EJN fens European Journal of Neuroscience

European Journal of Neuroscience, Vol. 30, pp. 1960–1970, 2009 doi:10.1111/j.1460-9568.2009.06995.x

COGNITIVE NEUROSCIENCE

Distribution of colour-selective activity in the monkey inferior temporal cortex revealed by functional magnetic resonance imaging

Takuya Harada,[1,2,*] Naokazu Goda,[1,2,*] Tadashi Ogawa,[3] Minami Ito,[1,2] Hiroshi Toyoda,[4,5] Norihiro Sadato[2,4,5] and Hidehiko Komatsu[1,2]

[1]Department of Information Physiology, National Institute for Physiological Sciences, Okazaki 444-8585, Japan
[2]Department of Physiological Sciences, The Graduate University for Advanced Studies (SOKENDAI), Okazaki 444-8585, Japan
[3]Department of Integrative Brain Science, Graduate School of Medicine, Kyoto University, Kyoto 606-8501, Japan
[4]Department of Cerebral Research, National Institute for Physiological Sciences, Okazaki 444-8585, Japan
[5]Japan Science and Technology Corporation/Research Institute of Science and Technology for Society, Kawaguchi 332-0012, Japan

Keywords: colour vision, fMRI, IT cortex, macaque

Abstract

Previous electrophysiological, neuroimaging and lesion studies have suggested that the anterior part of the monkey inferior temporal (IT) cortex, or area TE, plays an important role in colour processing. However, little is known about how colour information is distributed in these cortical regions. Here, we explored the distribution of colour-selective activity in alert macaque monkeys using functional magnetic resonance imaging (fMRI) with two types of stimuli: a multicoloured ('Mondrian') pattern and an isoluminant colour grating. These two types of stimuli are both commonly used in human fMRI studies, but Mondrian stimuli, which contain a richer variety of hues and hence might be more suitable for activating higher-order areas than grating stimuli, have not been used to examine colour-selectivity in higher-order areas in earlier monkey studies. With the Mondrian stimuli, we observed that areas along the ventral pathway, V1, V2/V3, V4 and the IT cortex, responded more strongly to colour stimuli than to luminance stimuli. In the IT cortex, we found that colour-selective activities are not distributed uniformly, but are localized in discrete regions, each extending several millimetres in the anterior or posterior part of the IT cortex. The colour-selective activation in the anterior IT was observed only with the Mondrian stimuli, whereas the colour-selective activation in the posterior IT was observed with both the Mondrian and grating stimuli, with little overlap. These findings suggest that there are multiple subregions with differing stimulus selectivities distributed in the IT cortex, and that colour information is processed in these discrete subregions.

Introduction

In monkeys, colour information is primarily processed in the ventral pathway through V1, V2 and V4 into the inferior temporal (IT) cortex. Although many studies suggest that V4 and its surrounding areas play an important role in colour perception (for review, see Gegenfurtner, 2003; Conway, 2009), recent studies have shown that the anterior part of the IT cortex, the final stage of the ventral visual pathway, is also involved in colour perception. This region contains numerous colour-selective neurons, some of which are narrowly tuned to hues and/or saturations (Komatsu *et al.*, 1992) and exhibit task-related responses during colour discrimination (Koida & Komatsu, 2007; Matsumora *et al.*, 2008). In addition, lesion studies have shown that bilateral ablation of the anterior IT disrupts colour discrimination (Horel, 1994; Heywood *et al.*, 1995; Buckley *et al.*, 1997; Huxlin *et al.*, 2000), though ablation of V4 does not (Heywood *et al.*, 1992, 1995).

The aforementioned studies highlight the role of the anterior IT in colour perception, but little is known about how colour-selectivity is distributed in this region, as compared with the distribution in earlier areas such as V4. Recent fMRI studies revealed that colour-selectivity is clustered in discrete millimetre-scale patches in the posterior IT (Conway & Tsao, 2006; Conway *et al.*, 2007), but these studies did not cover the anterior IT. Some studies have suggested that colour-selective neurons are clustered in subregion(s) within the anterior IT (Komatsu *et al.*, 1992; Tootell *et al.*, 2004), but there is variation in the numbers, locations and extents of these subregions among the studies. Moreover, colour-selective neurons also existed at various sites within the anterior IT (Desimone *et al.*, 1984; Komatsu *et al.*, 1992; Kobatake & Tanaka, 1994), suggesting that colour-selective neurons are widely distributed in this region.

In the present study, we used functional magnetic resonance imaging (fMRI) in alert monkeys to clarify the functional organization of colour-selectivity in higher-order areas, including the

Correspondence: Dr N. Goda, [1]Department of Information Physiology, as above.
E-mail: ngoda@nips.ac.jp

*T.H. and N.G. contributed equally to this work.

Received 2 September 2009, revised 15 September 2009, accepted 16 September 2009

anterior IT. To identify colour-selective areas/regions, two paradigms have been commonly employed in human fMRI studies. One is to compare responses to a multicoloured ('Mondrian') pattern with responses to its achromatic counterpart (Beauchamp *et al.*, 1999; Bartels & Zeki, 2000; Wade *et al.*, 2002, 2008); the other is to compare responses to an isoluminant, colour-varying pattern (e.g. a red-blue grating) with responses to a luminance-varying pattern (Hadjikhani *et al.*, 1998; Mullen *et al.*, 2007). Earlier imaging studies of the monkey IT cortex used only the second paradigm (Tootell *et al.*, 2004; Conway & Tsao, 2006; Conway *et al.*, 2007), but the first paradigm may be more suitable for activating higher areas, as the Mondrian stimuli containing various hues could elicit responses from many neurons, each tuned to a specific hue. For that reason, we used both the first and the second paradigms. We found that colour-selectivity is not uniformly distributed in the IT cortex, but is clustered in multiple discrete subregions that are differentially responsive to the Mondrian and grating stimuli. This distributed clustering pattern may provide important clues to the functional organization of the IT cortex.

Materials and methods

Subjects

Two male macaque monkeys (*Macaca fuscata*, 4–7 kg) were used in the present study. Before the experiments, each monkey was implanted with a magnetic resonance-compatible polysulphone headpost, which was anchored to the skull using dental acrylic and small ceramic screws (Uwe Thomas Recording, Giessen, Germany). All surgical procedures were performed while the animal was under general anesthesia with intravenous injection of Nembutal (a total amount of 39 mg/kg for monkey M1 and 24 mg/kg for monkey M2) following sedation with intramuscular injection of ketamine hydrochloride. After surgery, the monkey was allowed to recover for atleast one week before the training began. During this period, antibiotic (Cafazolin, 60 mg) was given every 12 hours. All experimental procedures were conducted in accordance with NIH guidelines and were approved by Animal Experiment Committee of Okuzuki National Research Institutes.

Each monkey was trained to fixate on a central fixation spot (a square fixation window 2–3 deg on a side) for several seconds (typically for 3 s) and not to move its body. The monkey had to maintain the fixation and its body posture to get a liquid reward; if the monkey made a saccade or the intensity of the body movement exceeded a certain threshold, the trial was aborted without a reward and the inter-trial interval (ITI) was extended. The ITI was also extended if the monkey moved its body during the ITI.

Apparatus

During experiments, each monkey was seated in the so-called 'sphinx' position in a horizontally oriented, custom-made monkey chair. Using the headpost, the monkey's head was rigidly fixed to a head-holder on the chair. Visual stimuli were generated using a VSG 2/5 graphics board with 15-bit resolution (Cambridge Research Systems, Rochester, England) and projected from a LCD projector (800 × 600 pixels, 60 Hz refresh rate; Victor, Yokohama, Japan) onto a screen that was positioned in front of the monkey's eyes at a distance of 47 cm. The display system was calibrated by measuring the spectral power distributions of the red, green and blue primaries using a spectrophotometer (PhotoResearch PR-650 SpectraScan, Chatsworth, CA, USA). Eye movements were recorded using an infrared (IR) eye-tracking system (Matsuda *et al.*, 2000), which computed horizontal and vertical eye positions based on the centre of the pupil in an image of the eye captured using an IR-sensitive CCD video camera (60 Hz interlace; Sony, Tokyo, Japan). IR light was directed at an eye using a fibre optic cable. Body movements were automatically detected in images of the monkey's body captured by a second CCD camera (Akizuki Denshi Tsusho, Tokyo, Japan). The eye-tracking and motion-detection systems sent signals to a computer, which ran custom-made software controlling the behavioural task and stimulus display.

Visual stimuli and behavioural task

In the first experiment (Experiment 1), we used chromatic and achromatic Mondrian stimuli that were comprised of a 6 × 6 array of rectangular patches (6° × 6°). For each presentation, the colour of each patch in the chromatic Mondrian stimulus (Fig. 1A top-left) was chosen randomly from the 12 chromaticities shown in Fig. 1B. These chromaticities correspond to points that equally divide the sides of a triangle whose vertices correspond to the chromaticities of the RGB primaries of the LCD projector. The luminance of each patch was chosen randomly from a contrast range of ± 80% around a mean luminance of 20 cd/m^2. The achromatic Mondrian stimulus (Fig. 1A top-right) had the same luminance contrast as the chromatic one, but the chromaticities of the patches were the same as that of the grey background (CIE x = 0.31, y = 0.33). These stimuli were presented for 2000 ms in a cosine temporal envelope (0.25 Hz) on a grey background (CIE x = 0.31, y = 0.33, 20 cd/m^2). The chromatic and achromatic Mondrian stimuli were hence identical in spatiotemporal structure.

In the second experiment (Experiment 2), we used colour-varying and luminance-varying radial sine wave gratings (5° radius), both of which were of low spatial frequency (0.33 cycles/deg) and moved slowly inward or outward (1 Hz). The colour-varying grating

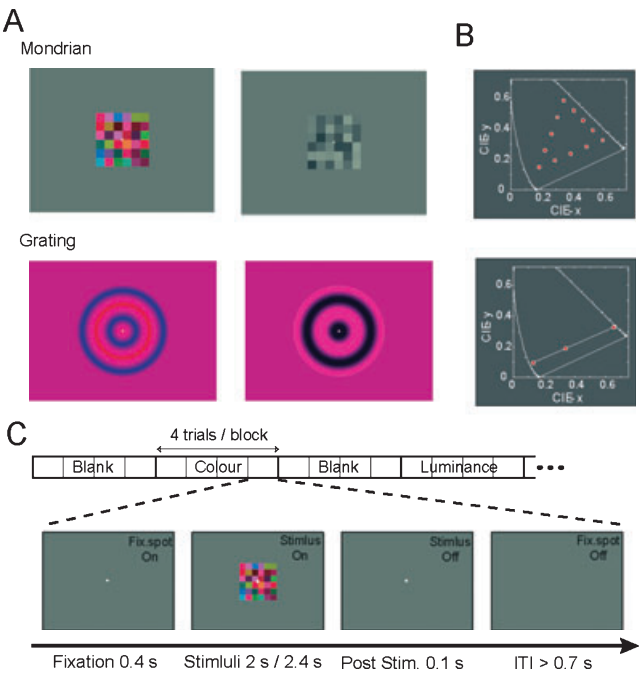

FIG. 1. Stimuli and task. (A) Chromatic (top-left) and achromatic (top-right) Mondrian stimuli used in Experiment 1, and colour-varying (bottom-left) and luminance-varying (bottom-right) grating stimuli used in Experiment 2. (B) The CIE chromaticity coordinates of each colour stimulus (top: Mondrian; bottom: grating). (C) The experimental paradigm and time sequence of the fixation task the monkeys performed during the measurements. ITI, inter-trial interval.

(Fig. 1A bottom-left) was modulated along an axis between the chromaticities of the red and blue primaries. This red-blue grating was made by superimposing a red-black grating and a blue-black grating in antiphase with a luminance ratio of 2.3 (red-black range, 0–28 cd/m^2; blue-black range, 0–12 cd/m^2). This resulted in 40% luminance contrast. The luminance ratio was chosen to replicate the stimuli used in an earlier monkey fMRI study (Conway & Tsao, 2006). The luminance-varying grating (Fig. 1A bottom-right) was made by superimposing the same two gratings in an isophase relationship (100% contrast). The luminance ratio between the red and blue gratings was nearly constant (2.3) at all points, so that the chromaticity of the whole grating remained constant. These grating stimuli were presented for 2400 ms (in a raised-cosine temporal envelope for the first and last 400 ms) on a purple background whose chromaticity and luminance were the same as the mean chromaticity and luminance of the gratings (CIE x = 0.35, y = 0.19, 20 cd/m^2). The direction of movement was randomly switched for each presentation.

In the third experiment (Experiment 3), we used five kinds of stimuli: three Mondrian stimuli and two grating stimuli. These stimuli were presented for 2000 ms on a grey background (CIE x = 0.31, y = 0.33, 20 cd/m^2) within the same run. Of the three Mondrian stimuli, two were the same as the chromatic and achromatic stimuli in Experiment 1. In addition, we employed a photometrically isoluminant chromatic Mondrian stimulus, which was identical to the chromatic Mondrian except that all patches had the same luminance as the background (20 cd/m^2). The remaining two grating stimuli were colour-varying and luminance-varying gratings with the same spatial configuration as the stimuli used in Experiment 2. The colour-varying grating was a red-blue grating made as in Experiment 2, except that the luminance ratio between the red and blue grating was set at 1.0 for M1 and 2.3 for M2. These luminance ratios were determined in a separate experiment, where five colour-varying gratings having different luminance ratios (0.67, 1.00, 1.50, 2.33 and 3.00) were presented to determine which one elicited the least activity in area MT of each monkey. The luminance-varying grating was an achromatic white-black grating that varied only in luminance around a grey background (100% contrast).

The monkeys performed a fixation task (Fig. 1C bottom). Each trial began with the onset of a small central fixation spot, on which the monkeys had to fixate. After they had maintained fixation within 2° × 2°square fixation window for 400–600 ms, a stimulus was presented for 2000–2400 ms. The fixation spot then disappeared 100 ms after the stimulus offset. Each trial was continued even when a saccade or body movement was detected so that stimulus duration was kept constant across trials. In those cases, a reward was not given in about half of the runs, but was given in the remaining half of the runs. In Experiment 3, to improve fixation performance, one monkey (M1) was also required to respond with an optical switch to the dimming of the fixation spot occurring at a random time after stimulus offset to get a reward (the reaction time had to be < 900 ms). In all experiments, there was an ITI of more than 700 ms, during which no fixation spot appeared.

We used a block design in which each stimulus block consisted of four trials with the same stimulus condition (Fig. 1C top). In Experiments 1 and 2, blocks of colour and luminance stimuli were arranged in an alternating design, interleaved with a four-trial blank block in which only the fixation spot appeared. Each stimulus block was repeated six times in Experiment 1 and four times in Experiment 2 within each run, and the order of the blocks was alternated every run. In Experiment 3, the five stimulus blocks were arranged in a pseudorandom order and interleaved with blank blocks. Each stimulus block was repeated two times within each run. The fixation performance and head movements were analysed offline, and data from runs in which the performance was poor or there was an excessive amount of head movement were discarded (see Data analysis).

Data acquisition

Images were acquired using a Siemens 3T Allegra scanner (Siemens, Erlangen, Germany). Functional images were collected using a gradient-echo echo-planar pulse sequence sensitive to blood oxygen level-dependent contrast (TR 2 s, TE 20 ms, flip angle 80 deg, 1.25 mm in-plane resolution, slice thickness 1.6 mm, slice gap 0.32 mm, superior-inferior phase-encoding direction). A surface coil (9 × 11 cm inner diameter; Takashima Seisakusho, Tokyo, Japan) was positioned immediately over the head. Each volume consisted of 31 coronal slices, covering the occipital and temporal cortices. Each monkey underwent 17–52 runs in each experiment (175–185 volumes/run for Experiment 1; 125–135 volumes/run for Experiment 2; 156 volumes/run for Experiment 3). T2-weighted anatomical images (inversion recovery turbo spin-echo, 0.75 mm in-plane resolution) scanned at the same locations as those used for the functional images, as well as whole-brain 3D magnetization-prepared rapid-acquisition gradient-echo (MPRAGE) anatomical images (0.8 mm isotropic voxel), were acquired during each session to register the functional images. High-resolution anatomical images (MPRAGE; 0.5 mm isotropic voxel) were also collected in a separate session, during which the monkey was anaesthetized with Nembutal. The high-resolution anatomical image was placed in the stereotaxic space (the origin was placed at the middle of the interaural line; Saleem & Logothetis, 2007) and used to reconstruct the cortical surface of each hemisphere using CARET software (Van Essen *et al.*, 2001).

Data analysis

Functional data were analysed using SPM2 (Wellcome Department of Imaging Neuroscience, London, UK) as well as custom Matlab codes. The first and last several volumes (in blank block) in each run were eliminated to allow for stabilization of the magnetization and to equate the number of volumes per run for each monkey and experiment (M1: 175 for Experiment 1, 125 for Experiment 2 and 156 for Experiment 3; M2: 171 for Experiment 1, 128 for Experiment 2 and 156 for Experiment 3). All functional images were motion-corrected and aligned with a reference functional image from a particular session and registered to the same-slice position anatomical image. The functional–anatomical registration was improved by adjusting the offset in the phase-encoding direction. The images were then registered to the high-resolution anatomical image in the stereotaxic space and resampled in 1.0-mm isotropic voxels. The data were temporally filtered with a three-point temporal median filter to remove movement-related outliers (Mazaika *et al.*, 2007), and were spatially filtered using a Gaussian filter (2 mm full width at half maximum) to improve signal-to-noise ratios.

The functional data from each run were used for analysis only if the monkey's head did not move too much (the percentage of volumes with head movement over 0.5 mm total translation or over 0.5 deg rotation was < 5%) and the fixation performance was good throughout the run (the overall percentage fixation from the start of fixation to the offset of the fixation spot was more than 95%). We also discarded a run if the percentage of rewarded trials in the run was < 70%. With these criteria, we retained more than 16 runs for each monkey in each

experiment (M1: 20 for Experiment 1, 17 for Experiment 2 and 52 for Experiment 3; M2: 26 for Experiment 1, 25 for Experiment 2 and 48 for Experiment 3).

We conducted voxel-wise statistical analysis for each monkey based on a general linear model (Friston *et al.*, 1995). To detrend the data, they were globally scaled and high-pass filtered (2 cycles/total scan time in each run for Experiments 1 and 2, 1 cycle/total scan time in each run for Experiment 3). The signal time course was modelled using a boxcar function convolved with a human canonical haemodynamic response function and run effect. The regressors were set at the onset of the stimulus presentation for each stimulus condition. Head-movement parameters were also included as regressors of no interest. To test hypotheses about regionally specific condition effects, the estimates for each model parameter were compared with the linear contrasts. The resulting set of voxel values constituted a statistical parametric map of the t statistic, SPM$\{t\}$. The statistical threshold was set at $P < 0.001$, uncorrected for multiple comparisons. The statistical parametric map was projected onto the surface of each hemisphere using the CARET 'average voxel' method with a 1.5-mm averaging radius. Only clusters with a surface area equal to or greater than 3 mm^2 were retained.

Visual area definition

To define areal boundaries, the cortical surfaces were registered to the macaque F99UA1 atlas using surface-based registration of spherical maps as constrained by sulcal landmarks on the individual and atlas hemispheres (Van Essen, 2002). The borders of the early cortical areas (V1, V2/V3, V4 and MT) were then determined based on the areal partitioning scheme of Lewis & Van Essen (2000). The IT cortex was defined as the temporal lobe region extending from the anterior V4 border to the temporal pole, including the lateral surface and lower bank of the superior temporal sulcus (STS). The IT cortex was further divided into the anterior IT and posterior IT based on the anterior–posterior stereotaxic coordinates. The coordinates for the anterior–posterior border were defined as the midpoint between the anterior end of the anterior middle temporal sulcus (AMTS) and the posterior end of the posterior middle temporal sulcus (PMTS), the latter of which corresponded to the anterior border of V4. The lateral geniculate nucleus (LGN) was defined based on an anatomical atlas (Saleem & Logothetis, 2007).

Colour-selectivity index (CSI)

To quantitatively examine response magnitudes and degrees of colour-selectivity, we selected a voxel that showed the most statistically significant difference between its responses to colour and luminance (i.e. local maxima of SPM$\{t\}$ obtained by contrasting colour vs. luminance) within the LGN, V1, ventral V2/V3 and V4 in each hemisphere in each experiment. We also selected from the lateral surface of the IT cortex a voxel in the anterior IT and one in the posterior IT using the same criteria. When there was not significant activation at the threshold of $P < 0.001$, we lowered the threshold to $P < 0.01$ to select the voxel; this lower threshold was used only for the posterior IT in M1 left in Experiment 2.

The raw time series for these voxels were extracted, high-pass filtered and converted to units of percent signal change relative to the baseline computed by averaging signals obtained from the periods for 4 s prior to the stimulus blocks. To exclude movement-related artefacts, we removed signals occurring at the time of large head movements (see Data analysis). The time series was aligned with block onset (the onset of the first stimulus in each stimulus block) and averaged across the stimulus blocks for each condition (colour or luminance). The mean response amplitude for each stimulus condition was computed by averaging signals between 6 and 20 s after the block onset and then averaging across hemispheres. We then assessed the colour-selectivity by computing a CSI from the mean response amplitude. The CSI was defined as follows: $\mathrm{CSI} = (R_{\mathrm{COL}} - R_{\mathrm{LUM}})/(R_{\mathrm{COL}} + R_{\mathrm{LUM}})$ where R_{COL} is the response amplitude to the colour stimuli (chromatic Mondrian stimulus or colour-varying grating stimulus) and R_{LUM} is the response amplitude to the luminance stimuli (achromatic Mondrian stimulus or luminance-varying grating stimulus). An index with a larger value indicates a higher selectivity for colour.

Correlation analysis

To assess the topographical similarity of the colour-selective activities elicited by different types of stimuli or in different experiments, we examined the spatial correlations among the activities. For this analysis, we defined regions of interest (ROIs) on the lateral surface of the IT cortex (surrounded by the lips of the STS and the occipito-temporal sulcus; OTS) in the posterior IT (PostIT ROI) and anterior IT (AntIT ROI), which were divided in the same way described in the 'Visual area definition' section. These were restricted to visually responsive voxels that were defined by contrasting summed responses during all stimulus conditions with responses during the fixation baseline ($P < 0.001$, uncorrected for multiple comparison). For comparison across experiments, voxels that were visually responsive in any one of the experiments were included in the ROIs. For each of these ROIs, we computed a Pearson correlation coefficient between a pair of unthresholded SPM$\{t\}$, each obtained by contrasting the colour condition with the corresponding luminance condition. The statistical significance was assessed for each pair using a permutation test. The stimulus conditions were randomly shuffled in each run in order to produce 'null' data for SPM$\{t\}$ (e.g. shuffled colour vs. luminance). We obtained 1000 null data for each stimulus type and for each experiment, and the correlation coefficients were computed using 1000 pairs of the null data. If the correlation coefficient (or the average of the correlation coefficients across all hemispheres) obtained using real data was greater than the 95th percentile of that obtained using the null data, then it was deemed to be significant at the $P < 0.05$ level.

Results

Colour-selective activity: mondrian stimulus

We first measured colour-selective activity by presenting chromatic and achromatic Mondrian stimuli to alert monkeys while they performed a fixation task. Because the chromatic and achromatic stimuli differed only in colour/luminance conditions, the difference between the activities to these stimuli should reflect the relative sensitivity to colour and luminance. We defined the differential activity between the chromatic and corresponding achromatic stimuli as 'colour-selective activity' in the present study. Figure 2 shows the distribution of the colour-selective activity obtained by contrasting the chromatic Mondrian with the achromatic Mondrian in one monkey (M2). The colour-selective activity was mapped onto the reconstructed cortical surface of the right hemisphere (Fig. 2A and B), and superimposed on the sagittal and coronal sections (Fig. 2C and D). In the occipital cortex, colour-selective activities were found in V1 (on the opeculum), V2d/V3d (in the posterior bank of the lunate sulcus), V2v/V3v (in the inferior occipital sulcus; IOS), V4d (in the anterior bank of the lunate sulcus and on the prelunate gyrus) and V4v (in the anterior bank and the anterior lip of the IOS). In addition, activation

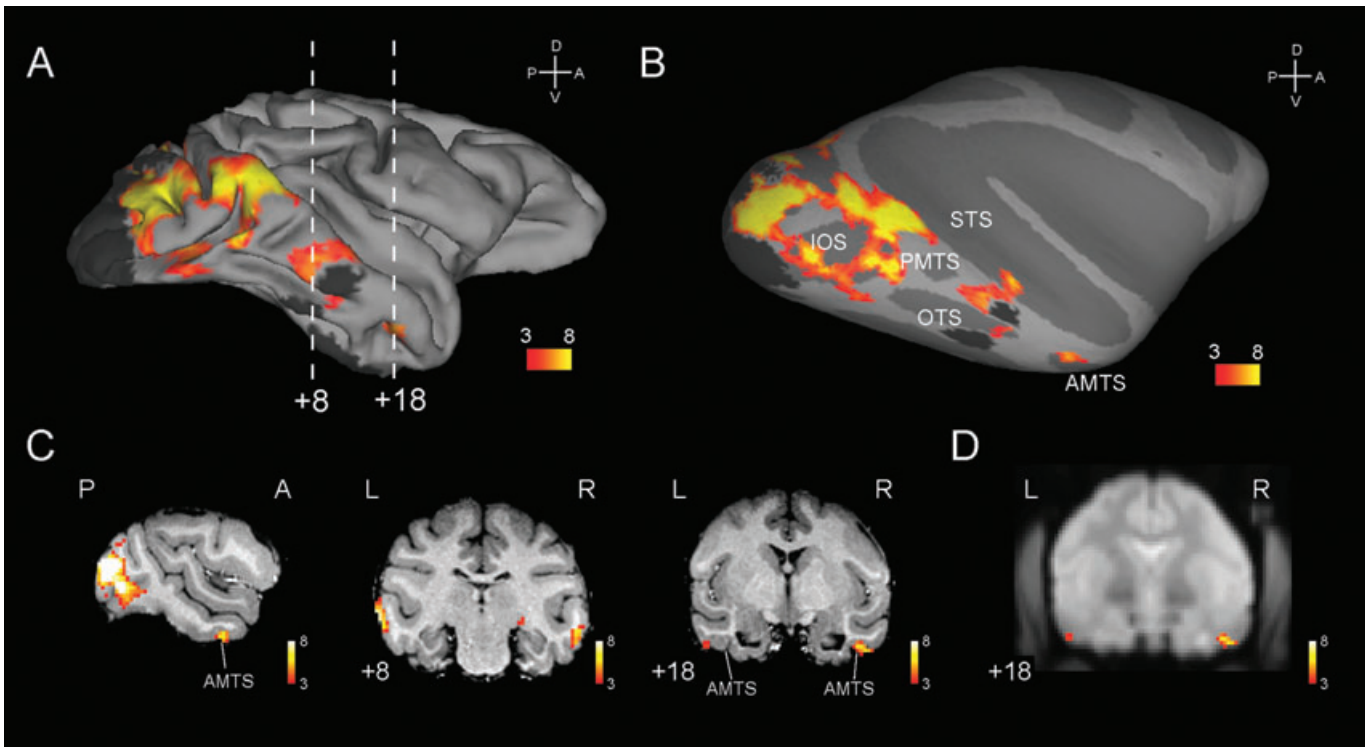

FIG. 2. Colour-selective activity elicited by Mondrian stimuli in monkey M2. (A and B) Statistical parametric maps (SPM{*t*}) indicating voxels that are significantly more active when the subject is viewing a chromatic Mondrian stimulus than an achromatic one ($P < 0.001$, uncorrected for multiple comparisons) are superimposed on the folded cortical surface (A) and inflated surface (B) of the right hemisphere of M2. The colour scales indicate the *t*-scores. The overlaid black regions indicate signal drop-out. (C) Statistical parametric maps are superimposed on sagittal (left hemisphere) and coronal sections of M2. The locations of the coronal sections are indicated in millimetres relative to the interaural line (positive values are anterior) and by the vertical dashed lines on the surface map (A). (D) Statistical parametric maps are superimposed on a mean functional image. The position of the section is the same as the right section in (C). A, anterior; AMTS, anterior middle temporal sulcus; D, dorsal; IOS, inferior occipital sulcus; L, left; OTS, occipital temporal sulcus; P, posterior; PMTS, posterior middle temporal sulcus; R, right; STS, superior temporal sulcus; V, ventral.

was also found in the LGN (data not shown). Overall, the locations of the activated regions in these areas were consistent with those reported in an earlier fMRI study of colour-selective activity in the monkey visual cortex (Conway *et al.*, 2007).

We also found colour-selective activity in the IT cortex. This activity was not uniformly distributed, but was clustered in two discrete regions, each covering ~35 mm^2. One of the regions was located in the lateral bank of the AMTS and the other was located on the gyrus anterior to the PMTS in the right hemisphere (Fig. 2A–C). These regions of colour-selective activity were observed bilaterally, though the position of the activity varied slightly across hemispheres (Fig. 2C and D). Although signal drop-out due to susceptibility-induced field inhomogeneities (Ojemann *et al.*, 1997) occurred in some areas of the IT cortex (black regions in Fig. 2A and B), a signal was obtained from most of the IT, so that signal drop-out cannot account for the presence of discrete colour-selective regions.

Colour-selective regions were consistently found in the anterior IT in all four hemispheres examined and in the posterior IT in three of the four hemispheres. Figure 3 shows the spatial distributions of the activity in the IT cortex in all four hemispheres. With respect to the sulcal landmarks (AMTS and PMTS), the locations of the activated regions in the anterior and posterior IT were largely consistent across hemispheres. The activated regions in the anterior IT were located in the fundus of the AMTS in both hemispheres of M1, on the gyrus lateral to the posterior end of the AMTS in the left hemisphere of M2, and in the lateral bank of the AMTS in the right hemisphere of M2. The activated regions in the posterior IT were located near the anterior

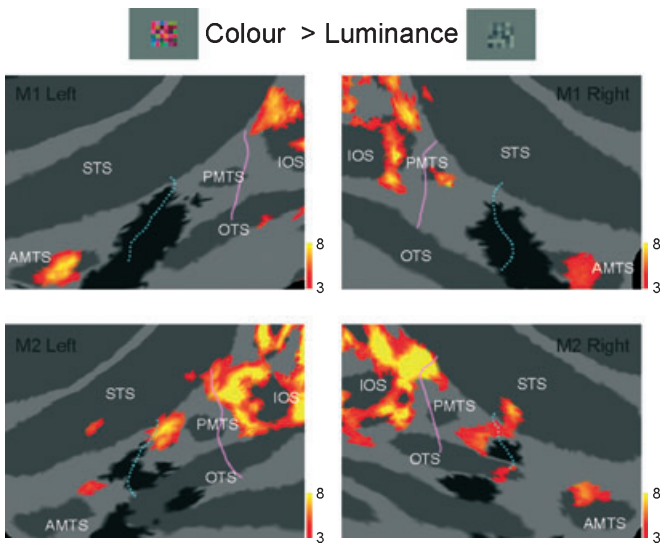

FIG. 3. Colour-selective activity elicited by Mondrian stimuli in the IT cortex in four hemispheres. Colour-selective activities are superimposed on the flattened surfaces of the IT cortex in four hemispheres ($P < 0.001$, uncorrected for multiple comparisons). The solid light purple lines indicate the anterior border of V4, and the dotted light blue lines indicate the border between the anterior and posterior IT (see Materials and methods). AMTS, anterior middle temporal sulcus; IOS, inferior occipital sulcus; OTS, occipital temporal sulcus; PMTS, posterior middle temporal sulcus; STS, superior temporal sulcus.

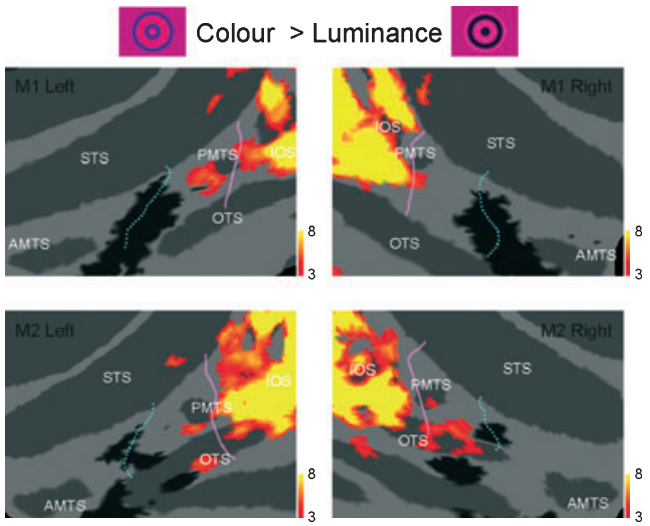

FIG. 4. Colour-selective activity elicited by the grating stimuli in the IT cortex in four hemispheres. Statistical parametric maps indicating the voxels that are significantly more active when the subject is viewing the colour grating than the luminance grating are superimposed on the flattened surfaces of the IT cortex in four hemispheres ($P < 0.001$, uncorrected for multiple comparisons). AMTS, anterior middle temporal sulcus; IOS, inferior occipital sulcus; OTS, occipital temporal sulcus; PMTS, posterior middle temporal sulcus; STS, superior temporal sulcus.

end of the PMTS in the right hemisphere of M1 and on the gyrus 2–3 mm anterior to the anterior end of the PMTS in both hemispheres of M2. In addition, there were bilateral activations in the lower bank of the anterior STS in M2 but not M1.

Figure 5B shows the *t*-values taken from the voxels showing the most significant colour-selective activity within the LGN, V1, V2/V3, V4, the posterior IT and the anterior IT averaged across hemispheres. This indicates that the most statistically significant colour-selective responses were observed in V1 and V4, and less though still highly significant responses were seen in the IT cortex. Taking into consideration that the *t*-statistics reflect not only response magnitude but also the amount of noise that could be affected by susceptibility-induced field inhomogeneity, we also looked at the response magnitude of those voxels (Fig. 5A and C) and assessed the colour-selectivity by calculating the CSI from the response magnitude (Fig. 5D left). The CSI varied among colour-selective areas/regions in a manner that differed from statistical significance. The CSIs were higher in early areas such as the LGN and V1 than in extrastriate areas such as V2/V3 and V4. Notably, the CSIs were higher in the IT cortex than extrastriate areas; in particular, the CSI was higher in the anterior IT than in the early areas. This suggests that the degree of colour-selectivity in the IT cortex is comparable to or even higher than that in earlier areas such as V1 and V4.

Colour-selective activity: grating stimulus

We next examined colour-selective activity using a red-blue colour-varying grating and a luminance-varying grating. We designed the stimuli so as to replicate those in earlier imaging studies in monkeys (Tootell *et al.*, 2004; Conway & Tsao, 2006; Conway *et al.*, 2007). The colour grating was modulated between highly saturated red and blue, with 40% luminance contrast. In the luminance grating, luminance was modulated with 100% contrast, which was much larger than that of the colour grating. The gratings were of low spatial frequency (0.33 cycles/deg) and moved slowly (1 Hz).

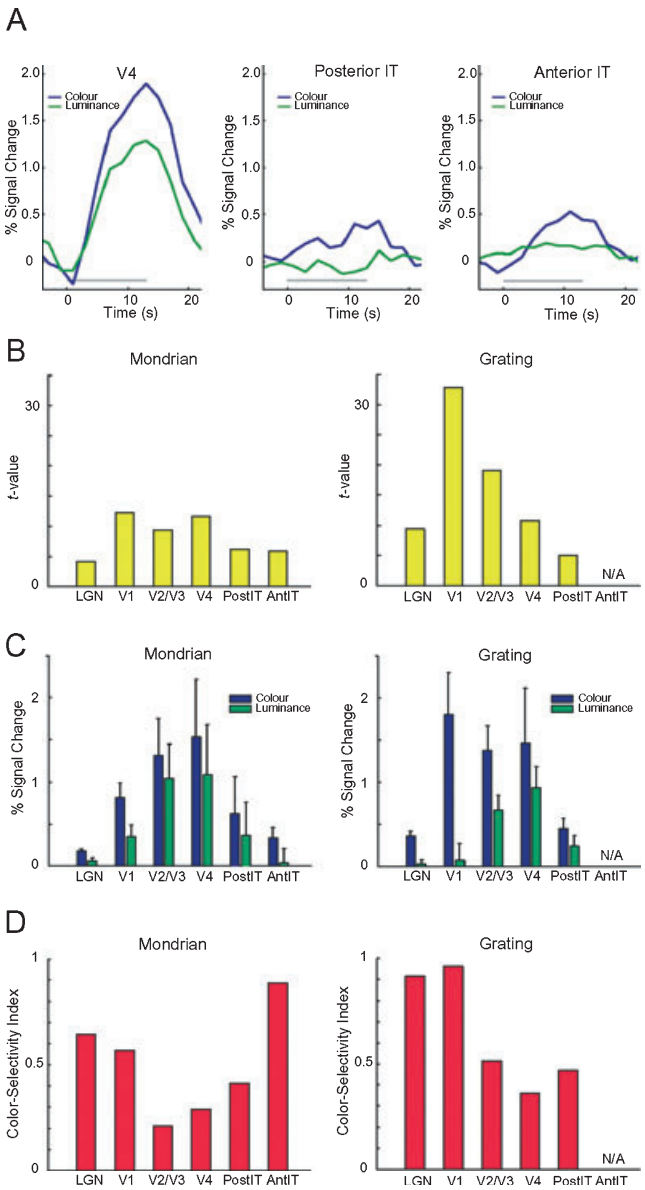

FIG. 5. Comparison of colour-selective activity among regions/areas. (A) Time courses of the activation elicited by Mondrian stimuli in the most significant voxel within V4, the posterior IT and the anterior IT in the right hemisphere of M2. The blue and green solid lines indicate the time courses obtained from blocks of the colour and luminance stimuli, respectively. The visual stimulation epoch is indicated by the horizontal grey bars. (B) *T*-values taken from the most significant voxel within V1, V2/V3, V4, the posterior IT (PostIT) and the anterior IT (AntIT). (C) Mean amplitudes of the responses elicited by the colour and luminance stimuli taken from the most significant voxels and averaged across three or four hemispheres are indicated by solid blue and green bars, respectively. Error bars indicate standard error of the mean. (D) Colour-selectivity indices (CSIs) calculated from the mean response amplitudes across four hemispheres. The response amplitude and CSI for the anterior IT were not plotted for the grating stimulus because it elicited no activation in the anterior IT. LGN, lateral geniculate nucleus.

Colour-selective activities obtained by contrasting the colour grating with the luminance grating were found in the LGN, V1, V2/V3 and V4. The observed activities in these early visual areas were largely consistent with those obtained with the Mondrian stimuli, but the activations tended to be stronger and broader. Colour-selective activities were also found in the posterior IT (Fig. 4). These activities were located in the lower bank of the PMTS or on the gyrus ventral to

the PMTS in all hemispheres and in the lower bank of the posterior STS in two hemispheres (M1 left and M2 left). The colour-selective regions observed near the PMTS were close to, but slightly more posterior than, those observed with the Mondrian stimuli in the posterior IT (Fig. 3). In one monkey (M2), we also observed bilateral activation in the medial bank of the OTS. These results were largely consistent with the earlier studies (Conway & Tsao, 2006; Conway *et al.*, 2007). No significant activity was seen in the anterior IT of either monkey.

The regional distribution of CSIs obtained with the grating stimuli (Fig. 5D right) was similar to that obtained with the Mondrian stimuli (Fig. 5D left), in that the CSIs were higher in the early areas than the extrastriate areas. There was, however, a general tendency for CSIs obtained with the grating, especially for the early areas, to be higher than those obtained with the Mondrian. This tendency, together with the absence of significant grating-evoked activation in the anterior IT, suggests that the colour grating is effective for eliciting colour-selective activity in the early and extrastriate areas, whereas the colour Mondrian is especially effective for activating the anterior IT.

Stimulus dependencies of colour-selective activities in the IT cortex

Both Mondrian and grating stimuli elicited colour-selective activities along the ventral pathway, including the IT cortex. However, the relative strengths of the activities elicited by the two stimulus types differed in the anterior IT. Moreover, the locations at which they elicited colour-selective activities tended to differ, especially in the posterior IT. There are differences in several aspects between the two stimulus types, some of which are likely responsible for the observed differential activation in the IT cortex. Colour Mondrian stimuli contain a richer variety of colours than grating stimuli, which may account for the difference in elicited activities. In addition, the luminance contrast in the chromatic Mondrian stimulus matched that in the achromatic Mondrian, whereas the colour grating stimulus contained much less luminance contrast than the luminance grating. Consequently, contrasting responses to the colour grating with responses to the luminance grating will subtract away regions that are sensitive to both colour and luminance contrast. This also could account for the differences obtained with the two types of stimuli. To examine the effect of luminance contrast on the activity, we conducted a separate experiment (Experiment 3) in the same two monkeys with the aim of measuring response to a new Mondrian stimulus that was photometrically isoluminant, along with responses to the Mondrian stimuli used in Experiment 1. This isoluminant Mondrian contained much less luminance contrast than the achromatic one (± 80%), even if there existed residual luminance contrast due to the individual difference in the psychophysical/physiological isoluminance points. In addition, to directly compare the colour-selective activities obtained with different types of stimuli, we also measured responses to a red-blue chromatic grating as well as responses to an achromatic grating in which only luminance was modulated around a grey background, within the same run. The red-blue grating, in which residual luminance contrast may possibly become large, was adjusted to be physiologically isoluminant for each monkey (see Materials and methods). We then performed a detailed analysis on the topography of the colour-selective activities in the IT cortex.

Figure 6A–C shows detailed maps of colour-selectivity on the IT gyrus in one hemisphere obtained with different types of colour stimuli. In each map, SPM$\{t\}$ obtained by contrasting chromatic stimuli and corresponding achromatic stimuli are shown using a pseudo colour scale without statistical thresholding in the visually-responsive regions of the IT gyrus (Fig. 6D). These maps allow for visual inspection of the topography of both strong and weak activation across the IT cortex. The isoluminant Mondrian stimulus produced weak but significant colour-selective activity in the anterior and posterior IT (isoMon, Fig. 6A) at locations that mostly overlapped those activated by the Mondrian stimulus containing matched luminance contrast (Mon, Fig. 6B). Note also that the spatial distributions of activities within the anterior and posterior IT were similar, irrespective of the presence of luminance contrast. To quantitatively assess the relationship between the spatial distributions of the colour-selective activities, the correlation coefficient (r) was computed between a pair of unthresholded colour-selective activity maps (unthresholded SPM$\{t\}$) across all visually responsive voxels in the anterior IT (AntIT ROI) and the posterior IT (PostIT ROI). This analysis revealed that there is a significant positive correlation ($P < 0.05$, permutation test) between the colour-selectivity maps of isoMon and Mon in both the posterior and anterior IT (Fig. 6A and B; AntIT: $r = 0.590$, PostIT: $r = 0.627$), and this significant positive correlation was observed in all four hemispheres examined (AntIT: $r = 0.584$, PostIT: $r = 0.604$ on average; Fig. 6E). Thus, reducing the luminance contrast in the colour stimulus to nearly zero did not affect the topography of the colour-selective activity across the IT cortex, although it reduced the magnitude of the colour-selective activity. This reduction in the activation seen with the isoluminant stimulus suggests that this region is sensitive to luminance contrast as well as to colour contrast.

By contrast, the pattern of the activity obtained with isoluminant Mondrian (isoMon, Fig. 6A) was different from that obtained with the colour grating (Gra, Fig. 6C). Figure 6E shows that there was no significantly positive correlation between the maps obtained with these two different stimulus types (AntIT: $r = 0.179$, PostIT: $r = 0.091$ on average). Thus, the difference in the topography of the colour-selectivity obtained with the Mondrian and grating stimuli cannot be simply attributed to the contribution of the luminance contrast to the activity; it should instead reflect differences in other stimulus parameters. The correlation analysis also showed that the maps obtained with the same types of stimuli in different experiments were significantly correlated; that is, the responses were reproducible across experiments even though there were long time intervals between the experiments.

Discussion

In this study, we observed robust colour-selective activity along the ventral pathway in monkeys. Both spatially large and statistically significant colour-selective responses were found in areas V1, V2/V3 and V4, which is consistent with earlier imaging studies in monkeys (Tootell *et al.*, 2004; Conway & Tsao, 2006; Conway *et al.*, 2007; Wade *et al.*, 2008). In addition to these activities, we found that colour-selective activity is clustered in discrete regions of the monkey IT cortex, and that these colour-selective regions are distributed in both the anterior and posterior IT. Colour-selective regions in the anterior IT are located in or around the AMTS, and possibly in the anterior part of the STS. In the posterior IT, they are located near the PMTS and in the posterior part of the STS. Moreover, we found that different regions of the IT cortex are activated by Mondrian and grating stimuli. This difference in the response patterns was preserved, even when different types of stimuli were presented in the same run, indicating the difference cannot be explained by fluctuations in the signal intensity across runs. Taken together, these findings suggest that there are multiple colour-selective subregions with differing stimulus selectivities distributed in the anterior and posterior IT cortex. This distributed clustering pattern may be analogous to those for some

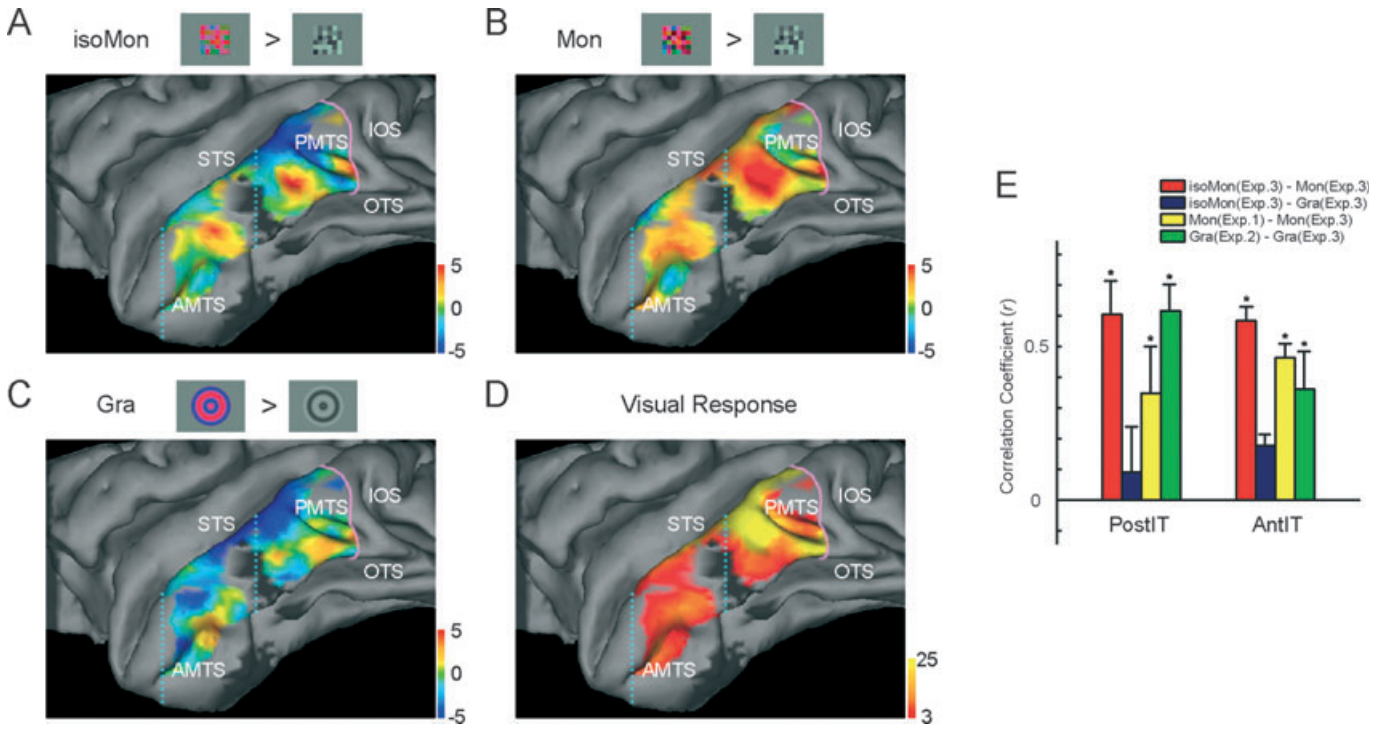

FIG. 6. Comparison between the patterns of colour-selective activity obtained with different types of stimuli. (A–C) Colour-selective response maps superimposed on the IT gyrus of the folded cortical surface of M2. These maps were obtained by contrasting isoluminant chromatic Mondrian vs. achromatic Mondrian (A, isoMon), chromatic Mondrian vs. achromatic Mondrian (B, Mon), and chromatic grating vs. achromatic grating (C, Gra) in Experiment 3. The maps were not statistically thresholded, but were restricted to the visually responsive region shown in (D). Positive values (green to red) represent the biased responses to chromatic stimuli, and negative values (green to blue) represent the biased responses to achromatic stimuli. (D) The visually responsive region superimposed on the same surface seen in the other three panels. This map was obtained by contrasting summed responses during all stimulus conditions with the responses during the fixation baseline in Experiment 3 ($P < 0.001$ uncorrected for multiple comparisons). (E) Correlation coefficient between pairs of colour-selective response maps in the posterior IT (PostIT ROI) and the anterior IT (AntIT ROI) averaged over four hemispheres. The column colour represents the pair of colour-selective response maps. The error bars represent the standard error of the mean over four hemispheres. The asterisks indicate that the average correlation coefficients between the pairs of maps were significantly positive ($P < 0.05$, permutation test). AMTS, anterior middle temporal sulcus; IOS, inferior occipital sulcus; OTS, occipital temporal sulcus; PMTS, posterior middle temporal sulcus; ROI, region of interest; STS, superior temporal sulcus.

visual categories (Logothetis *et al.*, 1999; Tsao *et al.*, 2003, 2006; Pinsk *et al.*, 2005) and provide important insight into the functional organization of the IT cortex with regard to the processing of colour information.

Colour-selective subregions in the anterior IT

Using Mondrian stimuli, we found a colour-selective region in or around the AMTS in the anterior IT. This suggests that, although colour-selective neurons may be scattered across the anterior IT cortex, this activated region contains larger numbers of colour-selective neurons and/or neurons that are more strongly colour-selective. Previous electrophysiological and imaging studies showed that there are numerous colour-selective neurons in the anterior IT (Komatsu *et al.*, 1992; Komatsu & Ideura, 1993; Tamura & Tanaka, 2001; Edwards *et al.*, 2003; Koida & Komatsu, 2007), and some studies have suggested that there are subregions with a relatively high proportion of colour-selective neurons in or around the AMTS (Komatsu *et al.*, 1992; Tamura & Tanaka, 2001; Tootell *et al.*, 2004; Yasuda *et al.*, 2004). Our present results are consistent with the findings of those earlier studies.

It should be noted, however, that different stimuli were used in those earlier studies, and the reported colour-selective subregions were in slightly different locations. For instance, using simple geometric shapes that were painted uniformly with single colours, Komatsu *et al.* (1992) and Yasuda *et al.* (2004) found that many colour-selective neurons are clustered in regions on the lateral bank of the AMTS and the gyrus lateral and slightly posterior to the AMTS. On the other hand, Tamura & Tanaka (2001) found that neurons preferring colourful natural image stimuli were more frequently located in the region medial/ventral to the AMTS than in the region lateral/dorsal to the AMTS. Using 2-deoxy glucose (2DG) imaging with grating stimuli, Tootell *et al.* (2004) identified colour-selective regions on the gyrus posterior to the AMTS. Thus, colour-selective responses are commonly observed around the AMTS, but the precise locations are not entirely consistent.

When we used Mondrian stimuli, we found that the activation was located in the fundus/lateral bank of the AMTS, or on the gyrus lateral and slightly posterior to the AMTS. This location is close to where colour-selective neurons were observed by Komatsu *et al.* (1992) and Yasuda *et al.* (2004), but is different from the results by Tamura & Tanaka (2001). This suggests that colour stimuli with simple geometrical patterns are effective for activation of the fundus/lateral bank of the AMTS, whereas more complex object images are necessary for activation of the area medial to the AMTS. Although the grating stimuli used in the present study is similar to those used by Tootell *et al.* (2004), we did not observe clear activation in the anterior IT with this stimulus. However, the grating stimuli did evoke weak localized activation near the posterior end of the AMTS (Fig. 6C), which may be strong enough to be detected by 2DG imaging, but not strong enough to be detected by fMRI.

Colour-selective subregions in the posterior IT

Using colour grating stimuli, we found colour-selective activity in a region ventral to the PMTS and in a region in the posterior STS within the posterior IT. Judging from the sulcal landmarks, the region near the PMTS is likely in area TEO. In earlier 2DG imaging and fMRI studies using grating stimuli, colour-selective activity was detected in TEO (Tootell *et al.*, 2004; Conway *et al.*, 2007), and a positron emission tomography study in monkeys also reported strong activation in TEO when monkeys performed a colour-discrimination task (Takechi *et al.*, 1997). With respect to the numbers and positions of the colour-selective subregions, our present results obtained using colour grating stimuli are largely consistent with those earlier findings.

Colour-selective regions in the posterior IT activated by Mondrian stimuli were located more anterior than those activated by grating stimuli. Judging from the sulcal landmarks, these regions are located in TEO or extend into the posterior part of area TE. Given that TEO has a coarse retinotopy (Boussaoud *et al.*, 1991; Brewer *et al.*, 2002; Yasuda *et al.*, 2009), the difference between the locations of the activated regions might in part reflect the difference in the extents of the two stimulus types in the visual field. However, the retinotopy cannot, by itself, explain the positional difference of the activations because the visually responsive regions obtained with each stimulus type largely overlapped. It is more likely that these regions have different stimulus selectivities.

Colour-selective activation in the posterior IT in response to the grating and Mondrian stimuli suggest clustering of colour-selective neurons in these regions. We recently found that sharply tuned colour-selective neurons are clustered in a region around the PMTS (Yasuda *et al.*, 2009). This region is close to the region in which grating stimuli evoked the colour-selective activation. An earlier electrophysiological study found a column containing neurons selective for multicoloured patterns in the IT gyrus, slightly anterior to the PMTS (Fujita *et al.*, 1992), at a position close to where we found colour-selective activity using Mondrian stimuli. However, this study did not examine whether the presence of those neurons was consistent across individuals, or whether they were clustered in this region. We suggest that columns preferring multicoloured patterns relatively concentrated in regions anterior to the PMTS.

Colour-selective activity in the STS

A recent study in which single-unit recording combined with fMRI revealed that a patch in the posterior STS contains a high proportion of colour-selective neurons (Conway *et al.*, 2007). By contrast, little is known about how colour-selective neurons distribute in the anterior part of the STS. Although earlier electrophysiological studies found colour-selective neurons in the anterior STS, there has been no study that conducted a systematic mapping around this region and no imaging study that addressed this issue. In our study, strong colour-selective activations in the anterior part of the STS were found only in two hemispheres of one monkey using Mondrian stimuli. This implies that there are colour-selective subregions in the anterior STS, but they were not effectively activated by our Mondrian or grating stimuli.

Potential influence of susceptibility artefact

Although we examined colour-selective activity in the entire IT cortex, we might have underestimated colour-selective activity in some regions, especially around the middle of the IT gyrus, where there was a region affected by susceptibility artefact. The locations of the affected region varied, depending on the hemisphere, some of which were close to or overlapped the colour-selective regions in the anterior and posterior IT. The susceptibility artefact may explain why some colour-selective regions were not reliably identified in some hemispheres, and also why the statistical significance of the colour-selectivity was relatively weak. This also leaves the possibility that some colour-selective activities in this region could have been overlooked. Measurements with methods that are free of the susceptibility artefact will be needed to test this possibility.

Stimulus-dependent activation of colour-selective subregions

Our results have shown that Mondrian and grating stimuli produce different patterns of colour-selective activation in the IT cortex. A remarkable difference was seen in the anterior IT; the Mondrian activated a region in the anterior IT, whereas the grating did not. This is in accordance with human fMRI studies; Mondrian stimuli activate multiple colour-selective areas/regions extending from the posterior to the anterior part of the fusiform gyrus (Beauchamp *et al.*, 1999; Bartels & Zeki, 2000; Brewer *et al.*, 2005), whereas isoluminant gratings produce colour-selective activation in a relatively posterior part of the fusiform gyrus, but not in more anterior regions (Hadjikhani *et al.*, 1998). This suggests that Mondrian stimuli are more suitable for identifying higher-order colour-selective areas/regions located more anteriorly within the ventral cortex.

Given that Mondrian and grating stimuli differ in many aspects – e.g. luminance contrast, chromatic structure, spatiotemporal frequency, global shape and motion – which is the critical factor responsible for the differential activation in higher-order areas is an intriguing question. To address that question in part, we used an isoluminant Mondrian stimulus to assess the influence of luminance contrast and found that the magnitudes of responses to nearly isoluminant Mondrian were diminished in the IT cortex. This suggests that the use of isoluminant stimuli is less effective for identification of colour-selective regions in the IT cortex, probably because these regions are sensitive to luminance contrast as well as colour contrast. However, the difference in the responses to the Mondrian and grating stimuli in the IT cortex cannot be attributed solely to the difference in luminance contrast; the topography of the colour-selectivity within the anterior and posterior IT was largely invariant with respect to luminance contrast (Fig. 6).

A salient difference between the Mondrian and grating stimuli is in their chromatic structure. Whereas the colour grating was modulated only along a red-blue axis, the colour Mondrian contained a variety of hues. This difference might have caused the difference in the responses across areas/regions, depending on the colour-tuning characteristics. Some areas/regions, typically the LGN, contain colour-selective neurons broadly tuned either to L − M or S − (L + M) cone-opponent signals (Derrington *et al.*, 1984; De Valois *et al.*, 2000; Hanazawa *et al.*, 2000), whereas other areas/regions contain colour-selective neurons narrowly tuned to hues and/or saturations (Lennie *et al.*, 1990; Komatsu *et al.*, 1992; Gegenfurtner *et al.*, 1996; Hanazawa *et al.*, 2000; Kusunoki *et al.*, 2006; Conway *et al.*, 2007; Kotake *et al.*, 2009). A multicoloured Mondrian stimulus may effectively elicit responses in regions containing many such hue-selective neurons, but a red-blue grating stimulus may not, as this grating cannot activate neurons narrowly tuned to specific hues such as green, yellow, orange, etc. This may explain why some colour-selective subregions in the IT were

effectively activated by the Mondrian stimulus but not by the grating stimulus.

In addition, the Mondrian and grating stimuli differ with respect to their spatiotemporal structures, such as spatial frequency, temporal frequency, global shape and motion. For example, the grating stimulus contained only low spatial and temporal frequencies (0.33 cycles/deg, 1 Hz), whereas the Mondrian stimulus contained a variety of spatial frequencies and an even lower temporal frequency (0.25 Hz). The difference in the spatiotemporal frequency could affect overall colour responsivity in V1 and V4, where responses to colour contrast are dependent on these factors (Schluppeck & Engel, 2002; Wade *et al.*, 2008). However, little is known about the extent to which colour responsivity and response topography in the monkey IT are dependent upon the spatiotemporal structure of the stimuli. Consequently, which factor was most critical for the difference in the responses between Mondrian and grating stimuli remains an open question for future study.

Functional correspondence between cortical areas in humans and monkeys

Do the regions we found in the monkey IT cortex correspond to any human areas/regions? Previous fMRI studies in humans revealed the presence of colour-selective areas/regions along the fusiform gyrus. These include V4 (McKeefry & Zeki, 1997), V8 (Hadjikhani *et al.*, 1998), the VO cluster (Brewer *et al.*, 2005), V4α (Bartels & Zeki, 2000) and regions on the anterior part of the fusiform gyrus (Beauchamp *et al.*, 1999; Bartels & Zeki, 2000; Brewer *et al.*, 2005). Among these, human V8 and the VO cluster are retinotopic areas lying next to V4 (Hadjikhani *et al.*, 1998; Wade *et al.*, 2002; Brewer *et al.*, 2005), whereas V4α and the regions in the anterior fusiform gyrus are presumably non-retinotopic areas located far anterior to V4. Correspondingly, single-cell activity recorded from monkeys suggests that there are retinotopic maps in the posterior part of the IT cortex (Boussaoud *et al.*, 1991; Yasuda *et al.*, 2009), but not in the anterior part of the IT cortex. The presence of retinotopic organizations and the anatomical locations with respect to V4 suggests that colour-selective regions in the macaque posterior IT may correspond to human V8/VO, and those in the macaque anterior IT may correspond to human V4α and the regions in the anterior fusiform gyrus, although there are some differences in the configuration of the retinotopic map between the monkey posterior IT and human V8/VO. Recent human fMRI studies and single-unit recording experiments in monkeys seem to shed some light on this issue. Recent imaging studies have suggested that in humans the anterior fusiform regions are active during conscious colour perception (Nunn *et al.*, 2002; Morita *et al.*, 2004; Murphey *et al.*, 2008) or when subjects perceive object colour and retrieve knowledge about object colour (Martin *et al.*, 1995; Zeki & Marini, 1998; Chao & Martin, 1999; Simmons *et al.*, 2007). These observations appear to be consistent with the recent findings that the activities of colour-selective neurons in the anterior IT correlate with the monkey's colour judgement (Koida & Komatsu, 2007; Matsumora *et al.*, 2008) and colour-object association (Edwards *et al.*, 2003).

Acknowledgements

We are grateful to K. Matsuda for providing the eye-tracking software. We also thank M. Togawa for technical assistance and T. Ohta for his assistance with animal training. This work is supported by a grant for Scientific Research on Priority Areas <System study on higher-order brain functions> (17022040) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

Abbreviations

2DG imaging, 2-deoxy glucose imaging; AMTS, anterior middle temporal sulcus; CSI, colour-selectivity index; fMRI, functional magnetic resonance imaging; IOS, inferior occipital sulcus; IR, infrared; IT cortex/IT gyrus, inferior temporal cortex/gyrus; ITI, inter-trial interval; LGN, lateral geniculate nucleus; MPRAGE, magnetization-prepared rapid-acquisition gradient-echo; OTS, occipitotemporal sulcus; PMTS, posterior middle temporal sulcus; ROI, region of interest; STS, superior temporal sulcus.

References

Bartels, A. & Zeki, S. (2000) The architecture of the colour centre in the human visual brain: new results and a review. *Eur. J. Neurosci.*, **12**, 172–193.

Beauchamp, M.S., Haxby, J.V., Jennings, J.E. & DeYoe, E.A. (1999) An fMRI version of the Farnsworth-Munsell 100-Hue test reveals multiple color-selective areas in human ventral occipitotemporal cortex. *Cereb. Cortex*, **9**, 257–263.

Boussaoud, D., Desimone, R. & Ungerleider, L.G. (1991) Visual topography of area TEO in the macaque. *J. Comp. Neurol.*, **306**, 554–575.

Brewer, A.A., Press, W.A., Logothetis, N.K. & Wandell, B.A. (2002) Visual areas in macaque cortex measured using functional magnetic resonance imaging. *J. Neurosci.*, **22**, 10416–10426.

Brewer, A.A., Liu, J., Wade, A.R. & Wandell, B.A. (2005) Visual field maps and stimulus selectivity in human ventral occipital cortex. *Nat. Neurosci.*, **8**, 1102–1109.

Buckley, M.J., Gaffan, D. & Murray, E.A. (1997) Functional double dissociation between two inferior temporal cortical areas: perirhinal cortex versus middle temporal gyrus. *J. Neurophysiol.*, **77**, 587–598.

Chao, L.L. & Martin, A. (1999) Cortical regions associated with perceiving, naming, and knowing about colors. *J. Cogn. Neurosci.*, **11**, 25–35.

Conway, B.R. (2009) Color vision, cones, and color-coding in the cortex. *Neuroscientist*, **15**, 274–290.

Conway, B.R. & Tsao, D.Y. (2006) Color architecture in alert macaque cortex revealed by fMRI. *Cereb. Cortex*, **16**, 1604–1613.

Conway, B.R., Moeller, S. & Tsao, D.Y. (2007) Specialized color modules in macaque extrastriate cortex. *Neuron*, **56**, 560–573.

De Valois, R.L., Cottaris, N.P., Elfar, S.D., Mahon, L.E. & Wilson, J.A. (2000) Some transformations of color information from lateral geniculate nucleus to striate cortex. *Proc. Natl Acad. Sci. USA*, **97**, 4997–5002.

Derrington, A.M., Krauskopf, J. & Lennie, P. (1984) Chromatic mechanisms in lateral geniculate nucleus of macaque. *J. Physiol.*, **357**, 241–265.

Desimone, R., Albright, T.D., Gross, C.G. & Bruce, C. (1984) Stimulus-selective properties of inferior temporal neurons in the macaque. *J. Neurosci.*, **4**, 2051–2062.

Edwards, R., Xiao, D., Keysers, C., Foldiak, P. & Perrett, D. (2003) Color sensitivity of cells responsive to complex stimuli in the temporal cortex. *J. Neurophysiol.*, **90**, 1245–1256.

Friston, K.J., Holmes, A.P., Poline, J.B., Grasby, P.J., Williams, S.C., Frackowiak, R.S. & Turner, R. (1995) Analysis of fMRI time-series revisited. *Neuroimage*, **2**, 45–53.

Fujita, I., Tanaka, K., Ito, M. & Cheng, K. (1992) Columns for visual features of objects in monkey inferotemporal cortex. *Nature*, **360**, 343–346.

Gegenfurtner, K.R. (2003) Cortical mechanisms of colour vision. *Nat. Rev. Neurosci.*, **4**, 563–572.

Gegenfurtner, K.R., Kiper, D.C. & Fenstemaker, S.B. (1996) Processing of color, form, and motion in macaque area V2. *Vis. Neurosci.*, **13**, 161–172.

Hadjikhani, N., Liu, A.K., Dale, A.M., Cavanagh, P. & Tootell, R.B. (1998) Retinotopy and color sensitivity in human visual cortical area V8. *Nat. Neurosci.*, **1**, 235–241.

Hanazawa, A., Komatsu, H. & Murakami, I. (2000) Neural selectivity for hue and saturation of colour in the primary visual cortex of the monkey. *Eur. J. Neurosci.*, **12**, 1753–1763.

Heywood, C.A., Gadotti, A. & Cowey, A. (1992) Cortical area V4 and its role in the perception of color. *J. Neurosci.*, **12**, 4056–4065.

Heywood, C.A., Gaffan, D. & Cowey, A. (1995) Cerebral achromatopsia in monkeys. *Eur. J. Neurosci.*, **7**, 1064–1073.

Horel, J.A. (1994) Retrieval of color and form during suppression of temporal cortex with cold. *Behav. Brain Res.*, **65**, 165–172.

Huxlin, K.R., Saunders, R.C., Marchionini, D., Pham, H.A. & Merigan, W.H. (2000) Perceptual deficits after lesions of inferotemporal cortex in macaques. *Cereb. Cortex*, **10**, 671–683.

Kobatake, E. & Tanaka, K. (1994) Neuronal selectivities to complex object features in the ventral visual pathway of the macaque cerebral cortex. *J. Neurophysiol.*, **71**, 856–867.

Koida, K. & Komatsu, H. (2007) Effects of task demands on the responses of color-selective neurons in the inferior temporal cortex. *Nat. Neurosci.*, **10**, 108–116.

Komatsu, H. & Ideura, Y. (1993) Relationships between color, shape, and pattern selectivities of neurons in the inferior temporal cortex of the monkey. *J. Neurophysiol.*, **70**, 677–694.

Komatsu, H., Ideura, Y., Kaji, S. & Yamane, S. (1992) Color selectivity of neurons in the inferior temporal cortex of the awake macaque monkey. *J. Neurosci.*, **12**, 408–424.

Kotake, Y., Morimoto, H., Okazaki, Y., Fujita, I. & Tamura, H. (2009) Organization of color-selective neurons in macaque visual area V4. *J. Neurophysiol.*, **102**, 15–27.

Kusunoki, M., Moutoussis, K. & Zeki, S. (2006) Effect of background colors on the tuning of color-selective cells in monkey area V4. *J. Neurophysiol.*, **95**, 3047–3059.

Lennie, P., Krauskopf, J. & Sclar, G. (1990) Chromatic mechanisms in striate cortex of macaque. *J. Neurosci.*, **10**, 649–669.

Lewis, J.W. & Van Essen, D.C. (2000) Mapping of architectonic subdivisions in the macaque monkey, with emphasis on parieto-occipital cortex. *J. Comp. Neurol.*, **428**, 79–111.

Logothetis, N.K., Guggenberger, H., Peled, S. & Pauls, J. (1999) Functional imaging of the monkey brain. *Nat. Neurosci.*, **2**, 555–562.

Martin, A., Haxby, J.V., Lalonde, F.M., Wiggs, C.L. & Ungerleider, L.G. (1995) Discrete cortical regions associated with knowledge of color and knowledge of action. *Science*, **270**, 102–105.

Matsuda, K., Nagami, T., Kawano, K. & Yamane, S. (2000) A new system for measuring eye position on a personal computer. *Program No. 744.2. 2000 Abstract Viewer/Itinerary Planner*, *Society for Neuroscience*, New Orleans, LA.

Matsumora, T., Koida, K. & Komatsu, H. (2008) Relationship between color discrimination and neural responses in the inferior temporal cortex of the monkey. *J. Neurophysiol.*, **100**, 3361–3374.

Mazaika, P., Gabrieli, S.W. & Reiss, A. (2007) Artifact repair for fMRI data from high motion clinical subjects. *13th Annual Meeting of the Organization for Human Brain Mapping*, Chicago, IL.

McKeefry, D.J. & Zeki, S. (1997) The position and topography of the human colour centre as revealed by functional magnetic resonance imaging. *Brain*, **120**, 2229–2242.

Morita, T., Kochiyama, T., Okada, T., Yonekura, Y., Matsumura, M. & Sadato, N. (2004) The neural substrates of conscious color perception demonstrated using fMRI. *Neuroimage*, **21**, 1665–1673.

Mullen, K.T., Dumoulin, S.O., McMahon, K.L., de Zubicaray, G.I. & Hess, R.F. (2007) Selectivity of human retinotopic visual cortex to S-cone-opponent, L/M-cone-opponent and achromatic stimulation. *Eur. J. Neurosci.*, **25**, 491–502.

Murphey, D.K., Yoshor, D. & Beauchamp, M.S. (2008) Perception matches selectivity in the human anterior color center. *Curr. Biol.*, **18**, 216–220.

Nunn, J.A., Gregory, L.J., Brammer, M., Williams, S.C., Parslow, D.M., Morgan, M.J., Morris, R.G., Bullmore, E.T., Baron-Cohen, S. & Gray, J.A. (2002) Functional magnetic resonance imaging of synesthesia: activation of V4/V8 by spoken words. *Nat. Neurosci.*, **5**, 371–375.

Ojemann, J.G., Akbudak, E., Snyder, A.Z., McKinstry, R.C., Raichle, M.E. & Conturo, T.E. (1997) Anatomic localization and quantitative analysis of gradient refocused echo-planar fMRI susceptibility artifacts. *Neuroimage*, **6**, 156–167.

Pinsk, M.A., DeSimone, K., Moore, T., Gross, C.G. & Kastner, S. (2005) Representations of faces and body parts in macaque temporal cortex: a functional MRI study. *Proc. Natl Acad. Sci. USA*, **102**, 6996–7001.

Saleem, K.S. & Logothetis, N.K. (2007) *A Combined MRI and Histology Atlas of the Rhesus Monkey Brain in Stereotaxic Coordinates*. Elsevier, London.

Schluppeck, D. & Engel, S.A. (2002) Color opponent neurons in V1: a review and model reconciling results from imaging and single-unit recording. *J. Vis.*, **2**, 480–492.

Simmons, W.K., Ramjee, V., Beauchamp, M.S., McRae, K., Martin, A. & Barsalou, L.W. (2007) A common neural substrate for perceiving and knowing about color. *Neuropsychologia*, **45**, 2802–2810.

Takechi, H., Onoe, H., Shizuno, H., Yoshikawa, E., Sadato, N., Tsukada, H. & Watanabe, Y. (1997) Mapping of cortical areas involved in color vision in non-human primates. *Neurosci. Lett.*, **230**, 17–20.

Tamura, H. & Tanaka, K. (2001) Visual response properties of cells in the ventral and dorsal parts of the macaque inferotemporal cortex. *Cereb. Cortex*, **11**, 384–399.

Tootell, R.B., Nelissen, K., Vanduffel, W. & Orban, G.A. (2004) Search for color 'center(s)' in macaque visual cortex. *Cereb. Cortex*, **14**, 353–363.

Tsao, D.Y., Freiwald, W.A., Knutsen, T.A., Mandeville, J.B. & Tootell, R.B. (2003) Faces and objects in macaque cerebral cortex. *Nat. Neurosci.*, **6**, 989–995.

Tsao, D.Y., Freiwald, W.A., Tootell, R.B. & Livingstone, M.S. (2006) A cortical region consisting entirely of face-selective cells. *Science*, **311**, 670–674.

Van Essen, D.C. (2002) Windows on the brain: the emerging role of atlases and databases in neuroscience. *Curr. Opin. Neurobiol.*, **12**, 574–579.

Van Essen, D.C., Drury, H.A., Dickson, J., Harwell, J., Hanlon, D. & Anderson, C.H. (2001) An integrated software suite for surface-based analyses of cerebral cortex. *J. Am. Med. Inform. Assoc.*, **8**, 443–459.

Wade, A.R., Brewer, A.A., Rieger, J.W. & Wandell, B.A. (2002) Functional measurements of human ventral occipital cortex: retinotopy and colour. *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, **357**, 963–973.

Wade, A., Augath, M., Logothetis, N. & Wandell, B.A. (2008) fMRI measurements of color in macaque and human. *J. Vis.*, **8**, 1–19.

Yasuda, M., Koida, K., Goda, N. & Komatsu, H. (2004) Regional Specialization for Color Processing in Area TE of the Monkey. *Program No. 174.1. 2004 Abstract Viewer/Itinerary Planner*, *Society for Neuroscience*, San Diego, CA.

Yasuda, M., Banno, T. & Komatsu, H. (2009) Color selectivity of neurons in the posterior inferior temporal cortex of the macaque monkey. *Cereb. Cortex*, in press. DOI:10.1093/cercor/bhp227.

Zeki, S. & Marini, L. (1998) Three cortical stages of colour processing in the human brain. *Brain*, **121**, 1669–1685.