To examine the possibility that these two effects were mediated by distinct classes of neurons, Chen *et al.*[1] divided the population into two groups: difficulty-enhanced neurons, which on average increased responses with increased task difficulty, and difficulty-suppressed neurons, which showed decreased responses with increased task difficulty. These two groups of neurons differed in their direction selectivity, contrast sensitivity and interspike interval distribution, supporting the idea that they correspond to distinct classes of neurons. To test this directly, the authors examined action potential waveform width, a parameter that has been found to vary across anatomically distinct classes of neurons. Difficulty-enhanced neurons tended to have narrow action potentials, whereas difficulty-suppressed neurons tended to have broad action potentials. Studies in anesthetized animals and cortical slices, where different types of neurons can be distinguished on the basis of morphology and protein expression, have found that parvalbumin-expressing GABAergic interneurons with basket or chandelier morphology have narrow action potentials. Pyramidal neurons, on the other hand, typically have broad action potentials. As the authors are careful to note, this separation of neurons into putative interneurons and pyramids on the basis of action potential width is not one-to-one; there are a few narrow-spiking pyramidal neurons[2] and a substantial fraction of interneurons that have broad action potentials. However, given that 70–80% of all cortical neurons are broad-spiking pyramidal neurons, it is probable that the large majority of broad-spiking neurons are indeed pyramidal neurons. Furthermore, as narrow-spiking pyramidal neurons are uncommon, it is probable that most narrow-spiking neurons recorded in this study are indeed inhibitory interneurons. Thus, the authors propose that the center-surround organization that they observed is mediated by two distinct classes of neurons: narrow-spiking inhibitory interneurons that tend to show elevations in activity when attention is directed to a stimulus in the receptive field and broad-spiking pyramidal neurons that tend to be suppressed when attention is directed outside of the receptive field (**Fig. 1**).

The present study advances our understanding of attention in several ways. First, it is one of the few studies to date that have examined differences in attentional modulation across distinct classes of neurons. This is an essential step forward for understanding the cortical circuits that mediate attention. Second, this study shows that, as in area V4, attention increases the responses of inhibitory interneurons[3]. Third, these findings strongly support models of attention in which reductions in the neuronal responses evoked by distracters result from attention-dependent increases in the activity of inhibitory interneurons[4–7]. This study provides particularly strong support for the proposal that attention modulates the circuits that give rise to center-surround interactions[8–10]. If so, the influence of a stimulus appearing in the surround should be diminished when attention is directed to the neuron's classical receptive field center and magnified with attention to the surround stimulus. Chen *et al.*[1] did not measure the influence of the extra-receptive field stimuli in their study in the absence of attention, but if the present findings do reflect attentional modulation of center-surround interactions, the neurons that were suppressed by attention would be predicted to be those that were suppressed by inhibitory interneurons whose responses were magnified by attentional feedback[10]. It will be interesting to see this prediction tested in future experiments.

The central importance of attention in perception and behavior has been recognized since the dawn of experimental psychology and its scientific investigation has been marked by a progressive improvement in our understanding of underlying mechanisms. Research from multiple laboratories has revealed that when attention is directed to a location in space, feedback signals are generated in attentional control centers of the brain[11–15]. These signals feed into the visual cortices, where they enhance the neural signals evoked by attended stimuli and diminish responses evoked by task-irrelevant distracters. In the present study, Chen *et al.*[1] have shed light on the neural circuits in the visual system that transform attentional feedback signals into these two forms of attentional modulation. They have thus made a substantial contribution to our understanding of the neural substrates of this essential cognitive function.

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Face to face with cortex

Chris I Baker

Two new studies in *Science* and *Nature Neuroscience* combine functional magnetic resonance imaging and electrical microstimulation to reveal face-selective temporal and frontal areas and their connectivity.

Faces are everywhere, and we are very good at extracting all sorts of information (such as identity, emotional state, direction of attention, etc.) from them. This effortlessness belies the difficulty of the tasks, as faces are complex stimuli, with a great deal of similarity between different faces. In both human and non-human primates, there is considerable neural architecture that is devoted to processing faces, and researchers have identified multiple 'face-selective' brain regions in the temporal lobe that respond more when observers view faces than when they view other objects. However, exactly how these regions connect to each other and whether they constitute part of a specialized 'face network' that extends throughout the brain is a matter of current debate[1–3].

In two studies in *Science* and *Nature Neuroscience*, Moeller *et al.*[4] and Tsao *et al.*[5] used a powerful and technically challenging combination of functional

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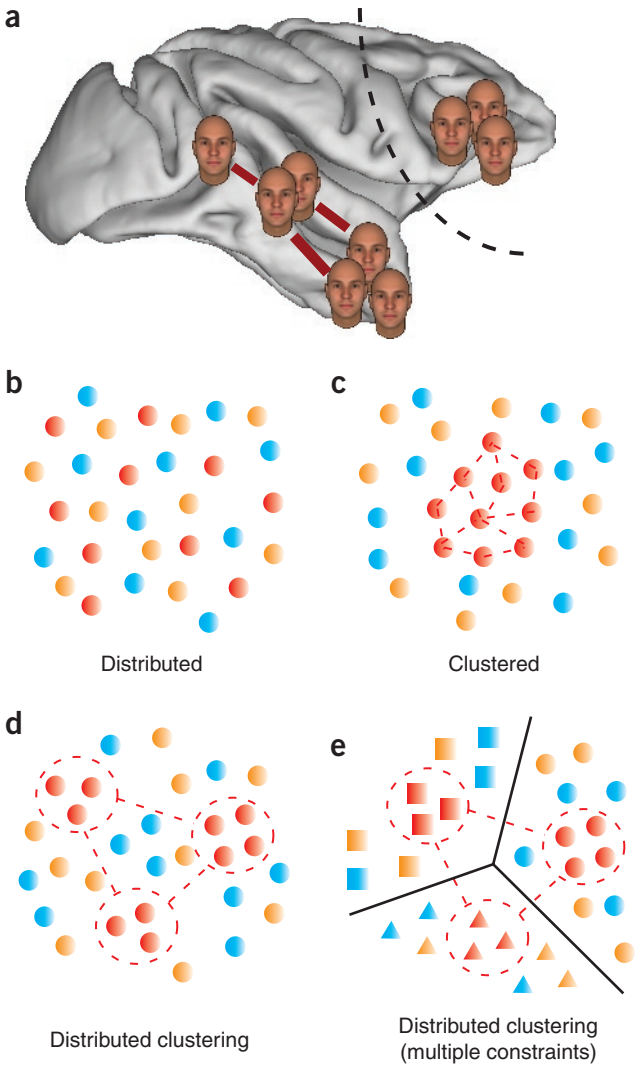

Figure 1 Distributed face-selective patches in monkey temporal and prefrontal cortex. (**a**) Functional imaging in monkeys has revealed nine face-selective patches in temporal and prefrontal cortex. Combined electrical microstimulation with fMRI shows that the temporal face patches are tightly connected with each other, but not with other parts of cortex. (**b–e**) Possible organization of face selectivity in cortex. Although face-selective neurons (red) could be distributed throughout cortex (**b**) and intermixed with non–face-selective neurons (blue and gold) in principle, constraints on wiring length could produce clustering of face selectivity (**c**). However, constraints on wiring length based on stimulus domain alone cannot explain the distributed clustering observed in both human and monkey cortex with multiple clusters of face selectivity (**d**). Such distributed clustering may reflect multiple constraints on the organization of cortex (**e**) arising for example from a combination of anatomy, function and underlying neural properties leading to a larger scale organization (denoted by circles, squares and triangles) with stimulus-based clustering in each larger grouping (macaque brain image from CARET atlas, http://brainmap.wustl.edu/caret/).

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magnetic resonance imaging (fMRI) and electrical microstimulation to investigate the connectivity between face-selective patches in the monkey temporal lobe and to determine whether there are face-selective patches outside of the temporal lobe. Temporal lobe face-selective patches turn out to be tightly connected and may constitute a 'unified system' for processing faces that extends into frontal regions of the brain. These findings provide provocative new insights into the cortical organization and specialization of visual processing for faces.

To investigate the connectivity of the face-selective patches in the temporal lobe, Moeller *et al.*[4] first identified these patches using fMRI while the monkeys viewed either faces or other objects. Up to six face-selective patches in the temporal lobe had substantially greater responses to faces compared with other objects (**Fig. 1**). The researchers then carefully lowered an electrode into a specific face-selective patch and applied electrical microstimulation, measuring the resultant changes in activity by fMRI. Prior work in primary visual cortex (V1)[6] has shown that electrical microstimulation produces not only a spread of activity around the electrode tip, but also in far away areas that are connected to the stimulation site. Thus, stimulation inside a face patch can reveal the cortical regions that the face patch connects to. Remarkably, stimulation of single face patches produced activation almost exclusively in other face patches, even when they were separated by several millimeters of cortex, suggesting that these face patches are connected. Furthermore, face-patch stimulation did not produce consistent activation in any other non-face cortical regions (although some subcortical regions, including the amygdala and pulvinar, were activated). Conversely, stimulation outside of the face patches did not produce substantial activation in the face patches (except for those that were very close to the stimulation site), but did produce activation in other non–face-selective patches of cortex. Importantly, not all face patches were equally connected; stimulating different face patches produced activation in different subsets of the other patches, providing important clues as to the flow of activity through the different patches.

Although these results demonstrate strong connectivity between the face patches, they do not necessarily show that the patches constitute an encapsulated and modular face-processing circuit. Combined microstimulation with fMRI may only be able to pick up the most prominent connections (diffuse connections may be missed entirely) and may predominantly reveal only monosynaptic connections[6]. Notably, microstimulation-induced activation was much weaker in the hemisphere contralateral to the stimulation site than in the ipsilateral hemisphere, even though there is thought to be strong inter-hemispheric connections in inferior temporal cortex. Furthermore, the spread of activation around the microstimulation site extended outside the stimulated face patch. Although this activation could simply reflect passive spread of current, it could also reflect transfer across local synaptic connections, and the spread of activity around the electrode tip in V1 is larger than expected assuming passive spread[6]. One possibility is that there is some short-range connectivity between the face patches and the adjacent cortex (possibly between the face patches and related cortex such as that selective for body parts[7]), but that long-range connectivity is predominantly between the other face patches.

In this issue, Tsao *et al.*[5] extended their focus to the frontal lobe and asked whether there are patches of face selectivity outside of temporal cortex. Prior single-unit recordings in monkeys have revealed the presence of face-selective neurons in

prefrontal[8] and orbitofrontal[9] cortex, but whether these neurons were clustered into discrete face patches, similar to those in the temporal lobe, remained unclear. With the same experimental design that Moeller *et al.*[4] used to localize the face patches in the temporal lobe, Tsao *et al.*[5] revealed three additional face-selective patches in prefrontal cortex (**Fig. 1a**). Two of these patches were found in all four of the monkeys tested and correspond very closely with the previously reported locations of face-selective neurons[8,9], whereas the third patch was only observed in two monkeys. Thus, clustered selectivity for faces is not restricted to the temporal lobe, but can be found in prefrontal cortex as well.

Unfortunately, in the microstimulation study on connectivity, the slice prescriptions did not always include the prefrontal cortex, so the connectivity between the temporal and frontal patches remains an open question. However, after recording from individual face-selective neurons in the lateral prefrontal cortex (probably corresponding to PL in the present study), a previous study[8] injected anatomical tracers into the physiologically defined areas and found connections from the ventral bank of the superior temporal sulcus and the adjacent inferior temporal gyrus. These regions might correspond to the anterior temporal lobe face patches, AL and AM.

The data presented by Moeller *et al.*[4] and Tsao *et al.*[5] substantially advance our understanding of the neural substrate for face processing, but also give rise to a number of questions. First, what, if any, functional differences are there between the face patches? Important clues are provided by a second experiment in which Tsao *et al.*[5] presented the monkeys with either neutral or expressive faces. Although the response in all temporal and prefrontal face patches tended to be higher for expressive than for neutral faces (perhaps reflecting increased attention to expressive faces), the difference was only significant in one of the anterior temporal lobe patches (AL) and the orbitofrontal patch (PO). Selectivity was much greater in PO than in AL (see Supplementary Fig. 2 in Tsao *et al.*[5]), suggesting that PO may have a specific role in processing the emotional content of faces.

Elucidating the different functional properties of the face patches may require the greater resolution afforded by single-unit recording. In an earlier study using fMRI to guide electrode penetrations[10], 97% of single neurons recorded in the middle face patches (ML, MF) were found to be face selective. Furthermore, activity from these neurons provided both category and identity information. However, sampling was restricted to only three recording track locations (spanning 3 mm) in each monkey. Wider sampling is needed to reveal the functional homogeneity of the face patches and to determine how well their fMRI-measured extent corresponds with the underlying neural data. Further fMRI-guided single-unit recording in multiple face patches will help to determine the extent to which different properties of faces (for example, view, identity, expression, gaze direction) are coded in each patch.

Second, why should face processing be organized in a series of tightly connected patches? Computationally, there's no reason why neurons with a preference for faces should be organized into patches at all; such neurons could be distributed throughout the cortex (**Fig. 1b**). However, a constraint on connection length between neurons (as a result of the cost of wiring[11]) could lead to clustering of neurons with similar preferences, allowing a sharpening of selectivity through local interactions (**Fig. 1c**). This constraint can lead to the formation of large-scale shape maps across the cortical sheet, as has recently been reported for shape in inferior temporal cortex[12]. However, simple shape topography alone cannot easily explain the observed distributed clustering into multiple face patches (**Fig. 1d**), which would seem to violate the wiring cost constraint. Therefore, there must be other constraints on the organization. One possible explanation is that the system minimizes wiring costs across several dimensions[13] or constraints simultaneously (**Fig. 1e**), such as physical properties (for example, shape topography), functional properties (for example, semantic relations and task demands), anatomy (for example, connectivity with other structures such as the amygdala) and underlying neural properties (for example, receptive field size and retinotopic biases). Under this view, any individual patch is the product of a minimization of wiring costs on the basis of stimulus domain (for example, faces) and the separation between individual patches highlights organization on the basis of a combination of these other constraints. These constraints must be at least as important as 'faceness' for determining the distribution and location of face selectivity in cortex. Elucidating these constraints will provide important insights into the nature of functional processing in cortex.

In humans, fMRI experiments have also revealed a number of different face-selective regions[1–3] including regions in the inferior occipital cortex, the banks of the superior temporal sulcus, the fusiform gyrus and anterior inferior temporal cortex[14]. There may also be a face-selective region in inferior frontal cortex[15]). Although it is difficult to identify direct homologies between humans and monkeys, face-selective regions in human cortex may also reflect a tightly coupled 'face network'[1–3]. It is possible that observed deficits in human face perception (such as congenital prosopagnosia) may be reflected in deficits in connectivity and not just in deficits in particular functional regions (M. Behrmann *et al. Soc. Neurosci. Abstr.* 702.2, 2006). The findings of Moeller *et al.*[4] and Tsao *et al.*[5] emphasize that a full understanding of cortical face processing will require an understanding of not only the individual regions, but also the connectivity and interactions between regions.

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