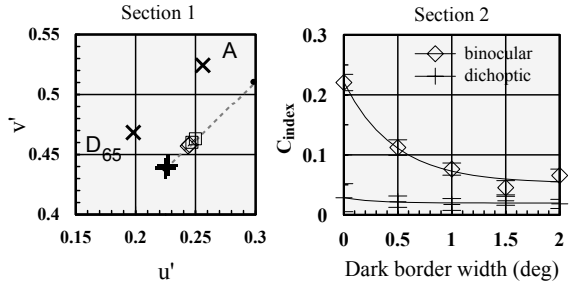

Figure 2. *Typical shifts of chromaticity subjects need to eliminate changes in the perceived colour of the test patch when the surround illuminant changes from daylight to tungsten (section 1). The x symbols plot the chromaticities of the two illuminants. The dotted grey line shows the chromaticities of the test patch under each of the two illuminants. The crosses (+) show the results when the test patch is presented to one eye and the surrounding Mondrian to the other eye. The diamonds (◊) and the squares (□) show the results for binocular and monocular views, respectively. Section 2 shows the magnitude of the ICC index measured for binocular and dichoptic conditions as a function of the width of the dark border introduced between the test patch and the surrounding Mondrian stimulus.*

Experiment 2

Colour vision has been investigated in pioneering, brain imaging studies (7; 13) by comparing the level of brain activity generated when viewing multi-coloured Mondrians with black and white displays (13). In this study we employed multi-coloured Mondrians both in the reference and test phases of stimulation. The experiments were carried out on a three Tesla scanner fitted with a Lambertian, back-projection screen. The photometric calibration procedure developed for psychophysical studies was also applied in situ for the calibration of the back projected images. The test employed a conventional stationary, stochastic experimental design with an equal number of presentations for each of the two phases of the stimulus. Six different illuminants, equally spaced on a mired scale (Mireds = 10^6/K) from 2041K to 9600K were employed. For each of these illuminants we computed both the luminance and chromaticity of each patch in the Mondrian. During the test stimulus phase, both the chromaticities and luminances of the patches in the display changed every 0.5s, as dictated by a change of illuminant. This arrangement caused changes of both chromaticity and luminance and the subject perceived local flicker and colour changes. The test phase continued for 15s and was followed by the reference phase when the same luminance changes were allowed every 0.5s, but the chromaticities of the patches remained unchanged and set to correspond to an illuminant half way (on a Mired scale) between the two extremes (i.e., 3533K). Although both phases consisted of multi-coloured Mondrians, the test stimulus phase was more likely to drive ICC mechanism since the changes of chromaticity as dictated by the random change of illuminant caused significant changes in chromatic context. The test and reference phases of stimulation were repeated for five minutes and the experiments were carried out in six subjects. Statistical analysis of the fMRI data identified those areas of the brain that showed significant differences in neural activation between the two phases of stimulation. The results were consistent amongst the six subjects and similar to those shown in Fig. 3.

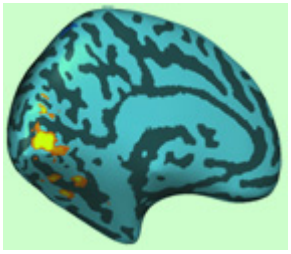

Figure 3. *Single subject data obtained by averaging six sets of measurements. The highlights shown on the "blown up" representation of the left hemisphere of the brain indicate those areas that responded preferentially to changes in chromatic context brought about by random changes of illuminant. Although traces of increased neural activity can be detected in a number of extra-striate areas, the major area of activation is found in the primary visual cortex.*

Discussion and Conclusions

The rapid and large reduction in ICC index, observed when the test patch is separated from the surrounding Mondrian by a black border of increasing width, illustrates the importance of the immediate surround. The spatial extent of this interaction subtends less than two deg and is therefore well within the range of spatial interactions demonstrated in V1 (9). The contribution to ICC from more distant areas that

surround the test patch remains significant, but is much reduced (Fig. 1). The almost absence of constancy when the test patch and the surround are viewed dichoptically suggests that the major contribution to ICC is from monocular dominant areas that precede the stages involved in conscious perception of colour. The preliminary fMRI data are completely consistent with the psychophysical findings. The two phases of stimulation include the same multi-coloured Mondrian display. Each of the two phases contains the same random changes of patch luminance every 0.5s (as dictated by a change of illuminant), but only the test stimulus phase includes changes in chromatic context as a result of illuminant changes. The confinement of areas of dominant activation to the primary visual cortex suggests that the neural computations needed to achieve rapid colour constancy are carried out largely in the neural substrates of V1 that are rich in monocularly driven neurons.

Author Biographies

John Barbur graduated in Physics from Imperial College, London, where he also continued his postgraduate studies in Optics and Visual Science. John heads the Applied Vision Research Centre at City University where he has worked since 1980. His current research interests cover both fundamental studies of visual mechanisms and clinical applications. He has been closely involved with the activities of the Applied Vision Association and the Colour Group of Great Britain and and the International Color Vision Society. For current research projects see: http://www.city.ac.uk/avrc

Karoline Spang studied medicine and obtained her PhD from the University of Heidelberg by carrying out "Basic and clinical investigations for the evaluation of short wavelength (blue) perimetry". Karoline's current interests cover visual perimetry, colour vision and fMRI with emphasis on clinical applications. Since 1999 Karoline has been working in the Human Neurobiology Group at the University of Bremen where she carries out a number of fundamental and clinical studies.

References

[1] Barbur, J. L., de Cunha, D., Williams, C. B., & Plant, G. (2004). Study of instantaneous colour constancy in human vision. *Journal of Electronic Imaging* **13:** 15-28.

[2] Barbur, J. L., Pinney, H. D., & Saunders, J. E. (1989). A method for quantifying changes in colour appearance. *Perception* **18:** 530.

[3] Bramwell, D. I. & Hurlbert, A. C. (1996). Measurements of colour constancy by using a forced-choice matching technique. *Perception* **25:** 229-241.

[4] Kamermans, M., Kraau, D. A., & Spekreijse, H. (1998). The cone/horizontal cell network: A possible site for colour constancy. *Visual Neuroscience* **15:** 787-797.

[5] Land, E. H. (1977). The retinex theory of color vision. *Scientific American* **237:** 108.

[6] Ling, Y. & Hurlbert, A. C. (2005). Color constancy is as good as memory allows - a new color constancy index. *ECVP Abstract 2005*.

[7] Lueck, C. J., Zeki, S., Friston, K. J., Deiber, M. P., Cope, P., Cunningham, V. J., Lammertsma, A. A., Kennard, C., & Frackowiak, R. S. (1989). The colour centre in the cerebral cortex of man. *Nature* **340:** 386-389.

[8] von Kries, J. (1905). Die Gesichtsempfindungen. In W.Nagel, *Handbuch der physiologie des menschen (Physiologie der sinne vol.3)*109-282. Braunschweig: Vieweg und Sohn.

[9] Wachtler, T., Albright, T. D., & Sejnowski, T. J. (2001). Nonlocal interactions in color perception: nonlinear processing of chromatic signals from remote inducers. *Vision Res.* **41:** 1535-1546.

[10] Wachtler, T., Sejnowski, T. J., & Albright, T. D. (2003). Representation of color stimuli in awake macaque primary visual cortex. *Neuron* **37:** 681-691.

[11] Walsh, V. (1999). How does the cortex construct color? *Proc. Natl. Acad. Sci U. S. A* **96:** 13594-13596.

[12] Zeki, S. M. (1983). Colour coding in the cerebral cortex: the reaction of cells in monkey visual cortex to wavelengths and colours. *Neuroscience* **9:** 741-765.

[13] Zeki, S. M., Watson, J. D. G., Lueck, C. J., Friston, K. J., Kennard, C., & Frackowiak, R. S. J. (1991). A direct demonstration of functional specialization in human visual cortex. *Journal of Neuroscience* **11:** 641-649.