Functional architecture of eye position gain fields in visual association cortex of behaving monkey

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Abstract

In the behaving monkey, inferior parietal lobe cortical neurons combine visual information with eye position signals. However, an organized topographic map of these neurons’ properties has never been demonstrated. Intrinsic optical imaging revealed a functional architecture for the effect of eye position upon the visual response to radial optic flow. The map was distributed across two sub-divisions of the inferior parietal lobule, area 7a and the dorsal prelunate area, DP. Area 7a contains a representation of the lower eye position gain fields while area DP represents the upper eye position gain fields. Horizontal eye position is represented orthogonal to the vertical eye position across the medial lateral extents of the cortices. Similar topographies were found in three hemispheres of two monkeys; the horizontal and vertical gain field representations were not isotropic with a greater modulation found with the vertical. Monte Carlo methods demonstrated the significance of the maps and they were verified in part using multiunit recordings. The novel topographic organization of this association cortex area provides a substrate for constructing representations of surrounding space for perception and the guidance of motor behaviors.

Key Words: Vision, inferior parietal cortex, cortical topography, monkey, eye position.

Introduction

Classical studies of the primate inferior parietal lobule began with shrapnel injuries during World War I (Head and Holmes 1911; Critchley 1953). Modern electrophysiological measurements revealed the subdivisions and defined the neuronal properties of the inferior parietal lobules of the macaque monkey cortices have two visual association areas that lie upon the
cortical gyrii, area 7a and the dorsal prelunate (DP) area (Siegel and Read 1997b). The receptive fields of electrically recorded single neurons in monkeys for these regions often approach 60° in size, can be bilateral and at least those of area 7a are selective to navigational optic flow (Motter and Mountcastle 1981; Read and Siegel 1997; Siegel and Read 1997a). The gain of the visual responses of inferior parietal lobule neurons is modulated by the position of the eye in the orbit and the monkey’s behavioral state (Bushnell et al. 1981b; Andersen et al. 1985; Read and Siegel 1997). There has been no evidence from any measurements of single cells for a mapping of these properties across the inferior parietal lobule’s surface in the behaving monkey (Blatt et al. 1990; Andersen et al. 1990).

Anatomical projections between the inferior parietal lobule and the frontal and temporal lobes suggest that there may be topographies. The projections are patterned regions of interdigitated columns and regions of overlap (Cavada and Goldman-Rakic 1989; Andersen et al. 1990; Lewis and Van Essen 2000). When retrograde tracers are injected in two projective areas (e.g. area 8 and 46), stripes of overlapping cell bodies which can diverge are found in area 7a (Andersen et al., 1990). Such projection patterns elsewhere (e.g. between V1 and V2 (Ts'o et al. 2001)) have been correlated with functional architectures and could indicate the presence of similar organizing principles in the inferior parietal lobule. Given the relatively small surface area of the cortical regions in the inferior parietal lobule and the large receptive and gain fields, the paucity of published electrophysiological mapping data may simply indicate that the orbital gain fields overlap substantially across the surface and have no topography. Alternatively the single unit methodology may be technically unable to unveil a functional architecture in chronic behaving monkey studies because there are substantial errors in the localization of electrode penetrations over the one or two years needed for recording (Andersen et al. 1990; Siegel and Read 1997a). Another possibility is the relationship of gaze direction to cortical topography may be dynamic in ways that require large areas to be examined.
simultaneously (or nearly so) for these properties. The absence of explicit knowledge for an inferior parietal lobule functional architecture has substantially hindered an exploration of how the underlying circuitry can compute a neuronal correlate for spatial cognition.

Optical imaging utilizes light to assess the oxygenation of hemoglobin (Hb) and thus indirectly measure neuronal metabolism and activity. This technology permits multiple measurements over an extended period of time and space in the behaving monkey (Shtoyerman et al. 2000), and allows for a direct assessment of maps in the inferior parietal lobule. In the current study, intrinsic optical imaging has revealed a novel map of eye position modulating visual responses in the inferior parietal lobule. This architecture is discussed in terms of constraints upon subsequent spatial perceptual and motor processing.

**Experimental procedures**

**Surgical details**

Two monkeys were prepared for chronic behavioral studies using standard methods (Siegel and Read 1997a). The use of the artificial dura permits long term studies and followed published methods (Shtoyerman et al. 2000) with modifications as described here. During the implant surgery performed under sterile conditions and isoflurane (0.5-2% in O₂) anesthesia, the animal was given Rocephin antibiotic (ceftriaxone sodium, Roche, 100-150 mg/kg/day IM); mannitol (25% 1ml/kg IV) and furosimide (1mg/kg IM) prior to opening the dura. The latter two minimized cerebral edema. The artificial dura consisted of a thin 50 µm silicon sheet with an embedded silicon ring (Shtoyerman et al. 2000); it was inserted after resecting the biological dura in an “X” shape within the stainless steel recording chamber. The flaps of the dura were glued to the chamber edge and the 25 mm diameter artificial dura was inserted between the real dura and the cortex. A silicon ring (18mm diameter) prevented movement of the artificial dura. The chamber was rinsed with body temperature saline and sealed. Antibiotics were continued for 7-10 dy; analgesics (buprenorphorphine; 2-6 mcg/kg IM) were given for ~3 dy. Typically the granulation tissue
in the chamber sealed against the edge of the silicon ring providing a watertight seal within 3 dy of the surgery.

Monkey 1 had recordings made from its right hemisphere from March 1999-July 2002 and is referred to as M1R; Monkey 2 had recordings from its right hemisphere from June 2001-August 2001 and is referred to as M2R. A second chamber was implanted overlying the left hemisphere in M2 in September of 2002; recordings collected two months after the implant are described and are referred to as M2L.

The full angle-of-gaze study (see below) for M1R was mainly collected over the first 75 days following the implant; controls and other experiments were collected subsequently. M2R had a sub-dural bleed (4x4 mm) which obstructed the cortex two weeks after the implant that prevented electrical recording and extensive optical recording. After the bleed cleared, additional optical recordings were made for six weeks until granulation tissue under the artificial dura obscured the cortex. Upon removal the artificial dura was found to have a small tear which probably initiated the bleeding. M1R and M2R chambers continue to be studied in additional experiments as of December 2002.

All procedures were approved by the Rutgers University Animal Institutional Review Board and were in accordance with the NIH Guidelines on the Care and Use of Animals in Research.

**Behavior**

The monkey pulled back a key within an 800 msec time window of the fixation point onset. Two seconds after the fixation point onset, the dot stimulus would start (Figure 1a). During 4000-6000 msec after fixation onset, the stimulus would change its structure (Figure 1b) and the monkey had to release the key within a 150-800 msec reaction time window for 0.1-0.2 cc juice reward. Breaking of eye fixation (greater than 1° deviation) terminated the trial with no reward (Siegel and Read 1997a). In most experiments, the
fixation point was placed in one of nine positions in a 3x3 grid, 20° on a size, and the expansion optic flow field was placed over the fixation point (Figure 1c). Optic flow is known to modulate the firing rate of neurons in area 7a (Siegel and Read 1997a). As the receptive fields in area 7a are 20-40° in size (Andersen et al. 1985; Read and Siegel 1997), 20° diameter flow stimuli were used.

In some experiments, another stimulus set was utilized to examine upper and lower gaze field tuning. Two fixation positions (e.g. (0, 10°) and (0,-10°)) were used; over the fixation one of two different optic flows (expansion, compression, clockwise and counterclockwise) were presented in each trial; The fixation conditions for which expansion and compression optic flow was presented were analyzed as part of the current study; the remaining data serve as the basis for a study of optic flow (Raffi and Siegel, in preparation; Raffi and Siegel 2002).

**Optical imaging technique**

The monkey’s head was firmly attached to a floating Newport air table via an implant made of Palacos R radiopaque bone cement (cat. 12-0001, Smith+Nephew Richards Inc., Memphis, TN) over the skull held with up to 20 Synthes (Paoli, PA) titanium screws. This implant was made in a recovery surgery 1-6 months prior to the artificial dura implant. The implant covered the skull from the occipital notch to the frontal bone and laterally replaced the insertion points of the temporalis muscles. Embedded in the cement was a custom stainless steel t-bar fixture with a 6.35 mm x 50 mm x 30 mm hardened steel plate in the frontal plane. This combination provided exceptional rigidity. The camera was also attached to the Newport table using off-the-shelf components.

Intrinsic optical imaging methods were used to study the cortical topography (Shtoyerman et al. 2000). The macroscope somewhat based upon optical principles of Ratzlaff and Grinvald (1991) consisted of a Nikon Nikkor AF Micro 60 mm/2.8D lens and a 50 mm Nikon 1.2 lens (#385083) as the objective. Unlike the Ratzlaff/Grinvald
macroscope where the matched lenses are focused at infinity, the 60 mm Nikkor Micro lens focused on the inverted image from the 50 mm objective lens. Adjusting the focal plane of the 60 mm Nikkor lens permitted variation of the magnification as well as an unusually long 30 to 80 mm working distance while maintaining a narrow depth of field. Images were taken from two monkeys who had 20 mm diameter chambers implanted over a trephination in the skull (as described above), based upon magnetic resonance images (Figure 2a and 2b). The chamber was filled with 0.9% saline and hydraulically sealed with a glass plate for optical imaging.

Typically 750x480 pixel images were collected at 605 nm with 17.3 µm/pixel resolution at a depth of 500 µm below surface capillaries (imaged with green light). These were resampled to provide a 34.6 µm/pixel resolution. The data was not spatially or temporally filtered, other than the reduction of the spatial resolution by a factor of two to avoid inducing spatial distortions or filtering artifacts. Major veins and arteries could be distinguished based upon the presence of pulsations.

**Image analysis**

The Optical Imaging Company 2001 system (Rehovot, Israel) was used to collect optical data. Data collection was initiated by first collecting a reference image in the interval between trials while the monkey was not in the task. This reference image served to set the amplifiers’ gains and offsets. Two-hundred and fifty six frames at 30 Hz were averaged; a reference image was collected every sixteen trials (~160 sec). This reference image was stored in memory and subtracted from incoming images in real time by the Optical imaging system. This difference image was digitized by the imaging system and stored on disk. Offline, the reference image and difference image were combined to provide measurements of total reflectance with up to 16 bits precision. Optical images were collected for every trial. At the same time, a behavioral control computer kept records of the animal's performance (Siegel and Read, 1997a) and was synchronized with the Optical
Imaging system via a set of digital lines. An IBM SP2 computer and an imaging package (Khoral Research Inc., Albuquerque, NM) were used for subsequent analysis and display. All trials for which the monkey incorrectly performed the trial (e.g. eye movement, incorrect lever movement) were rejected from the data set. A typical run would result in 30-90 trials per condition or 270-810 trials each day.

**Baseline normalization analysis (BNA):** A regression analysis was utilized. It normalized each trial’s data by a baseline value collected at the start of the trial. The evoked reflectance signal was quantified by subtracting the “baseline” image (averaged for -1000 to 0 msec relative to stimulus onset) from the signal averaged over the 2000-3000 msec after stimulus onset. At this time the monkey was fixating an initial red target and holding back the manipulandum. The resulting difference image for the $i^{th}$ presentation was expressed as a percentage change from the “baseline.” Thus the percentage change in reflectance was:

$$D_i(I,J) = 100 \frac{E_i(I,J) - B_i(I,J)}{B_i(I,J)}$$  

where the mean evoked response was $E_i(I,J) = \frac{\sum_{t=2000}^{3000\text{msec}} U(I,J)}{N}$ (N is the number of frames in the interval (2000,3000) and similarly for the mean baseline response $B_i(I,J)$. Four hundred to 1200 images corresponding to all behaviorally correct trials were collected per experiment.

Data from some trials needed to be rejected as outliers, either from excessive movement of the monkey’s torso which could move the brain slightly or from an error in the data collection system. Failure to perform this rejection could result in a topography that would be dominated by the gargantuan signal from one aberrant trial. This rejection was performed offline by an automated algorithm. A mask was superimposed on each of these images solely to perform offline automated trial rejection (Figure 3). The mask served to exclude large blood vessels and dimly illuminated cortex from the rejection procedures.
The masked image was computed with the following heuristic. The mean reference image (Figure 3a) on a pixel-by-pixel basis of the ~26-52 reference images were computed. From this average image, the mean and standard deviation of all its pixel values was computed. The pixels of the image were thresholded to “1” if they were one-half of a standard deviation greater than the mean to form the mask and to “0” otherwise (Figure 3b). This mask excluded the larger blood vessels. This binary mask was then multiplied on a pixel-by-pixel basis with the individual difference images from each trial and the mean and standard deviation of this masked collection of pixels was thus computed. The distribution of the means of the masked regions followed a reasonable approximation to a normal distribution (Figure 3d) and only trials that fell within one standard deviation of the mean were further analyzed. A plot of the mean versus the standard deviation yielded a parabolic-like curve, which was further utilized for automated rejection (Figure 3d). Points that had standard deviations within 0.1% of the value 0 were rejected; such trials arose from an error in the data collection software and were less than 1% of the total trials. This parabolic relationship is expected from a normal distribution of the pixels values within each image and could be exploited in the future for additional higher order noise based analysis. In short, trials for which the mean evoked signal was more than one standard deviation from the mean of all evoked signals were rejected to remove outliers. These varied between 10-20% of the behaviorally correct trials. This automated approach differs from earlier studies for which trial rejection was performed manually (Grinvald et al. 1991) or not at all (Vnek et al. 1999).

The mean image for each stimulus condition was computed resulting in nine average images per experiment corresponding to the nine fixation points. Parameter maps were constructed using standard linear regression methods (PROC GLM, SAS Co., Durham, NC) on individual pixel values. The nine average images in units of percentage change in luminance (units of %) were used. For every pixel, the equation:
\[ D_i(I,J) = \alpha_x(I,J)E_x + \alpha_y(I,J)E_y + \beta(I,J) + \varepsilon(I,J), \]  

was evaluated, where \( D_i(I,J) \) is the \( i \)th trial’s change in reflectance for the \((I,J)\) pixel (%), \( \alpha_x(I,J) \) and \( \alpha_y(I,J) \) are the slopes of the regression for each pixel (%/deg), \( \beta(I,J) \) is the intercept for each pixel (%), \( \varepsilon(I,J) \) is the error values, and \( E_x \) and \( E_y \) are the fixation point (and stimulus center) position. This equation defines a plane with a maximum slope of \( \sqrt{\alpha_x^2 + \alpha_y^2} \) at an angle of \( \theta = \arctan(\alpha_y/\alpha_x) \) relative to the \( x \)-axis (indices \((I,J)\) omitted here for clarity). As the optical signal is the negative of the expected rate of neuronal firing (Shtoyerman et al. 2000), the angle maps were constructed by multiplying each slope parameter by \(-1\) prior to computing the quadrant for each \( \arctan \). The same parameter maps were obtained whether the average single condition maps were used or all the individual trials were used in the regression, presumably because the error is approximately a normal distribution about the mean. Generally the average single condition images were used to reduce computational requirements. Regions of interest (ROI) were chosen for simple computations of means and standard deviations as described in **Results**. A Monte Carlo analysis was used to establish the error for this entire analysis. In summary, the BNA was devised to examine the changes in the optical signal from a defined baseline and is analogous to electrophysiological studies where the changes in firing rate relative to baseline are assessed (Siegel and Read, 1997).

**Results**

An image of monkey 1’s right (M1R) hemisphere's exposed cortex (Figure 2a) taken with green (540 nm) illumination reveals the angioarchitectonics of the inferior parietal lobule (Figure 2b and 6a). In order to reduce the contribution of the blood vessels to the signal and to emphasize the oxygenation signal (Shtoyerman et al. 2000), the cortex was imaged at a wavelength of 605 nm with a modified macroscope (Ratzlaff and Grinvald 1991) at a depth of 500 µm.
Prior single unit studies have established that both area 7a and DP neurons have "gain fields" (Andersen et al. 1985; Andersen et al. 1990; Read and Siegel 1997; Colby and Goldberg 1999). The concept of a “gain field” means that the amplitude of a response to a visual stimulus can be increased or decreased by the position of the eye in the orbit. To determine if there was a cortical topography of the gain field, two monkeys performed the motion detection task with the fixation point placed in one of nine locations in a 20x20° grid (Figure 1c) while a 13x8 mm region of cortex was imaged. A navigational optic flow stimulus was presented 2000 msec after fixation point onset and was always centered over the fixation point.

**Time course of optical signal**

In the inferior parietal lobules of the monkeys performing the task, the time course of the optical signal differed from that typically reported in primary visual cortex in behaving animals. In primary visual cortex studies, the initial event triggering the alteration in blood flow that underlies the optical signal is the actual visual mapping stimulus (Shtoyerman et al. 2000). In the reaction task used here, there were multiple retinal and extra-retinal events that could alter the neural activity of inferior parietal lobe and hence the hemoglobin and optical signal. The initial relevant event in the recording sequence is the onset of the fixation point closely followed (< 500 msec) by the saccadic eye movement to the fixation point and the hand pulling the key. Both area 7a and DP neurons are sensitive to eye position, fixation point onsets and the planning of motor activity (Andersen et al. 1985; Andersen et al. 1987; Andersen et al. 1990; Siegel and Read 1997a), so it was not unexpected that these three events taken together were correlated with changes in the optical signal measured at 605 nm (Figure 5). The region of interest in the two images is illustrated in the line drawing above each time course. Temporal signals were computed by spatially averaging an 1x1 mm square region of cortex; but not averaging in time. Often, but not always, there was a negative dip in the optical signal followed by a positive overshoot (e.g. dark thick line of Figure 5a). The timing and amplitude of the initial
changes over the first 1000 msec of the trial was variable across experiments reflecting the uncontrolled behavioral state prior to fixation (c.f. Figure 5a and 5b; for M1R and M2L respectively.) Variation was found both within animals and within cortical areas, hence the differences in Figure 5a and 5b were not simply as result of the cortical region or animal studied. The baseline period from -1000 to 0 msec before the stimulus was used to normalize the optical signal, as complete behavioral control was obtained just before this interval and the time course was reasonably similar.

Based upon gain field single unit work (Siegel and Read 1997a), the optical signal should modulate as a function of the position of the eye in the orbit and the visual stimulus. In order to evaluate the optical correlate of the gain field effect, expansion or compression flow stimuli were presented in a 2x2 factorial design with either up or down fixations in M1R and M2L. The flow stimulus began two seconds after the fixation point and was centered over that location (Figure 5). Although there is variability in the time course prior to the (-1000,0) interval, at that time the time courses converge indicating that the optical signal is similar across the different fixations. For the area DP region of Figure 5a, at about 1000 msec after stimulus onset, the optical time course depended on the type of optic flow for upwards fixation (c.f. the heavy and thin black lines). The differential response to the optic flows was also found for downwards fixation (c.f. heavy and thin grey lines.) For the 7a region of Figure 5b, the dependence of the optical signal on the type of optic flow is best seen for the downwards (grey lines) fixation. For this particular patch of cortex, there is a weak dependence of the signal on the visual stimulus.

Across experiments, maximal differences were seen in the 2000 to 3000 msec interval following the onset of the visual stimulus. Hence the 2000-3000 msec interval after flow onset was used as a measure of the underlying visually evoked neural activity; optical measurements were expressed as the percentage change from the baseline signal and is the basis of the baseline normalization analysis.
This type of experiment was repeated over 10 times in M1R and 6 times in M2L. The reflectance signal depended on the expansion and compression stimulus as well as eye position. The modulation depended on the position on the cortex. Indeed this optical tuning in area DP is the first evidence for optical flow selectivity in DP. These results suggest a mapping of optical flow as well as gain fields across the inferior parietal lobe which serves as the basis of another study under preparation (Raffì and Siegel 2002). The remainder of the current report only examines the effect of eye position upon the expansion optic flow evoked response.

**Cortical topography of optical signal**

In order to explore the dependence of the reflectance upon eye position, only expansion optic flow was used. The monkeys performed the fraction of structure detection task for nine different fixations on a 20x20° grid (Figure 1c). In each case, the expansion stimulus was centered over the fixation point. Two experiments in M1R are presented in Figures 2/4 and Figure 6. For M1R, averaging across all fixation conditions, the modulation in the reflected light over the baseline was about 0.5% and varied across the cortex (Figure 2c and 6b). There was a smaller (~0.1%) amplitude light evoked response that depended on the monkey’s eye position (Figure 2d and 6g). The reflected light varied both as a function of the particular eye position and the particular location on the cortex, suggesting there was a cortical topography for the gain field. The two experiments performed one day apart have similar effects in the single condition maps (c.f. Figure 2 and 6). Thus when the fixation and the stimulus were at the upper right on the screen (10°,10°), a bright signal was found at the right portion of area 7a. When the fixation and stimulus were at lower left on the screen (-10°,-10°), a bright signal was found in the right portion of DP (Figure 2d and 6g). There was a clear border between 7a and DP at the blood vessels that runs across the middle of the images. By low power microscopic examination it was determined that the superior temporal sulcus did not extend that far dorsally, so that the border ran under the
large vessel, but across a flat cortical surface. Thus in both experiments there appears to be a discontinuity in the representation underneath this blood vessel.

In order to combine the data from these nine maps, the mean optical signal at every pixel was linearly regressed upon the orbital position using the baseline normalization analysis (Methods). Maps of the regression parameters were constructed. The intercept parameter map (Figure 4a and 6d) is the change in measured light expected when the monkey was fixating straight ahead and the stimulus was over the fixation point. The map of the vertical slopes ($\alpha_y$) of the regression (Figure 4c and 6f for M1R) illustrate how the optical signal depended on both the horizontal and vertical fixation position. DP had predominantly negative values for the vertical regression coefficient, while 7a had positive values. This means that fixation in the upper visual field leads to smaller (i.e. more negative) optical signals in DP. Similarly, the positive vertical coefficient values in area 7a indicate a maximal reflected light response for upper field fixations. There is also a horizontal eye position dependence of the reflected light ($\alpha_x$) which can best be seen in DP (Figure 4b and 6e which depict the horizontal slope, $\alpha_x$). For example in Figure 4b, most of area 7a and DP have similar horizontal tuning except for the most lateral part of DP, which is darker.

The horizontal and vertical coefficient parameter maps were transformed from rectangular to polar coordinates (Methods.) In polar coordinates, each pixel was represented by a polar vector with an amplitude (Figure 4d, data not shown for Figure 6) and angle (Figure 4e and 6c). The “amplitude map” was constant across the imaged regions outside of the blood vessels and suggests that the optical signal strength is constant across the imaged region. In order to compute an “angle map” that reflected the underlying neuronal electrical activity, the sign of the slopes was changed to account for the negative relationship between the 605 nm signal and the neuronal signal (Shtoyerman et al. 2000); the angle map illustrates the gain fields’ dependence on eye position and cortical location.
The angle map had two clearly demarcated gain fields within the 13x8 mm image. Regions of interest are indicated for each map; the angle corresponding to that ROI is indicated in small type above and below each image. According to the angle map, neurons in DP should increase firing rate when a visual stimulus was presented over the fovea while the monkey was looking up; similarly neurons of 7a should be best activated when looking down and to the left. This 7a/downwards and DP/upwards split of the imaged regions was modulated within each region by the horizontal eye position. As one progresses counterclockwise from ventral DP, the direction of gain field tuning progresses clockwise. As the strength of the horizontal modulation was variable between the two experiments, the smoothness and completeness of the representation varies. A more lateral image of the gain field map taken from a third experiment in M1R is illustrated in Figure 4f; the gain field extends to the most posterior portions of DP that can be imaged; in this one lateral view, there appears to be another shift in the gain field in the more lateral portions of DP and 7a. In each of the three examples of the gain field map of M1R (Figure 4e, 4f and 6c), upper and lower field gain breakdown is seen. The horizontal tuning is weaker and more variable between these different experiments.

**Comparison of maps across days**

This main result of a division in the gain field between area 7a and DP was reproduced within M1R by collecting 14 maps over a period of 78 days. Two regions of interests (ROIs), one in area 7a and one in area DP were initially chosen for analysis (Figure 7). The ROI were placed so as to be observed in as many day’s data as possible (for comparisons between days) and to be roughly the same distance from the junction of the intra-parietal and lunate sulci as well as equidistant from the large vessel in the middle of the chamber. This was to make the effect of vessel induced pulsations equivalent for the two locations. The medial-lateral position was arbitrarily selected. A ROI was chosen to be about 2x2 mm square. The circular mean and standard error of the gain field for the ROIs
was 283±11° for area 7a, and 99±8° for area DP. The locations and means for six additional ROIs were computed as summarized in Figure 7 in order to sample across the cortex in more unbiased manner. Using the total of eight ROIs, there are a few key observations. The area 7a and DP regions clearly had differences in terms of upper and lower field representation at all positions. There appeared to be a slight trend for further modulation along the horizontal direction within each cortical field which might have been obscured by the averaging across days.

The measurements for the ROIs in area 7a and DP were compared for the most lateral position with a Watson’s F-test for circular means and were significantly different (P<.01, DF=11). The mean difference between the 7a and DP tuning on a day by day basis was 190±17°, and was significantly different from a uniform circular distribution. Thus DP and 7a have significantly different gain field representations for these two ROIs, with DP expected to have stronger electrophysiological responses for upper fixations, and area 7a having a stronger expected gain field representation for lower field fixations. Additional paired comparisons were made for each matched medial-lateral positions and each was found to be different for the upper and lower positions.

**Monte Carlo analysis**

To get an independent estimate of the reproducibility of the measurements and analysis within a day, Monte Carlo methods were used (Methods). The data from some of the full nine position gain field experiments were tested. The core idea behind the Monte Carlo study was to test the hypothesis that the maps were specifically linked to the stimulus conditions. More formally, the null hypothesis was that there was no relationship between the stimulus presentation and the resulting maps.

To test this hypothesis, two manipulations were compared. In the first manipulation, half of the data was randomly selected from the original data and the map computed. The other half of the data was used for another map. The second manipulation was to randomly
assign a stimulus condition to each trial for half the data and computing the map; the remaining data was used to construct another map continuing this randomization. (Formally, one would say that the data was randomly assigned to the stimulus conditions, without replacement.) Thus the specific relationship between the actual data and the stimulus used to collect it was destroyed. Maps were then constructed for the resulting “new” data set (Figure 8).

Each pass through the data set then provided four new maps; two were made respecting the relationship between the data and the stimuli and two with disrupted relationships. Two populations of parameter maps are constructed in this way and the resulting distributions are compared. The direction parameter map is reproduced from Figure 2 as Figure 8b. Figure 8a and 8c show some examples of the bootstrap parameter maps respecting and disrupting the relationships between the stimuli and data respectively. If the null hypothesis of no fixed relationship between the measured data and the stimulus condition was true, then the two populations would be the same. If there was indeed a relationship between the recorded data and the stimulus conditions, then the populations would be different. The distributions of the directional tuning in the ROIs are in Figure 8d. The distribution of the gain fields from the ROIs when randomization was not performed show a downward effect for 7a and upwards effect for DP. The directional distribution is essentially uniform for the ROI for which the randomization between the stimulus and signal was performed.

For the data of Figure 2, this procedure was repeated for 115 surrogate sets yielding 230 new maps. Additional ROIs could have been chosen, however the Monte Carlo analysis was too computationally intensive to permit this. Maps were generated and the same ROI were sampled. Circular means and errors were computed. A comparison in the two distributions was computed using a using a circular Watson F-test analysis. (Oriana Software, Kovach Computing Services, Anglesey, Wales).
For the data of Figure 2, the bootstrap circular mean and standard error was 132±2.2° for the area 7a ROI (region of interest), and was 42±1.8° for the area DP ROI. For comparison, if the optical measurements were randomly assigned to a stimulus, the circular standard error had a high value of 76° and 70° for DP and 7a respectively. The distribution of directions was essentially flat for the randomized data. These random versus the bootstrap distributions were significantly different (P<0.0001). Similar results were found for two other days tested a few weeks apart showing that within a single day, the maps had within day errors of less than 5°.

**Replication in a second monkey**

*Gain field maps:* The gain field map was replicated in two hemispheres of a second animal using the BNA; the data of M2R and M2L. The quality and number of the maps in M2R was few and of poorer quality than the other maps due to the sub-dural bleed. Nonetheless the primary result of an upper-lower gain field separation between 7a and DP could be confirmed (Figure 9a for M2R). The reds and yellow of the gain fields in area 7a indicate lower field effects while the blues and purples in DP indicate the upper gain field. As before the numbers at the edge of the images represent the average for the ROIs which appropriately correspond to the upper and lower gain fields. In M2L, the chamber placement was more lateral and the image is at a higher magnification. Hence the union of the IPS and LS are beyond the left of the panel (Figure 9b). Gain field maps were again obtained with the upper and lower gain field divisions. The periodicity seen in M2R (Figure 9a) is perhaps reminiscent of ocular dominance periodicity in primary visual cortex. However the present study does not provide any source for this structure and it was only seen in this one map.

*ROI analysis:* The circular mean and standard error the data of M2R for ROIs in 7a and DP were 240±23° and 75±8°, N=4, respectively; these two ROI were significantly different (P<0.01, DF=6, Watson’s F-test). In M2L, the ROIs were picked to be similar to
that of M1R with the means for the ROIs being 310±26° and 94±19°, N=5, for 7a and DP respectively; the ROIs were significant at P<0.01, DF=8, Watson’s F-test). The upper and lower breakdown between area 7a and DP was found in all these data to agree for all three hemispheres.

Monte Carlo analysis: The reproducibility of the maps within a day using the Monte Carlo analysis in M2R was similar to that of M1R (circular standard error of 4°.) A Monte Carlo analysis was also performed in M2L with an approximately double error. Thus we estimate that in three hemispheres the error of our measurement within a 2 x 2 mm region is approximately 4°.

In summary, our optical recordings have shown area 7a and area DP have gain field tuning. At least for the two regions imaged, there appears to be a division of labor with 7a representing the lower gain field and DP representing the upper gain field. There is also modulation with the horizontal eye position, although is clearly weaker in our hands.

**Electrophysiological confirmation of eye position maps**

Typically, for optical imaging experiments, single unit recordings are made to “verify” the optical responses correspond to classically defined electrophysiological responses (Shmuel and Grinvald 1996; Shtoyerman et al. 2000). This approach has worked very well in V1 where there is a columnar architecture for orientation and ocular dominance. The optical signal only indicates reflected light from the upper layers and it is reasonable to assume that the bulk of the changes in reflected light arise from metabolic changes in the smallest processes with the largest surface-area to volume ratio (Frostig et al. 1990; Malonek and Grinvald 1996; Malonek et al. 1997).

Low impedance electrodes were introduced through the artificial dura and measurements of gain fields were made. Recordings were only made in one animal M1R; the number of penetrations with the artificial dura was minimized because the electrodes caused a small pinhole in the artificial dura. In our hands, the artificial dura often self-
sealed, but at times, air could seep in under the artificial dura. This lead to concerns about sub-dural infections compromising the continuation of the studies; although this never occurred. As well, even though the size of the bubbles were small (being ~1 mm in diameter), they precluded any optical recording from 2 dy to 1 wk while they were being reabsorbed.

The multiunit response to the alteration of eye position (Figure 10) appeared similar to the responses obtained from single unit recordings as reported elsewhere (Read and Siegel, 1997). Gain fields in area 7a may be linear or humped (Read and Siegel 1997), and so a quadratic stepwise regression model was used; the stepwise selection only permits coefficients significant different from 0 at P<0.05 to remain in the model (Read and Siegel 1997). Both the peristimulus time histograms as well as the regression surfaces are illustrated (Figure 10). Following the approach from single unit studies on optic flow in the inferior parietal lobule (Read and Siegel 1997;Phinney and Siegel 2000), baseline activity was evaluated for 1 sec prior to stimulus onset. The response of the multi-unit activity was evaluated over 1 sec immediately following stimulus onset in order to combine phasic and tonic responses. To reduce variability caused by any instability of the recordings, the baseline rate was subtracted from the evoked response on a trial by trial basis.

Sample recordings from area 7a (Figure 10a, b) and DP (Figure 10c, d) illustrate the type of tuning found electrically. The gain field tuning of these cells was similar to that reported elsewhere with these stimuli (Read and Siegel, 1997).

Cells were recorded from a 5 mm strip in DP (9 penetrations) and a 1.25 mm strip in 7a (5 penetrations) in hemisphere M1R (Figure 11a). The region from which the area 7a recordings are taken is indicated by the black vertical bar, while the region for which the DP recordings are taken is indicated by the open white bar. Twelve of 54 area 7a multiunit recordings (22%), and 14/56 (25%) of area DP multiunit recordings were found to significantly depend on the position of the eye in the orbit. In 7a, half of the neurons had
significant linear coefficients, while the other six had only significant quadratic components. In DP, 11 of the cells only had a significant linear component; 3 were purely quadratic, and two had both a linear and quadratic components.

For the purely linear cells, the direction of the gain fields could be summarized by the vertical and horizontal slopes; for the purely quadratic cells the gain field was symmetric in the vertical and horizontal and the gain field was assigned a coordinate of (0,0°). For the neurons with both a linear and quadratic component, the gain field was appropriately corrected to place the peak in the appropriate quadrant (Figure 11b). The 7a recordings sites were mostly in the lower contralateral lower field while the DP recordings were mostly in the ipsilateral upper field.

As a population, the area 7a and DP neurons were statistically different. The significance between the DP and the 7a population regressions were computed three different ways. First, a Mann-Whitney test was used to determine if each of the regression coefficients were different across areas; all effects were significant at P<0.05, except for the second order “y” coefficient (αyy). Second, a canonical discriminant analysis (SAS PROC CANDIS, Durham, NC), which considers a linear combination of all five regression coefficients, was used. The sum 0.08β + 16.3αx+ 4.16 αy -17.4 αxx + 1.44 αyy was significantly different for the two populations at P<.001. Lastly, in order to determine the eye position for which the activity was maximal, the slope coefficients from each recording were converted into polar coordinates. The electrophysiological circular mean and standard error was 231±30° (N=5) and 27±30° (N=10), for 7a and DP respectively. The directional tunings for the two areas were significantly different (P<.05; DF=3, Watson’s F-test). Thus the directional tuning from the electrical recordings was able to discriminate between area 7a and DP, a novel finding not yet reported from electrophysiological recordings. The lack of any report of this in earlier studies may be because of the poor spatial electrode localization in earlier work obscured such effects.
Figure 11 illustrates both the average signal for the optical ROI and for the electrophysiological data. In comparison to the optical data, the multunit data replicated the upper and lower gain field divisions between 7a and DP; the ipsilateral-contralateral distinctions did not match that of the optical data. This may be due to the disparity in location of the optical and electrical recording sites, or differences in the source of the electrical and optical signals (Logothetis et al. 2001). Ideally, simultaneous, multisite, tangential electrode penetrations should be made within area 7a and DP to precisely match the two types of data.

Discussion

These experiments provide evidence for a functional architecture of orbital gain fields in area 7a and area DP of the inferior parietal lobule of the behaving monkey.

Relationship between optical signal and underlying activity

Key to the demonstration of these maps was the utilization of intrinsic optical imaging at 605 nm. The signal at this wavelength scales with the level of reduced-Hb (Frostig et al. 1990; Malonek and Grinvald 1996; Malonek et al. 1997). The optical signals mostly mirror the metabolism of the small neuronal elements such as presynaptic fibers, boutons and dendrites (Logothetis et al. 2001). Those elements have the smallest diameters and hence the largest surface-area-to-volume and maximal contribution to the oxidative metabolism. Hence the intrinsic optical signals are most similar to local field potentials (Logothetis et al. 2001). The question is how much of this signal is above threshold and will be impressed onto the spiking neuronal activity. There is a substantial literature in primary visual cortex that supports the assertion that intrinsic signals ultimately reflect outputs from cells (i.e. spiking). The principles underlying the source of the optical signal derived from striate studies should also be applicable to the current studies in inferior parietal lobe.
Our electrical measurements indeed confirm the optical results. The upper and lower gaze field division of representation between area 7a and DP are found with both methodologies. The optical parameter maps in one chamber were confirmed using multi-unit physiological recordings. Multi-unit recordings were made as the tip impedance needed to be low (~300kΩ) to permit piercing of the artificial dura. The percentage of selective cells was lower as compared earlier studies (Andersen et al. 1990; Read and Siegel 1997; Siegel and Read 1997a), perhaps because the stimuli parameters (e.g. retinal stimulus location, type of optic flow) used in the present study were not optimized for each recording site. A second reason for the lower number of significantly tuned recordings between the two studies is that multi-unit data can sum the contributions of single cells with disparate tunings resulting in a broadened and non-significant response. Despite these technical limitations, there was a reasonable match between the multi-unit cell physiology and the optical maps.

Confirmation of finer details of the maps, such as the horizontal modulation of the gain field, were not made in that it would have required repeated penetrations and damage to the artificial dura. Given that the optical methods provide a detailed map, and the substantial body of evidence supporting the neural underpinnings of these maps, we were restricted and conservative in the electrical recordings; mostly serving to verify the signal in two regions of interest.

**Time course of the optical signal**

The time course of the signal in this association cortical region shows novel properties as compared to earlier measures of the striate cortex. In our studies, the initiation of the task, known from electrophysiological data to activate parietal neurons (Motter and Mountcastle 1981; Andersen et al. 1990; Read and Siegel 1997; Siegel and Read 1997a) lead to an biphasic wave upon which the test visual responses ride. Once behavioral control is achieved, the baseline optical signal was similar across different fixation conditions. When
the optic flow stimulus started, there was a difference in the signal starting at about 1000 msec for the expansion versus the compression stimuli; this difference depended on whether the animal was looking up or down as well as the region of the cortex. (The interaction between the optical flow and the eye position tuning is the subject of work in progress, Raffi and Siegel, 2002). This later visual signal was dependent on the position in the orbit in a manner reminiscent of gain fields described from electrophysiological studies. Thus, both visual input and eye position contributes to the optical response.

**The baseline normalization analysis model**

For any single location, the strength of the optical signal depended on the eye position in the orbit. This dependence was modeled as a linear function. Other models might have been used, as about 40% of inferior parietal lobule neurons have peaked non-linear gain fields (Andersen et al. 1985; Read and Siegel 1997). In preliminary analysis, higher order functions such as a quadratic were used. The qualitative results in terms of an upper and lower field breakdown between area DP and 7a were similar; it was difficult to justify the higher order model on a pixel-by-pixel basis as the signal-to-noise was low. Hence the data was modeled with the linear regression and a Monte Carlo analysis was used to validate the model parameters.

The effect of eye position on the visual response was visualized with parameter maps. A positive dependence of the expected neuronal responses upon eye position was found in DP while the negative relation was found in 7a. This does not mean that DP exclusively represents upper field eye positions. Rather the results indicate that DP is modulated by both upwards and downwards eye positions, and that upwards positions leads to an increase in neural activity with downwards leading to a decrease in activity. Similarly 7a is modulated by both upper and lower eye positions with an opposite sign to that of DP. Interestingly, these parameter maps indicate that when the point of regard for the eyes is in the upper visual field, both areas should be modulated; similarly both are active for lower
fixations. Thus either projections from DP or 7a can provide information needed by recipient cortical zones. It is also possible that areas such as area 46 and 8a that receive interdigitated projection from both DP and 7a (Andersen et al. 1990) could use these complementary signals in a push-pull fashion. It is tempting to speculate that this differential signal computed from both 7a and DP could provide a more reliable signal to other cortices representing visual space or planning motor behaviors.

The nature of the topographic representation of the gain field

The gain field topography was found in three hemispheres of two animals. In all three monkeys, the upper and lower gain field representation was found distributed between 7a and DP. This was shown using the nine position gain field test in all three animals. The upper and lower representation was the strongest topography, while the contra/ipsi-lateral representation was markedly weaker. One possibility that could explain the weaker contra/ipsi-lateral representation is that it is in the more lateral 20 mm of 7a and DP that cannot be imaged in these experiments due to the chamber placement. For example, the ipsilateral lower gain fields could extend right up to the area 7a/7b border. The scant data that was acquired suggests that this is not the case (Figure 6f), although additional data is certainly needed to resolve this issue. In some experiments, the contra/ipsilateral modulation is clear and there appears to be an almost complete representation of the contralateral gain field; while in others the contra/ipsilateral representation is scarcely evident. The haemodynamic response and/or the noise in the optical signal may preclude a repeatable measurement or there is plasticity in this portion of the representation. Imaging with voltage sensitive sensors that more faithfully represent the signals in both space and time may resolve whether there is indeed a contra/ipsi representation.

In the animal for which extensive mappings were performed, the maps were not precisely the same day to day as evaluated across the three months of recordings. In comparison, the fine structure of ocular dominance is exquisitely reproducible across
months of recordings in striate cortex (Shtoyerman et al. 2000). The experimental procedures are essentially the same in the striate study as in the present study of the inferior parietal lobule; eye position control is similar, the wavelength of light is the same; the species are the same. Possible sources for the variation in the inferior parietal lobule maps appear to be linked to the cortical areas under study; the inferior parietal lobule areas receive both highly processed visual signals from dorsal and ventral stream areas as well as feedback from the frontal areas. It is clearly possible that the inferior parietal lobule maps are modulated by the state of the animal’s attentional, intentional, or vigilance systems. The possibility that the monkey’s behavioral state could cause plasticity on a day-to-day basis needs to be considered. Specific experiments to address the effect of these factors upon maps in the inferior parietal lobule will be necessary.

**A question of one or two cortical areas**

The question arises as to whether area 7a and DP can be considered one or two regions with respect to the eye position gain field topography. Area DP and 7a were distinguished initially on cytoarchitectonics (Von Bonin and Bailey 1947), which were later correlated with single unit physiology (Andersen et al. 1990). The distinction in single unit properties between the two regions was not particularly overwhelming in that earlier study. In the present work, DP and 7a have arbitrarily been assigned to regions above and below the vein that runs between the dorsal tip of the STS and the apex of the intra-parietal and lunate sulci. There is a clear change in gain fields as this vessel is crossed; there is no sulcus under this vessel which might conceal more gradual changes in the gain field suggesting this border is a result of the cortical circuitry. As the animals are still being studied, it is not possible to directly compare the cytoarchitectonics to the maps. However an alternative interpretation of the data is that the completion of the DP representation, i.e. the lower gain fields, lies ventrally towards dorsal V4. Similarly there is about 10x10 mm of area 7a that lies ventral to the recording chambers that have not been optically studied.
which may contain the missing upper portion of the gain fields. Thus the unity of the gain field representation between area 7a and DP cannot be asserted at this time, but remains an interesting conjecture.

This question of the individuality of area 7a and DP can be answered in part by tracer studies for which the projection patterns of these two most dorsal regions of the inferior parietal lobule are examined, and in part by a comparison of laminar and myeloarchitectonics. At this point, there does not appear to be a functional segregation in terms of electrophysiological studies. But even if these anatomical studies show different connectivity patterns and architectonics between putative area 7a and DP, there may be a deeper irresolvable issue. A similar question arose in the 1980’s with respect to area V4 which was subdivided by some into a dorsal and ventral area. Others considered V4 one cortical area. Even today there is not a accepted opinion of whether V4d and V4v are one or two areas (Pinon et al. 1998; Tootell and Hadjikhani 2001; Van Essen 2003). Thus the designation of the regions area 7a and DP as those with lower and upper gain fields respectively should be taken as an operational and functional definition, which will require additional anatomical analysis.

A novel functional architecture

The topographical maps are evidence of a functional architecture for the inferior parietal lobe association cortex. All other cortical maps in the visual system described to present have had retinotopy as their most coarse representation basis (e.g. V1 (Tootell et al. 1982), MT (Albright et al. 1984), or MST (Tanaka et al. 1986)) with columns (e.g. ocular dominance or motion direction) found mapped within the retinotopy with a 1 mm periodicity (Shtoyerman et al. 2000). The inferior parietal lobule maps are novel in that they are the first primate cortical visual map that uses eye position as its most coarse basis. Indeed, to our knowledge there is no report of a eye position topography to date. The transformation from a retinotopic map to an eye position based gain map is evidence for an
intermediate step in the transformation from visual to motor coordinates. The circuits subsuming the generation of this novel map likely utilize cortical feedback as 7a and DP do not have direct projections from sub-cortical structures that represent eye position (Siegel and Read 1997b). If the principles governing multiple scales of functional architectures in early vision hold for this association cortex, then the large-scaled gain field functional architecture described here may serve as the scaffolding upon which other sensory, attentional and intentional maps may be embedded at finer columnar scales. These distributed multi-scaled representations of visual and eye position can be then combined to construct appropriate perceptual and motor signals in recipient cortical areas (Pouget and Sejnowski 1997; Siegel 1998; Zhang and Sejnowski 1999).
Figure legends

Figure 1. Expansion optic flow used for the optical recording experiment in behaving monkey. Stimuli were expanding flow fields of 20° diameter. The average expansion rate was 60°/sec. The monkeys detected a change from the structured expansion flow stimulus (a) to the unstructured flow stimulus (b). The change occurred after the end of the optical imaging data collection and served to direct the animal’s attention at the flow stimuli. c, In any one trial, the animal viewed the stimuli at one of nine positions in a 20x20° grid. The grey or block filed circles indicate fixation points. In some experiments, compression optic flow was used as well as expansion flow (see text).

Figure 2. First stage of analysis of gain fields from M1R. a, Three-dimensional reconstruction of the sulcal and gyral patterns from magnetic resonance images. The intraparietal sulcus (IPS) joins with the lunate sulcus (LS) (red). The 20 mm diameter chamber is shown (green) with the recording region in yellow. b, Angioarchitectonics of the region of interest taken with 540 nm illumination. The large vessel at the top of the image lies over the intraparietal sulcus (IPS). A draining vein lies between the dorsal apex and the most dorsal portion of the superior temporal sulcus (STS) and was used to delimit the image into area 7a and DP. The superior temporal sulcus can be observed with a dissection microscope to begin just to the right of the “STS” label. c, The cocktail response is the average evoked response to stimulus onset across all conditions using 605 nm illumination. d, The single condition map varies both as a function of the location on the cortex and the eye position. The average evoked response displayed for each position had the cocktail response subtracted. The location of each image indicates the position of the fixation and optic flow stimulus. Dataset 3/20/2000/gm; the range of the gray scale for c is (-1,1%); and for d is (-0.2%,0.2%).
**Figure 3.** Automatic masking and data rejection procedure. Reference images were collected every 16 stimulus presentations (~160 sec) at a wavelength of 605 nm. These reference images were used to construct a mask in order to determine if there were outliers in the collected data which needed to be rejected. **a,** The mean of all the reference images were computed. Then the grand mean of the luminance of the average image as well as its standard deviation was computed. **b,** If the value of a pixel in the average reference image was greater than grand mean by 0.5 of the grand standard deviation, that pixel was masked as a “valid” pixel (a value of 1). Otherwise the pixel was set to “invalid” (value of 0). This masked image is provided. **c,** The normalized change in luminance was computed for each pixel for each behaviorally correct trial according to eqn. 1. Then the normalized change in luminance was masked using the image of **b,** and the mean and standard deviation of each the image for each trial was computed. The mean is expressed in units of 0.1%. The distribution of these values had an approximately normal distribution as illustrated. The mean and standard deviation of these masked images were used to determine which trials to reject. For this experiment, the mean and standard deviation was $-0.451 \pm 0.747\%$ and is indicated by the thin vertical lines. **d,** The final step of rejection was to eliminate trials with extremely low standard deviations. A plot of the mean versus the standard deviation illustrates that none of the trials in this experiment met that criterion.

**Figure 4.** Second stage of analysis of data from Figure 2. Regression for the linear dependence of the single conditions maps upon the eye position using the BNA model. Each pixel of the nine single condition maps was fit as a linear function of the horizontal and vertical eye position (Methods). The resulting parameters were used to construct three parameter maps. **a,** Parameter map for $\beta$, the intercept. The intercept parameter map is very similar to the cocktail image of Figure 2c. **b,** $\alpha_x$, the horizontal slope of the gain field . **c,** Parameter map for $\alpha_y$, the vertical slope of the gain field . In order to examine the dependence of the optical signal on both the horizontal and vertical eye positions, the rectangular coordinate system of $(\alpha_x, \alpha_y)$ was transformed to polar coordinates. **d,** Parameter
map for the amplitude of the vector formed from the two slope values $\sqrt{\alpha_x^2 + \alpha_y^2}$. e, Parameter map for the direction of maximal gain field response “arctan(-$\alpha_x,-\alpha_y$).” Area 7a and area DP have representations of the lower and upper gain fields respectively. As one progresses counter-clockwise from the ventral part of 7a, the gain field tuning goes clockwise from lower left to upper right angles of gaze. To compute the final map of (e), the slopes were multiplied by −1 prior to computing the angle, to correct for the optical signal being the inverse of the expected neural activity (Shtoyerman et al. 2000). The inset shows the color direction scale. Contralateral (red) is to the left and ipsilateral (blue) to the right of the colored circle. The thin squares show the region of interest. This data was collected 19 days after chamber placement. f, Parameter map for the direction of maximal gain field response for day 63. Again area 7a represents upper field and DP represents lower field with a horizontal gradient running dorsal to ventral. The thin dashed line indicates the lower and right edges of the cortex studied in panel e. Other conventions as in panel e. The range of grey scale levels are indicated in the upper left of each figure. (Datasets for a-e: 3/20/2000/gm, dataset f: 5/2/00/gm). The scale bar is 1mm.

**Figure 5.** Time course of the optical signal. The optical signals were averaged for ~2x2 mm of cortex. In order to determine if the visual responses depended on both the visual stimulus and eye position (i.e. gain field), the response to two different optic flows centered on the fovea was obtained in a 2x2 factorial design with two different angles of gaze (0, 10°) and (0, -10°). The animal indicated a change in the fraction of structure for the optic flow. The time course diverged for the different conditions after about 500 msec. The first yellow bar in indicates the period that the baseline was computed; the second yellow bar in b indicates the time that visual responses were assessed. The time -2000 msec corresponds to the fixation point onset; optic flow onset occurs at 0 msec. The brightness of the lines is used to encode fixation up versus fixation down; the thickness of the lines are used to indicate expansion versus compression. a, Data from M1R. The sketch shows the relationship of the region of interest in DP to the vasculature. There is a clear difference in
the amplitude and time course of the signal for the expansion versus compression stimulus for the upwards gaze position. Altering the eye position alters the difference between the expansion and compression stimulus. b, Data from M2L. The sketch shows the relationship of the region of interest in 7a to the vasculature. There is a clear difference in the amplitude and time course of the signal for the expansion versus compression stimulus for the lower gaze position. Altering the eye position alters the difference between the expansion and compression stimulus. All data was expressed as a 0.1 percentage change from the baseline time period. Error bars are standard errors. The small bar in each sketch is 1 mm. c, The task events are indicated relative to the time course in panel b. The change to unstructured optical flow occurred at a random time in the interval [4000,5000 msec] followed by the key release in an additional [150, 800 msec] time window. The change to unstructured motion and the key release occurred after the end of optical data collection.

**Figure 6.** A second gain field map recorded from M1R. a, Green light image of cortex. b, Cocktail response (average response) of cortex across all gaze angles. c, Angle for best gain field tuning derived from horizontal and vertical coefficient maps (e and f). d, Intercept parameter map of regression. e, Horizontal coefficient of regression. f, Vertical coefficient of regression. g, The single condition maps varies both as a function of the location on the cortex and the eye position. The average evoked response *displayed* for each position had the cocktail response subtracted. The location of each image indicates the position of the fixation and optic flow stimulus. The scale bar is 1 mm; the number in the upper left corner indicates the grey scale range. (Data set for 19-03-2000/grand.)

**Figure 7.** Region of interest analysis for M1R. In order to compare the tuning of the optical maps across days, regions of interest were chosen that could be located in as many maps as possible from hemisphere M1R. a, The circular mean for each condition is presented for both area 7a and DP. The data of area 7a indicated gain fields in the lower visual field while that of DP indicated data in the upper visual field; there was some contra-ipsi
modulation in both DP and 7a. The locations of the eight ROIs are indicated in the sketch drawn as a composite from the green light images collected in hemisphere M1R.

**Figure 8.** Monte Carlo analysis of parameter maps. The data of Figure 2 was analyzed multiple times either respecting (a) or disrupting (c) the relationships between the stimuli and optical images. Panel b shows the original parameter map and the ROIs used in the quantified portion of the analysis. In a, the upper and lower field breakdowns are maintained between 7a and DP, although the colors are not precisely the same each exemplar generated by choosing at data at random from the original data set. In c, the tuning varies widely between each exemplar. d, Distribution of directional tuning for the ROIs. The labels “rand DP” and “rand 7a” refer to the exemplars where the relationship between the collected images and stimuli are randomized (i.e. disrupted). The label “DP” and “7a” refer to the data where the relationship between the two is respected. These circular distributions are compared using a circular χ² test (see text).

**Figure 9.** Parameter map for the direction of the maximal gain field response for M2. a, gain field for M2R. The gain fields segregate between DP and 7a. Data collected 27 days after chamber placement. Conventions as in Figure 4e. (Dataset: 8/17/01/r1). b, Angle for best gain field tuning derived from horizontal and vertical coefficient maps in M2L. Data obtained 41 days after chamber implant. (Data set for 10/16/2002/gm.)

**Figure 10.** Multi-unit recordings verifying the optical maps. a, Multi-unit recording from 7a during a gain field experiment. The position of the peri-stimulus histogram indicates the fixation position as well as the position of the expansion flow field. This cell was tuned as a function of both vertical and horizontal eye position. b, linear regression for this neuron of the change in firing rate as a function of vertical and horizontal eye position.. \[ A = -0.45E_x - 0.48E_y + 94 \]. Although there appears to be a quadratic dependence upon the horizontal eye position, this was not significant in the stepwise analysis. c, peri-stimulus histograms for a recording made in area DP. This cell was only tuned as a function of the
vertical eye position, with the strongest responses found in the upper visual field. d, linear regression for this neuron. $A = 0.19E_x + 25.4$. Only parameters which were significant at $p<0.05$ were permitted in the stepwise linear regressions.

**Figure 11.** The two populations of multiunit recordings in DP and 7a represented different parts of the gain field space. a, The location from which the recordings were taken is indicated by the black and white rectangles. b, Each multiunit recording was fit by a stepwise quadratic regression for which only significant ($P<0.05$) coefficients remained in the model. Only two of the 110 recordings studied in DP had both a linear and quadratic term. For these DP recordings, the quadratic term was used to determine which quadrant the gain field would be maximal. and the gain field region for those recordings could be summarized by the horizontal and vertical slope components. The DP recordings appear to be primarily in the upper-contralateral quadrant while the 7a recordings are in the lower-ipsilateral quadrant. The population sum of all the vectors for DP and 7a are indicated by the solid arrows. The dotted arrows indicate the average measurements from optical recordings described in the test. For both sets of arrows, the thicker lines indicate the area 7a recordings; the thinner are the DP recordings. Note the gain field location for the purely quadratic neurons was $(0,0^\circ)$. (See text for additional details.)
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Siegel et al. Figure 3

C) Histogram of data distribution

D) Scatter plot showing correlation

(mean -4.51+/− 7.47%)
Siegel et al, Figure 5

A

B

C

Task events

Fix point on
Key pulled & fixate
Structured optic flow on
Unstructured optic flow
Key released

1 mm

235°

signal (0.1%)

-2000 -1000 0 1000 2000 3000

time (msec)

signal (0.1%)

-2000 -1000 0 1000 2000 3000 4000 4550

time (msec)
Siegel et al, Figure 7

A

Mean gain angle of ROI (deg)

- Medial
- MedCent
- LatCent
- Lateral

area 7a

area DP

B

IPS

7a

L LC MC M

LS

DP

1 mm
Siegel et al. Figure 8
Siegel et al, Figure 9