Large-Scale, High-Resolution Neurophysiological Maps Underlying fMRI of Macaque Temporal Lobe

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Large-Scale, High-Resolution Neurophysiological Maps Underlying fMRI of Macaque Temporal Lobe

Elias B. Issa, Alex M. Papanastassiou, and James J. DiCarlo

Maps obtained by functional magnetic resonance imaging (fMRI) are thought to reflect the underlying spatial layout of neural activity. However, previous studies have not been able to directly compare fMRI maps to high-resolution neurophysiological maps, particularly in higher level visual areas. Here, we used a novel stereo microfocal x-ray system to localize thousands of neural recordings across monkey inferior temporal cortex (IT), construct large-scale maps of neuronal object selectivity at subvoxel resolution, and compare those neurophysiology maps with fMRI maps from the same subjects. While neurophysiology maps contained reliable structure at the submillimeter scale, fMRI maps of object selectivity contained information at larger scales (>2.5 mm) and were only partly correlated with raw neurophysiology maps collected in the same subjects. However, spatial smoothing of neurophysiology maps more than doubled that correlation, while a variety of alternative transforms led to no significant improvement. Furthermore, raw spiking signals, once spatially smoothed, were as predictive of fMRI maps as local field potential signals. Thus, fMRI of the inferior temporal lobe reflects a spatially low-passed version of neurophysiology signals. These findings strongly validate the widespread use of fMRI for detecting large (>2.5 mm) neuronal domains of object selectivity but show that a complete understanding of even the most pure domains (e.g., faces vs nonface objects) requires investigation at fine scales that can currently only be obtained with invasive neurophysiological methods.

Introduction

As a noninvasive measure of whole brain activity, fMRI has become invaluable in studying human brain function. However, fMRI is only an indirect measure of neural activity—it depends on the potentially complex coupling between the neural events of interest and their temporally lagged, indirect influence on vascular events (Attwell et al., 2010; Kriegerkorte et al., 2010; Masamoto and Kanno, 2012). A previous study found that neural and fMRI signals were correlated over time at a given location (Logothetis et al., 2001) but did not measure whether the pattern of selectivity in fMRI across space corresponded to the underlying pattern in neurophysiology—an important remaining question given the widespread use of fMRI for inferring the 3D layout of brain function.

Studies in primary visual cortex (V1) have suggested that the spatial spread of fMRI signals is 2–4 mm [full-width at half-maximum (FWHM)] based on inference from previously known functional organization in V1 (Engel et al., 1997; Parkes et al., 2005; Olman et al., 2007). However, these studies did not compare neurophysiology to fMRI directly in the same subjects (Disbrow et al., 2000; Kim et al., 2000; Duong et al., 2001; Kim et al., 2004; Fukuda et al., 2006; He et al., 2008; Yacoub et al., 2008; Bell et al., 2011), which may be required in studying higher level areas such as inferior temporal cortex (IT) where neural spatial organization is not as well understood as in V1 (Hubel and Wiesel, 1974; Ohki et al., 2005) and where there may be more variability over individuals. A main methodological limitation has been that previous neurophysiology studies relied on coarse, extrapolative electrode localization techniques (Tsao et al., 2006; Bell et al., 2011) that do not support quantitative, fine-scale construction of neural maps for comparison to fMRI. Although optical imaging techniques have provided exquisite neural maps, they are limited to surface-accessible cortex and to imaging windows of a few millimeters (Wang et al., 1996; Tanigawa et al., 2010), whereas parts of IT cortex are buried in a major cortical sulcus or at the base of the skull and are thus invisible to these methods.

Here, we aimed to map the spatial organization present at the neural level in macaque IT, an area thought to contain object selective domains, to establish a neurophysiological gold standard for comparison to previously measured fMRI maps (Op de Beeck et al., 2008; Bell et al., 2009; Pinsk et al., 2009; Tsao et al., 2003, 2008a; Ku et al., 2011). Utilizing a novel stereo microfocal x-ray system for electrode localization (Cox et al., 2008), we obtained subvoxel (~300 μm resolution), in vivo estimates of electrode position while widely sampling recording sites across the whole of inferior temporal cortex (~15 × 10 × 3 mm) surpassing...
the coverage-resolution tradeoffs inherent in previous work (Wang et al., 1996; Bell et al., 2011). We found that neurophysiology maps contained reproducible structure at submillimeter spatial scales but were only weakly predictive of fMRI maps. However, spatially smoothed versions of the neurophysiology maps correlated quite well with fMRI maps. This finding provides empirical validation of the utility of current fMRI methodology in revealing large scale object selective structures in IT while also demonstrating its current limitations for discriminating the finer neural structure that is present in IT cortex.

Materials and Methods

Animals and surgery
Two rhesus macaque monkeys (Macaca mulatta) weighing 3–4 kg at the time of scanning and 5–7 kg at the time of electrophysiological recording (M1 = male, M2 = female; referred to as monkey 1 and monkey M, respectively, in previous fMRI work) (Op de Beeck et al., 2008) were used in this study. Monkeys were scanned at five years of age after reaching sexual maturity and after adult brain size is typically reached (Malkova et al., 2006), and physiological recordings were performed three years later. Despite the large gap in time between imaging and physiology experiments, anatomical scans revealed almost no longitudinal change in brain size during the intervening period and correlation of structural MR volumes across this time period was ~0.8 in the temporal lobe of both monkeys.

Details of headpost and recording chamber implant surgeries are described elsewhere (Issa and DiCarlo, 2012). Briefly, before behavioral training and fMRI scanning, a plastic, fMRI-compatible headpost was implanted in dentin acrylic anchored to the skull using ceramic screws. In a second surgery before electrophysiological recording, a plastic, cylindrical chamber was implanted for targeting recordings to the temporal lobe using a dorsal to ventral approach. All procedures were performed in compliance with National Institutes of Health guidelines and the standards of the MIT Committee on Animal Care and the American Physiological Society.

Images and behavioral training
Because fMRI and neurophysiology experiments were conducted separately, image presentation and task conditions varied slightly. For both fMRI and neurophysiology, we followed standard methodologies used in previous studies (Tsao et al., 2003; Hung et al., 2005). Here, we provide an integrated summary of the similarities and differences between experiments (also see Table 1). In both experiments, presented visual images contained a single object drawn from six possible categories, monkey faces, nonface objects, power spectrum matched scrambles of nonface objects, “smoothies,” “spikies,” and “cubes.” The latter three classes were synthetic objects generated in Matlab and are described in our previous work (Op de Beeck et al., 2008). In both experiments, images were presented at a size of six degrees of visual angle. However, an LCD projector was used during scanning (1920 × 1200, 75 Hz refresh rate, ~50 cm in front of the animal) while a CRT monitor was used during neurophysiology (1900 × 1200, 85 Hz refresh rate, 55 cm in front of animal). In fMRI experiments, monkeys were trained to fixate on a central fixation square (0.3 degree diameter) within a ±1.25 degree fixation window while at a ±2 degree fixation window was used in physiology experiments; however, in post hoc analyses we found that monkeys generally maintained fixation within a much smaller 1 degree region and do not scan across images (Issa and DiCarlo 2012, their Fig. 5A). During fMRI sessions, images were presented in block design such that image exemplars drawn from a single category were presented in a single block at slow presentation rates (300 ms on, 420 ms off or 1.4 Hz). In physiolog(experiments, images from all categories were randomly interleaved (10 or 20 exemplars each for faces, objects, and scrambled objects and 3 or 20 exemplars each for smoothies, spikies, and cubes) at much faster rates (rapid serial visual presentation: 100 ms on, 100 ms off or 5 Hz) (Hung et al., 2005; De Baene et al., 2007). In physiology experiments, each fixation trial lasted three to five seconds (15–25 images) while in fMRI experiments fixations lasted tens of seconds during category blocks lasting 45 s (~60 images). Although stimulus presentation conditions were not matched between electrophysiology (interleaved, rapid presentation) and fMRI (blocked, slower presentation), previous work has shown that rank order neural object selectivity is similar across both fast and slow stimulus presentation rates (Edward et al., 2003; De Baene et al., 2007). Furthermore, similar category selective regions are observed under fMRI using both blocked and interleaved (event-related) designs (Kanwisher et al., 1997; Mur et al., 2012; Vul et al., 2012).

In both monkeys, many sites were not tested with all six categories leading to variable number of sites per contrast in M2 (faces and objects, n = 1522; scrambled objects, n = 229; smoothies/spikies/cubes, n = 450) while all sites in monkey M1 were tested in this study with all six categories (n = 369). Also, in monkey M2, fewer exemplars were used per category, but at least 15 presentations (3 images × 5 repetitions) were collected per category and many more presentations were obtained in most cases across both monkeys (median = 57 trials/category).

Functional imaging

Functional scanning was conducted at the Martinos Center for Biomedical Imaging at Massachusetts General Hospital in a horizontal bore 3 tesla Siemens Tim Trio scanner using a surface coil. A contrast agent [monocrystalline iron oxide nanoparticle (MION)] was injected intravenously before scanning. Functional scans were acquired using a gradient echo planar (EPI) sequence with coronal slice prescription (1.375 mm slice thickness). In addition to functional scans, T1-weighted anatomical scans were obtained before functional imaging experiments and before neurophysiology experiments. Additional details of functional and anatomical scans can be found in our previous studies (Op de Beeck et al., 2008; Issa and DiCarlo, 2012).

Neurophysiological recordings

In both monkeys, neurophysiological recordings were obtained in the left hemisphere. Multiunit activity (MUA) and local field potentials (LFPs) were recorded as described previously using glass-coated tungsten microelectrodes (M1 = 389, M2 = 1522 total sites) (Issa and DiCarlo, 2012). Penetrations traveled vertically from dorsal to ventral, and the raw electrode signal was stored and the LFP was obtained with low-pass filtering (<300 Hz, 128 order elliptical filter) the raw electrode signal and notch filtering at 60 Hz and its harmonics (120, 180, and 240 Hz).

Table 1. Comparison of conditions in fMRI and neurophysiology experiments

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<tr>
<td><strong>θ of sample locations (M2)</strong></td>
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fMRI experiments were conducted separately from neurophysiology experiments following methodologies used in prior work (Tsao et al., 2003; Hung et al., 2005). This introduced some differences in the collection of fMRI and neurophysiology data. For example, images were presented at slower rates (1.4Hz) in fMRI experiments as opposed to neurophysiology experiments (3 Hz), and fMRI data were collected when monkeys were younger in age. A detailed explanation of similarities and differences in fMRI and neurophysiology is provided in Materials and Methods.
**Figure 1.** Neurophysiological mapping of IT cortex. **A**, Locations of neurophysiological recordings in subject M2 are shown on an inflated surface view of the brain. The locations of three example voxels are projected to their approximate locations on the surface (gray outlines). Locations spanned the posterior to anterior extent of IT (−20 mm) (cortical gray matter—white matter boundary shown; dark regions indicate sulci and light regions gyri; sites are projected from 3D to the nearest point on the 2D gray-white manifold; STS, superior temporal sulcus; LS, lateral sulcus; IOS, inferior occipital sulcus). The coronal sections demonstrate the locations of the physiology sites relative to the cortical gray matter (gray ribbon) as derived from T1-weighted anatomical scans and relative to example fMRI voxels (light shaded squares). Furthermore, the relative 3D positions of individual sites within three example voxels are shown. For each site, the response to faces and nonface objects was measured, and selectivity was computed as the difference in these responses in a 50–200 ms window post image onset (example poststimulus time (Figure legend continues.).
X-ray-based electrode localization

All electrophysiological recordings were visualized using a stereo microscope system developed previously in our laboratory (Cox et al., 2008), and details of reconstruction of recording locations in 3D space and coregistration to MRI are described elsewhere (Issa and D’Carlo, 2012). Although the ex vivo resolution of the x-ray system is ~30 μm, the in vivo accuracy is limited by factors such as tissue movement either from electrode forces or from brain movement across days. Based on preliminary testing using internal fiducials to monitor movement, these sources of motion error are on the order of a few hundred micrometers (Issa et al., 2010) and are not a limiting factor in comparisons to fMRI maps that were >2.5 mm in effective resolution (Fig. 2).

Analysis

MUA, LFP, and fMRI responses. For fMRI data, linear response weights were estimated using a general linear model (GLM) to fit the time series in each voxel [see the study by Op de Beeck et al. (2008) for detailed description of fMRI preprocessing and analysis]. Scans from multiple sessions collected before and after ~3 months of discrimination training for spikies (monkey M1) and smoothies (monkey M2) were motion corrected and registered, and the β weights in each voxel were averaged to yield a single volume for each contrast. For the majority of the analyses of this paper, fMRI maps were smoothed using a Gaussian kernel (FWHM = 2.5 mm). In our previous work, we showed that smoothing fMRI maps at 2.5 mm scales was optimal for reducing noise while preserving as much large scale structure as possible (Op de Beeck et al., 2008), see their supplemental Fig. 5. In the present work, we confirmed that reliable information in fMRI maps drops off sharply at 2.5 mm suggesting that little information was lost by smoothing fMRI maps (Fig. 2). Furthermore, when we repeated analyses using unsmoothed fMRI data, the main findings did not change (see Results). Multitunit firing rates for each object class were computed by averaging spike counts across all exemplars in a 50–200 ms window following image onset (Fig. 1A). LFP waveforms were first DC corrected, and the root mean square (RMS) amplitude of the average waveform across all image presentations of a category was computed. Category selectivity was measured as the difference in raw spike rates (MUA), RMS power (LFP), or β weights (fMRI). Computing a d’ or t statistic that normalizes by SD of the signal yielded similar results as using a simple difference of the means that has the added advantage of not relying on the number of trials collected and that as a linear operation allows for commutativity of applied transforms. Sites were included in analysis if their response to either category in a contrast was at least 1.65*SEM different from baseline (baseline computed in the 0–50 ms window following image onset; for LFPs, the mean of SD in each time bin was used to compute the SEM). In separate analyses that we conducted, distinguishing sites/voxels based on whether they were in white matter or gray matter (see Fig. 6B) or simply including all sites did not affect the main findings. No additional visual drive criteria were used in selecting fMRI voxels, so fMRI voxels were used in analysis purely based on whether they contained at least one neurophysiology site.

Spearman’s rank correlations were computed pointwise between MUA (or LFP) sites and corresponding fMRI voxels. It is important to note that all correlations were computed in native 3D space such that quantitative comparisons were done in the original fMRI volume (in one control analysis, correlations were done after projecting to the surface; see Fig. 6B). However, for the purpose of visualization, data are plotted after projecting onto a 2D surface (Figs. 3–5; see Fig. 1A for illustration of this projection). These visualizations are only meant for qualitative evaluation. Surface flattening is not a distance preserving transform (non-isometric) and may exaggerate some distances (e.g., in unfolding a sulcus) while compressing others (e.g., on the gyrus). Furthermore, sites are flattened to the surface less than 2D. However, surface flattening alters the spatial correspondence between fMRI and neurophysiology. In the present study, we took the conservative approach of performing quantitative fMRI and neurophysiology comparisons in 3D space.

Neurophysiology-to-fMRI transforms. We applied transforms to neural and/or fMRI maps to test specific hypotheses about the linkage between neurophysiology-determined and fMRI-determined maps. Each transform was tested individually or cascaded with a fixed spatial smoothing transform. Below, we list the 16 types of transforms that we applied (Fig. 6B): (1) Spatial smoothing: A three-dimensional Gaussian kernel was used to smooth neurophysiology maps to different degrees (FWHM = 0 to 24 mm) in native 3D space. (2) Balanced spatial smoothing: Since physiology sites were not uniformly sampled in space, smoothing estimates could be biased by regions where dense sampling was obtained by chance. For example, if only a few sites were collected near to the voxel to be predicted, then predictions based on smoothing might be inadverently dominated by the large number of distant sites. To ensure that the effects of uneven sampling were not a concern, we performed a control (called “balanced sampling”; Fig. 6B) where we averaged sites in 1 mm bins before smoothing. This procedure insured that the predicted fMRI response at each voxel was, for example, not dominated by dense samples of physiology sites at distant locations. This correction was performed in...
addition to smoothing with a Gaussian spatial kernel, and it is important to note that the form of the Gaussian kernel also acts to enforce the intuition that nearby sites should be weighted more strongly than distant sites. (3) Response windows: Responses in adjacent 50 ms response windows were tested. (4) d’: Mean response differences were normalized by the RMS of the SDs for the two categories tested \((\mu_1 - \mu_2)/\text{rms}(\sigma_1, \sigma_2)\). (5) Contrast: Mean response differences were normalized by the sum of the absolute value of the mean responses \((\mu_1 - \mu_2)/(|\mu_1| + |\mu_2|)\). (6) Binarized: Responses were set to \(-1\) or \(1\) based on category preference. (7) Rectified: If the strongest response in a category pair was inhibitory, then responses were rectified (i.e., if category 1 was more strongly inhibited than category 2 was excited, the negative response differential, \(\mu_1 - \mu_2\), was rectified). The rationale behind this transform is that if the fMRI signal is related to synaptic processing, then activity at both inhibitory and excitatory synapses may drive blood flow and that suppression of spiking may be as metabolically costly as enhancement of spiking (Logothetis, 2008). (8) Active: Only the most active physiology sites were included in analysis by finding an optimal activity threshold (0 to 100 Hz). (9) Selective: Sites were included in analysis by finding an optimal selectivity threshold for positive differences (category 1 preferring) and a second, separate threshold for negative differences (category 2 preferring) (–200 to 200 Hz rate difference tested for MUA; –16 to 16 µV difference tested for LFP). (10) Gray (white) matter: Sites falling in the gray (white) matter based on anatomical projections were separately tested for their correlation to fMRI. (11) Posterior/anterior (dorsal/ventral): Sites falling in the lower or upper 50th percentile of AP (DV) coordinates were analyzed separately for their correlation to fMRI. Posterior regions may have more well-defined spatial organization or be less susceptible to fMRI distortion than the anterior pole; alternatively, anterior regions may show stronger category selectivity and more position tolerance leading to less susceptibility to low-level confounds such as eye movements. (12) Concave/convex: Sites were divided into two groups based on the surface curvature of the gray–white matter boundary nearest to each site. (13) Scale/rotate/translate/all: The 3D neurophysiology coordinates were optimally rescaled in space \((0.8 \times \text{ to } 1.2 \times \text{ scaling})\), rotated \((-10 \text{ to } 10 \deg \text{ coronal and sagittal angles})\), or translated \((-3 \text{ to } 3 \text{ voxels in the } x, y, \text{ or } z \text{ directions})\). In the “all” condition, all six spatial transform parameters (one scale factor, two rotation angles, and three translations) were simultaneously optimized. (14) Decompress: Given that the electrode compresses the cortical tissue locally, we applied a first order compressive model where the skull provides a rigid boundary condition and compression increases with distance from the skull up to saturation according to a sigmoid function, \(\alpha r/(\beta + r)\). Both the plateau \(\alpha\) and sensitivity \(\beta\) of the sigmoid were optimized. (15) Surface: Physiology sites were remapped to the nearest point on the gray–white cortical surface, and correlations were computed with fMRI voxels at those vertex locations. A 2D surface-based analysis has an advantage over computing correlations in native 3D space as it respects the inherent organization of neural activity along the 2D cortical manifold and only uses voxels in the vicinity of the gray matter. (16) LFP frequency bands: The power spectrum of

Figure 3. Example neurophysiological maps of category selectivity in IT. Neurophysiological maps of object selectivity (left) appeared more heterogeneous compared with fMRI maps (right) that showed more gradual, large-scale gradients of category selectivity (e.g., note the presence of a large face-selective region, the middle face patch, in central IT). Optimal spatial smoothing yielded neurophysiological maps (middle) that more closely resembled the large-scale structure present in fMRI maps. This improvement was apparent in the smoothie versus spike map where smoothie and spike selective regions became more clearly segregated after spatial smoothing (middle) even though smoothie and spike selective sites were intermixed in raw neurophysiology maps (left). Neurophysiology and fMRI maps were quantitatively compared only at locations where sites were recorded, and fMRI data shown here are plotted as dots at these corresponding locations. It is also important to note that all correlations were computed in native 3D space; surface-based visualization is used here for qualitative visual comparison of contrast maps as surface flattening and projection of sites onto the surface is not a distance preserving transform (non-isometric) and alters the spatial correspondence between fMRI and neurophysiology.
Figure 4. Correspondence between spatially smoothed neurophysiology maps and fMRI in monkey M2. Optimally smoothed MUA (left) and LFP (right) maps are shown for comparison to fMRI contrast maps (middle). The gradients of category selectivity are comparable across maps [e.g., the smoothie vs spikie maps contain a posterior smoothie selective region (purple) followed by a spikie selective zone (yellow)]. However, for one contrast map (smoothies vs cubies), neurophysiology-to-fMRI correlations were low in both subjects (monkey M2 shown here; see Fig. 5 for maps in M1). In these interpolated neurophysiology maps, vertices that were not within 3 mm of at least three physiology sites were masked, and the same neurophysiology mask was applied to fMRI maps. To aid visual comparison, color values were histogram equalized across all three MUA/LFP/fMRI maps such that colors are not on an absolute scale.
individual LFP waveforms in a window 50–200 ms following image onset was computed using Welch’s moving average method with a window size of 128 samples (sampling rate = 1 kHz). Average power in six different spectral bands (0.5–10, 16–24, 24–40, 40–80, 80–160, and 160–300 Hz) was used for comparison to fMRI maps.

In all manipulations requiring optimization of a free parameter [i.e., (1) smoothing, (8) active, (9) selective, (13) scale/rotate/translate/all, and (14) decompression], parameter values were found for half of the sites, and reported correlation values were independently computed on the remaining, withheld half of sites. To ensure a true split of fMRI voxels,
sites that were sampling the same voxel were forced to be exclusively in the training or testing set and not distributed in both. In general, parameter values were optimized independently for each contrast map in each animal yielding 12 values. We also performed the spatial smoothing analysis using a single smoothing width (median of individual map FWHMs) for all 12 maps and found that this fixed smoothing model gave similar results to individually optimized smoothing kernels (Fig. 6B, rightmost bars).

Statistics
Spearman’s rank correlation was used to compare neurophysiology and fMRI maps. This measure is less susceptible to monotonic nonlinearities (e.g., saturation) in neurophysiology–fMRI relationships; however, similar results were obtained using a linear Pearson correlation coefficient. Since our goal was to predict fMRI category selectivity maps, all correlations were normalized by the maximum achievable explained variance given the reliability of the fMRI maps (Op de Beeck et al., 2008). This normalized correlation measure is termed $r$ and is used throughout the text and figures. It will reach a value of 1.0 for a perfect model of fMRI maps. The reliability of fMRI maps was determined by computing, for the voxels that contained physiology sites, the correlation between different runs collected for the same fMRI contrast (split halves approach, $n = 30$ iterations) and was corrected for the smaller number of trials using the Spearman Brown correction according to $N^*r/(1 + (N - 1)^*r)$ where $N = 2$. To estimate a lower bound on the spatial resolution of information in MUA, LFP, and fMRI maps (Fig. 2), high-pass filtered maps were obtained by subtracting smoothed maps from raw maps, and the split halves correlation of the high-passed maps was computed. The point where split halves correlations between high-passed maps dropped below 50% height provided an estimate of the spatial resolution at which reproducible structure is contained in object selectivity maps.

Results
Neurophysiological sampling of fMRI volumes
Our goal was to construct large-scale neurophysiological maps of IT for comparison with fMRI maps obtained previously in the same subjects (Op de Beeck et al., 2008). This entailed sampling across the posterior-to-anterior extent of IT ($\sim 15$ mm) at subvoxel (<1.25 mm) resolution. MUA and LFP recordings were localized in 3D with high resolution and in vivo using a stereo microfocal x-ray system developed previously (Cox et al., 2008). Using a common skull-based reference framework, physiology sites were coregistered to functional MRIs for performing direct spatial comparisons (see Materials and Methods). We measured responses to a set of visually-presented images drawn from six categories that included faces and synthetic objects as previous work had shown topographic organization for contrasts of these shape classes at the level of fMRI (Tsao et al., 2003; Op de Beeck et al., 2008).

Measuring neurophysiological maps using the same object contrasts allowed us to ask whether the structures that appear in fMRI can be explained by neurophysiology maps obtained with the same images. Furthermore, x-ray-based electrode localization allowed us to construct precise neurophysiological maps and extend previous work in IT (Kiani et al., 2007; Bell et al., 2011).
To illustrate the data used in the analyses below, three representative fMRI voxels are highlighted in Figure 1A. In this example, physiology sites sampled within each voxel were tested for their preference for faces versus nonface objects, a contrast that is commonly used in human and monkey fMRI studies (Kanwisher et al., 1997; Tsao et al., 2003). In this particular contrast map, we obtained dense sampling of a few voxels, but across all voxels in the 12 contrast maps collected, two sites were collected per voxel on average (Fig. 1B). An important issue is that neurophysiological maps were constructed serially such that recordings were made on different days and hence under slightly different conditions (e.g., different electrodes) unlike fMRI volumes where all voxels were measured nearly simultaneously. Nonetheless, we found no significant difference in correlations between nearby voxel were measured nearly simultaneously. Nonetheless, we found no significant difference in correlations between nearby sites collected on the same day and between nearby sites collected on different days ($\rho_{\text{within day}} = 0.31$ vs $\rho_{\text{between day}} = 0.36$, $p = 0.67$, $n_{\text{within day}} = 1586$, $n_{\text{between day}} = 1957$, pairs of sites separated by $<500$ micrometers; within penetration distances were calculated using microdrive readings that are of high spatial accuracy (~1 μm), while between-day distances relied on x-ray-based position estimates) with absolute correlation levels similar to those obtained in previous studies comparing patterns of image selectivity across nearby sites (Gochin et al., 1991; Fujita et al., 1992; Kreiman et al., 2006; Kiani et al., 2007). This suggests that we could return to similar neurophysiological locations/conditions across different days with the same accuracy as within the same penetration.

Given that reliable physiological maps could be constructed using our serial approach, an important first question to ask is at what scale do neurophysiology and fMRI maps for each object contrast contain reliable spatial structure. To quantify this, we subtracted smoothed maps from raw maps yielding high-pass filtered maps and asked whether these high-frequency residual signals contained any reproducible structure (i.e., split-half correlation > 0; see Materials and Methods). For MUA and LFP maps, reproducible structure was present down to the smallest scales measurable given the accuracy of the x-ray system (~200 μm) while fMRI maps showed little reproducible structure at spatial scales <2.5 mm (Fig. 2). Thus, neurophysiological maps of object selectivity contained information at more detailed resolution than fMRI maps, and the goal of this study was to determine the relationship, if any, between information present in neurophysiology and fMRI maps.

The simplest possible model would be that all the physiology sites in a voxel have the same category preference as determined by the fMRI of that voxel. This simple model was clearly false; for example, we found that, even in voxels that were highly face selective, sites within the same voxel had varying preferences for nonface objects versus faces. Across our maps, this heterogeneity led to low overall correlations between site and voxel preferences at the same 3D location (median $\rho = 0.26$, average of $n = 12$ object contrast maps; $\rho$ refers to the normalized correlation between fMRI and neurophysiology maps when adjusted for noise in fMRI maps, see Materials and Methods). Alternatively, there may exist a mass-action correspondence between the distribution of underlying neurophysiological preferences and the final fMRI “report” of the voxel (i.e., the face selective voxels may contain more face selective sites while the object selective voxels may contain more object selective sites). Perhaps surprisingly, computing this report as the fraction of face/object-prefering sites (termed voxel purity) or the mean selectivity of all sites in each voxel did not lead to any improvement in neurophysiology–fMRI correlations despite averaging out neurophysiological heterogeneity within a voxel (purity: median $\rho = 0.17$, $p = 0.17$; average selectivity: median $\rho = 0.26$, $p = 1$, $n = 12$). Importantly, voxel-based averaging or purity measures only pool information at a relatively local scale (1.25 mm) compared with the resolution of reliable information present in fMRI maps (2.5 mm) (Fig. 2), suggesting the need for spatial averaging at larger scales.

Spatial smoothing of neurophysiology maps

At larger spatial scales, fMRI and neurophysiology maps shared similar structure. For example, the faces versus nonface objects neurophysiology map demonstrated a posterior-to-anterior arrangement of face selective clusters similar to those seen under fMRI (Fig. 3). To test the spatial scale of the relationship between neurophysiology and fMRI, we smoothed neurophysiology maps at different resolutions using a 3D Gaussian kernel. We found that spatially smoothing MUA maps more than doubled MUA–fMRI correlations on average ($\rho_{\text{smooth}} = 0.57$ vs $\rho_{\text{raw}} = 0.26$, $p = 0.002$, $n = 12$) and produced neurophysiology maps that were often visually difficult to distinguish from fMRI maps across some object contrast maps—even when those object contrast maps were very different from each other (Figs. 4, 5). A fixed smoothing transform (FWHM = 3.5 mm) performed as well as a smoothing kernel optimized on a per map basis (Fig. 6B, $\rho_{\text{smooth}} = 0.57$ vs $\rho_{\text{fixed smooth}} = 0.52$, $p = 0.58$, $n = 12$). Thus, spatial smoothing was a generic transform that generalized across the particular choice of fMRI contrast whether derived from more natural (e.g., face vs object) or from synthetic (e.g., smoothie vs spike) object contrasts.

Two possible explanations for this improvement with spatial smoothing are that averaging across sites simply decreased noise inherent to neural firing rates or that smoothing more accurately captured the transform from neurophysiological activity to fMRI signals. Given that neurophysiology maps were already highly reproducible across trial splits such that neural noise was not a major limiting factor ($\rho_{\text{MUA,MUA raw}} = 0.84$, and pooling more trials had little added benefit, $\rho_{\text{MUA,MUA smooth}} = 0.96$), we suggest that the primary effect of spatial smoothing was not to reduce noise but to accurately model the fMRI signal. Even when normalizing for the measured improvement in neurophysiology SNR, MUA–fMRI correlations with smoothing remained significantly higher than MUA–fMRI correlations without smoothing (SNR normalized $\rho_{\text{smooth}} = 0.49$ vs $\rho_{\text{raw}} = 0.25$, $p = 0.003$, $n = 12$ object contrast maps).

MUA maps smoothed at an intermediate scale of 2–5 mm were the best predictors of fMRI maps in all object contrasts that we collected (12 object contrast maps across two monkeys) including those for synthetic objects (i.e., smoothies vs spikies, smoothies vs cubes, and cubes vs spikies) (Fig. 6A). MUA–fMRI correlations peaked at 3.5 mm smoothing widths (FWHM) (Fig. 6A), consistent with the scale where fMRI maps begin to contain reliable information (Fig. 2) but not at larger scales that reduced noise but did not accurately model the fMRI signal. In a follow-up analysis, we searched our fMRI maps for local regions (<2 mm) with high spatial frequency content ($p < 0.01$, split halves correlation of highpass-filtered fMRI maps using FWHM = 1.25 mm) using a spotlight analysis. Even in these local regions, smoothing MUA maps at 2–5 mm spatial scales was optimal (median = 4.7 mm), and no trend between fMRI power at high spatial frequencies and optimal neurophysiology smoothing widths was observed ($\rho = 0.01$, $p = 0.96$, $n = 43$), suggesting that stronger higher spatial frequency structure in fMRI did not correspond to the high resolution content in neurophysiology maps. Such an analysis, however, may require improved fMRI signal-
to-noise ratios at the 1–2 mm scale as noise may have overwhelmed our fMRI signal at high spatial frequencies even though some information was still present at these frequencies (Fig. 2).

Smoothing fMRI volumes (FWHM = 2.5 mm) did significantly average out noise in our fMRI maps increasing their reliability \( P_{\text{MUA-fMRI unsmoothed}} = 0.45 \) vs \( P_{\text{MUA-fMRI 2.5 mm smoothed}} = 0.78, p = 0.001, n = 12 \), and for this reason smoothing is a typical procedure in fMRI studies (Op de Beeck et al., 2008; Tsao et al., 2008b). We used smoothed fMRI maps under the logic that limited information was contained at scales smaller than 2.5 mm (Fig. 2). However, we also performed analyses using raw fMRI data to determine whether using smoothed fMRI maps may have biased our estimates of the optimal neurophysiology-to-fMRI kernel. We found nearly identical optimal neurophysiology-smoothing widths regardless of whether the resulting smoothed physiology map was compared with raw (unsmoothed) fMRI data or smoothed fMRI volumes (FWHM\(_{\text{raw}} = 4.4\) vs FWHM\(_{\text{2.5 mm}} = 3.5, p = 0.91, n = 12\). And absolute fMRI-neurophysiology-correlation levels were similar when using unsmoothed fMRI data as when using smoothed fMRI data after correcting for the reliability of these two different types of fMRI maps \( p_{\text{raw}} = 0.61\) vs \( p_{\text{2.5 mm}} = 0.57, p = 1, n = 12\).

Finally, we also measured LFP–fMRI correlations across multiple spatial scales. Baseline LFP–fMRI correlations (i.e., without any spatial smoothing) were higher than baseline MUA–fMRI correlations \( p_{\text{LFP}} = 0.47\) vs \( p_{\text{MUA}} = 0.26, p = 0.08, n = 12\) and only modestly improved with optimal spatial smoothing \( p_{\text{smooth}} = 0.67\) vs \( p_{\text{raw}} = 0.47, p = 0.11, n = 12\) (Fig. 6A). Slightly less spatial smoothing was required for optimal correlation of LFP maps and fMRI maps (3.2 mm) than was required for optimal correlation of MUA maps and fMRI maps (3.5 mm), although this difference was not significant \( p = 0.35, n = 12\) (Fig. 6A). Thus, MUA and LFP signals were both highly predictive of fMRI once smoothed at similar (3.5 mm) scales \( p_{\text{MUA}} = 0.57, p_{\text{LFP}} = 0.67, p = 0.71, n = 12\).

**Alternative neurophysiology to fMRI transforms**

Besides spatial filtering, many factors may contribute to the mapping from neurophysiology to fMRI signals. For example, although responses may be linear in some regime (Rees et al., 2000), there may be an intervening nonlinearity (e.g., saturation), or fMRI voxels near the gray matter or away from large draining veins in the sulci may be more reliable indicators of nearby neurophysiological signals (Duong et al., 2001; Goense and Logothetis, 2006; Olman et al., 2007). Also, there may be a slight scaling, rotation, or translation that could improve coregistration between physiology sites and fMRI voxels. Finally, previous work has shown that different aspects of the neural response (e.g., gamma band of the LFP) (Logothetis et al., 2001; Hermes et al., 2012) or different time windows (e.g., early feedforward response vs steady-state firing) (Kim et al., 2004) may better correlate with metabolic signals such as fMRI. To test the potential contribution of these factors, we transformed neurophysiology maps by using different time windows, frequency bands, selectivity metrics, or spatial registrations (see Materials and Methods for complete details). We also varied site and voxel selection criteria to see if neurophysiology–fMRI correlations improved in certain regions. For all transforms tested, we found no significant improvement in neurophysiology–fMRI correlations over baseline levels unlike the significant improvements seen with spatial smoothing of neurophysiology maps (Fig. 6B). Finally, we found no further improvement in neurophysiology–fMRI correlations when cascading the alternative transforms with spatial smoothing (data not shown). Thus, for block design fMRI experiments, the best neurophysiology-to-fMRI model was a 3.5 mm spatially weighted average of the difference in spike rate evoked by each of the stimulus conditions.

**Discussion**

We have reconstructed 3D neurophysiological maps of object selectivity across a wide extent of IT cortex in two monkeys and provided visual and quantitative evidence that spatial gradients of object selectivity in fMRI reflect underlying 3D neural organization at large (>3.5 mm) spatial scales. Spiking signals, once spatially smoothed, were as predictive of fMRI maps as LFP signals. These results extend previous work by showing that fMRI is spatially low passed version of neural signals as well as being a temporally low passed version (Logothetis et al., 2001). The widely held belief that fMRI signals are spatially blurred versions of neurophysiology signals (Heeger and Ress, 2002; Op de Beeck, 2010) had only been inferred in previous work (Disbrow et al., 2000; Bell et al., 2011; Hermes et al., 2012) and had yet to be directly tested before this study. Here, we were able to make that direct comparison because we developed and deployed a novel x-ray-based mapping procedure to measure neural maps of object selectivity at finer scales than previous neurophysiological work (Tsao et al., 2006; Bell et al., 2011). With our current x-ray mapping approach, we also found evidence of reproducible neural structure at scales smaller than those resolvable by current fMRI techniques (Fig. 2), a result consistent with previous neurophysiological work (Wang et al., 1996; Tsunoda et al., 2001; Kreiman et al., 2006); whether these currently-fMRI invisible spatial structures correspond to sharp borders (i.e., modular) or contain additional subregions is an open question for future study.

**Limitations of the spatial smoothing model**

Here, we have put forth, for an fMRI block design experiment, our best, current neurophysiology-to-fMRI model: a 3.5 mm spatially weighted average of the difference in spike rates evoked by each stimulus condition. This model is limited in that as fMRI techniques improve, the exact kernel size is likely to decrease. Furthermore, even for the present data, a spatial smoothing transform did not explain all of the variance in fMRI maps (~40% variance explained) (Fig. 6B). We used a normalized explained variance measure to account for the reproducibility of data across fMRI runs that absorbs effects such as subject motion during scanning, differences in MION strength across sessions, or inherent inaccuracy in coregistering functional scans to base anatomical volumes. To further ameliorate these issues, we took precautions such as not considering fMRI volumes when there was excessive movement, searching for optimal affine/deformation transforms, and correcting for magnetic field distortions. Nonetheless, systematic errors may persist depending on the severity of geometric distortions in fMRI maps. One important concern is that fMRI and neurophysiology maps were collected years apart. During this time, the brain may have changed in its anatomical or functional structure. Consistent with a longitudinal study finding little change in macaque brain size after five years of age (Malkova et al., 2006), we found almost no change in brain size in the two monkeys we tested (see Materials and Methods). Furthermore, our previous work showed that functional maps were remarkably stable over the course of a year and over the course of object-specific training (Op de Beeck et al., 2008). In our study, despite the differences between fMRI and neurophysiology methodologies (Table 1; see Materials and Methods), a
strong correspondence was observed between these modalities. Nevertheless, our absolute correlation numbers (0.6–0.7 after smoothing) should be taken as a lower bound on the correspondence between neurophysiology and fMRI, and our estimate of the optimal smoothing kernel (3.5 mm) should be taken as an upper bound.

Another limitation is that viewing each voxel as an identical lowpass filter is possibly an oversimplification. Each voxel contains a unique vascular pattern leading to a complicated spatio-temporal filter that, because of voxel undersampling, potentially aliases high-frequency spatial information into low spatial frequencies (Kriegeskorte et al., 2010). Such a neurovascular filter would allow decoding of information present in high spatial frequencies (Kamitani and Tong, 2005; Haynes and Rees, 2006) with the drawback that neural signals are distributed in space and not easily recoverable using a simple transform. While we do not dispute the possibility of aliasing effects in the fMRI signal, our results show that a large part of the fMRI signal reflects low spatial frequency power in neurophysiology maps—as quantified by our model.

Comparison to previous neurophysiology–fMRI work
Previous work examining the relationship between neurophysiology and fMRI signals over time instead of across space found that fMRI signals were slightly more correlated to LFP than to MUA signals (Logothetis et al., 2001), but another study found that fMRI signals were slightly more correlated to LFP than to ECoG. This implies that fMRI is shared between fMRI maps and underlying neurophysiology. We found that down to the scale where our fMRI maps contained information (∼2.5 mm), these maps were highly predictive of the structures produced by smoothing underlying neurophysiology.

Implications for current fMRI work
Our technique is comparable to standard fMRI done in humans and monkeys using 3T magnets (Tsaø et al., 2003, 2008a; Pitcher et al., 2011). We matched conditions (block design, gradient echo) commonly used while deploying MION, a contrast agent that improves signal-to-noise ratios (Leite et al., 2002) and may improve resolution over more standard BOLD imaging (Kim and Fukuda, 2008; Smirnakis et al., 2007). Our results demonstrate the utility of this standard scanning methodology in revealing the large scale organization in higher level visual areas approaching the current 3.5 mm limit of fMRI at 3T (Parkes et al., 2005), and our findings may explain why face selective regions in IT (or “face patches”) have been consistently detected in fMRI studies (Tsaø et al., 2003; Bell et al., 2009; Pink et al., 2009; Tsaø et al., 2008a).

In our previous study, the neurophysiologically determined diameter of the posterior lateral face patch in two monkeys was 3.75 and 5 mm, respectively, and the middle lateral face patch appears to be of similar size or larger (Tsaø et al., 2008a; Issa and DiCarlo, 2012). A neurophysiological structure of this size contains energy at spatial frequencies that would easily pass through the spatial smoothing kernel determined in this study (Gaussian, FWHM = 3.5 mm) are the most faithfully reflected in both shape and size in fMRI. However, a region with heterogeneous (i.e., “salt-and-pepper”) neural selectivity (red, FWHM = 3.5 mm) will also appear as a Gaussian in fMRI, and a region with a sharp modular boundary (blue, width = 3.5 mm) will have a similar graded profile in fMRI. Thus, graded, sharp, and heterogeneous regions are difficult to distinguish as they have similar amplitude and shape under fMRI. Finally, small single-peaked (purple, width = 0.5 mm) regions will appear to be much wider under fMRI although reduced in amplitude, and multi-peaked regions (green, width = 1.5 mm, 1 cycle/mm) will appear as single-peaked in fMRI and also have reduced amplitude.
3.5 mm) and would be visible in fMRI at a size similar to its true underlying size (Fig. 7).

However, a more precise description of the neural organization of face versus object maps given our observations (Fig. 3) is that they contain salt-and-pepper structure locally as well as biases in face selectivity at large scales. Under this biased salt-and-pepper model, fMRI smoothes out local heterogeneity but provides an accurate picture of large-scale face selectivity gradients. We speculate that the contrast (Smoothes vs Cubies; Figs. 4, 5) that gave the weakest correlations in both monkeys may have contained weak large-scale structure possibly because smoothies and cubies may be similar in shape space.

Finally, we have only shown that neurophysiology maps contain reliable structure at current fMRI-invisible scales in the statistical sense and have not provided an explicit description (e.g., columnar) of these fine scale structures. To do so would require denser, more even sampling and may require using different images that expose fine scale organization. Our spatial blurring model predicts that many other patterns of neurophysiological organization besides salt-and-pepper organization would appear to have a similar spatial fMRI profile as a large face selective region. For example, our models predict that signals that change selectivity rapidly across space (i.e., repeated motifs at fine scales such as orientation columns) will appear as relatively pure in fMRI as will impure (salt-and-pepper) regions (Fig. 7). Also, it predicts that a region of highly pure selectivity (module) much smaller than a face patch (0.5 mm) will appear to be much larger in fMRI (>3 mm) and could be confused with a large face patch (Fig. 7). These effects of spatial smoothing suggest cautious interpretation of regions of interest or “modules” when localized using fMRI, as many of the possible underlying neurophysiological patterns are not “modular” in the sense that they can be far from pure and need not have well-defined boundaries. Nonetheless, fMRI maps of object selectivity should be considered rough but still invaluable guides to the spatial organization of neural selectivity in IT.

References


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