

Influence of experience on orientation maps in cat visual cortex

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Experience is known to affect the development of ocular dominance maps in visual cortex, but it has remained controversial whether orientation preference maps are similarly affected by limiting visual experience to a single orientation early in life. Here we used optical imaging based on intrinsic signals to show that the visual cortex of kittens reared in a striped environment responded to all orientations, but devoted up to twice as much surface area to the experienced orientation as the orthogonal one. This effect is due to an instructive role of visual experience whereby some neurons shift their orientation preferences toward the experienced orientation. Thus, although cortical orientation maps are remarkably rigid in the sense that orientations that have never been seen by the animal occupy a large portion of the cortical territory, visual experience can nevertheless alter neuronal responses to oriented contours.

Two key properties, binocularity and orientation selectivity, characterize the responses of neurons in the primary visual cortex¹. Neurons with similar preferences with regard to these features are grouped in columns perpendicular to the cortical surface, giving rise to the well-known cortical maps of ocular dominance and orientation preference^{2–5}. In the case of ocular dominance, experimental manipulations such as monocular deprivation and reverse occlusion have firmly established that experience-dependent cortical plasticity involves competition of inputs from the two eyes for cortical territory^{6–8}. In contrast, it has remained controversial whether there is a similar effect on neuronal orientation preference of exposure to contours of a single orientation, such that more cortical territory would be allocated to the experienced orientation. Three different approaches have been used to address this question: rearing animals in striped cylinders^{9–12}, rearing with goggles that contain images of lines of a single orientation^{13,14} or rearing with strong cylindrical lenses that blur all but a narrow range of contour orientations^{15–17}.

The controversy centers on two issues. First, the potency of rearing in a striped cylinder to modify orientation preference has been questioned because head rotations may prevent such rearing from restricting exposure rigorously enough^{11,14}. Second, it has remained unclear whether biases in the distribution of preferred orientations, when observed, entail an active modification of the cells' response properties, that is, a change in their preferred orientations toward the experienced one⁹, or whether there is instead a passive loss of responses or a broadening of tuning of cells whose preferred orientations do not match the experienced one¹⁴. As all previous studies were done with single-neuron recordings, the differences between them could always be attributed to a sampling bias, and definite conclusions were difficult to draw.

Optical imaging based on intrinsic signals^{18,19} provides a means to gather information from a very large number of cells, thus over-

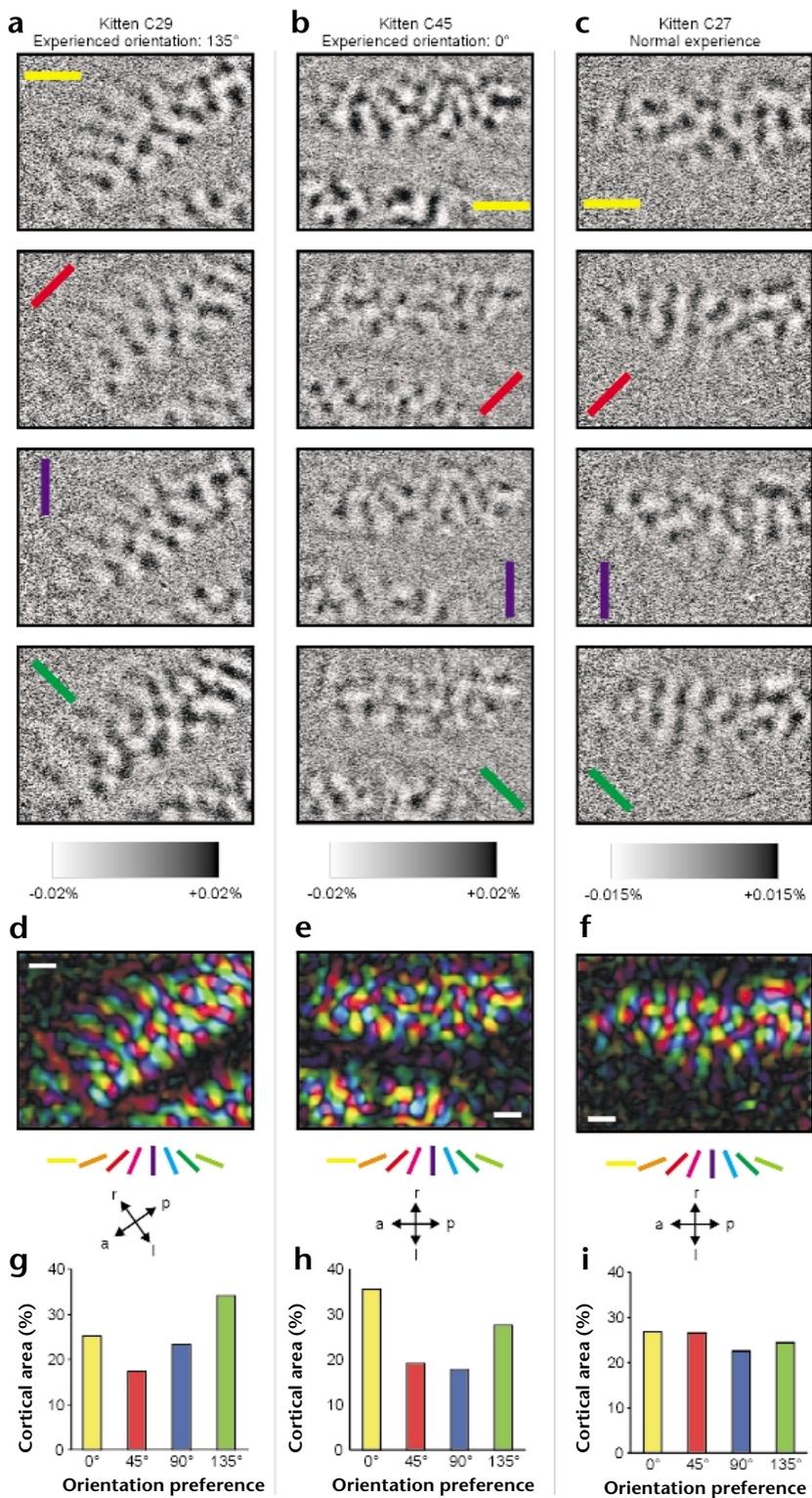
coming the problem of sampling bias. We therefore used this technology to address the above questions and determined the layout and relative surface area of orientation columns in the visual cortex of kittens reared in striped cylinders.

RESULTS

Six kittens were reared in striped cylinders providing a single-orientation environment (see Methods). When the animals were between 37 and 54 days old, we used optical imaging to examine the primary visual cortex. Two examples, a 44- and a 37-day-old kitten, are shown in the left and middle columns of Fig. 1. Qualitative visual inspection of the images shows that iso-orientation maps for the experienced orientation were strongest (Fig. 1a and b). Quantitative analysis confirmed this observation (Fig. 1g and h). This over-representation of the experienced orientation was observed in all four kittens reared in this fashion (Fig. 2a; kittens C16, C28, C29 and C45). In the most striking cases (C29, C45), the experienced orientation occupied about twice as much cortical area as the orthogonal orientation. In contrast, in a littermate control kitten that spent its time in a normal laboratory environment, all orientations were represented roughly equally (Figs. 1c, f, i and 2a; C27). The same was true for seven control animals that were not littermates, which were raised with normal (continuous) visual experience (data not shown).

Because head rotations could have prevented a stronger bias in favor of the experienced orientation (as they would have effectively produced a wider range of orientations in the retinal images), we reared two of the kittens in striped cylinders and additionally equipped them with goggles containing cylindrical lenses of -14.75 diopters (Fig. 2a; C67, C69). In an environment where all orientations are present, rearing with cylindrical lenses alone produces a pronounced imbalance in the cortical representation of orientations^{15–17}. The orientation of the lenses matched the orientation of the stripes that the animals were

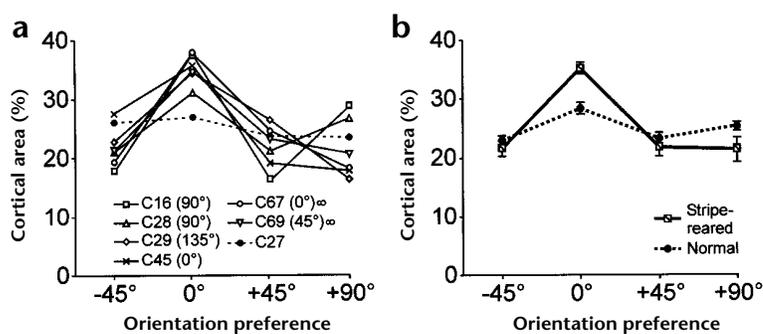
Fig. 1. Iso-orientation maps show an over-representation of the experienced orientation. **(a)** Iso-orientation maps of the visual cortex in kitten C29, which had been exposed to stripes of 135° orientation for a total of 100 hours. The images show mostly the right hemisphere, with a small part of the left visible in the lower right corner. (The gray band between the patchy areas corresponds to the midline of the brain.) Colored bars in the top left corners of each map indicate the four orientations tested. The cortical surface area responding best to the exposed orientation (135°; green) is enlarged, particularly when compared with the area for the orthogonal orientation (45°; red). The gray scale below the 135° map represents signal strength $\Delta R/R$ (where R refers to the cocktail-blank response, see Methods and ref. 19). **(b)** Similar data for kitten C45, which had been exposed to stripes of 0° orientation for a total of 86 hours. **(c)** Similar data for kitten C27, which had normal visual experience for a total of 93 hours. **(d–f)** Polar maps of orientation preference in the visual cortex of the kittens shown in **(a–c)**. These maps were computed by summing responses to all orientations vectorially. The vector angle is displayed using the pseudo-color code shown below the panels; the length of the vector is encoded as the brightness of the colors¹⁹; scale bars, 1 mm. Dark regions indicate areas of weak orientation selectivity or, more commonly, areas where cells with very different orientation preference are found in close proximity, as is the case in pinwheel centers. **(g–i)** Histograms of cortical areas responding most strongly to 0°, 45°, 90° and 135° orientations in kittens C29, C45 and C27. The experienced orientation is overrepresented in kittens C29 (135°) and C45 (0°).



exposed to, thereby ensuring that only a narrow range of orientations around that of the stripes could produce a focused retinal image. In one animal (C67), the relative representation of the experienced orientation was marginally stronger than in any of the four kittens reared without goggles, whereas results from the second kitten reared with goggles (C69) fell within the range of results obtained from animals without goggles. We therefore concluded that the observed distribution of orientation preferences had not been affected by head rotations, and we pooled results from all kittens (Fig. 2b). On average, the experienced orientation occupied 35.3% of the cortical surface, and the other three orientations each between 21% and 22%, corresponding to an overrepresentation of the experienced orientation by 64.7% compared with the orthogonal. In contrast, in the eight control animals with normal contour experience, the difference in representation of orthogonal orientations (0° versus 90° and 45° versus 135°) was on average 9.4%. Thus, the cortical area preferring the experienced orientation in the stripe-reared animals was significantly higher ($p < 0.01$, Mann–Whitney U-test) than the area preferring the best orientation in the kittens with normal contour experience.

For a conservative estimate of significance, the distributions of cortical area versus orientation for the eight control animals were aligned *post hoc* at the orientation yielding the largest area, designated 0° (Fig. 2b), a procedure which for normal rearing conditions actually overestimates the amount of anisotropy. (In four of the seven normal animals, the actual best orientation was 0°; in three, it was 90°.) We further observed that, despite the skewed distribution of orientation preferences, the general lay-

Fig. 2. Relative representation of orientations in the visual cortex of stripe-reared and normal kittens. **(a)** Distributions for individual stripe-reared animals. The experienced orientation is arbitrarily designated 0°; the actually experienced orientation is given in brackets in the key; ∞ denotes animals reared with cylindrical lenses. For the littermate reared in a normal laboratory environment (C27), the curve is also shifted to peak at 0° for better comparison. The orientation represented most strongly in this animal was actually 45°. **(b)** Average representation of orientations in six stripe-reared animals compared with representation in eight kittens with normal contour experience, including littermate C27 shown in **(a)**. In control animals, distributions were aligned with peaks at 0° for the most strongly represented orientation before averaging. Note that the actual anisotropy in normal animals is considerably smaller, because this procedure yields the largest possible bias away from a flat distribution. Data are mean ± s.e.



out of orientation preference maps appeared normal in all of the stripe-reared kittens. In particular, the density of pinwheel centers did not differ significantly ($p > 0.1$) between stripe-reared cats (2.47 ± 0.27 pinwheel centers per mm^2 , mean ± s.d.) and normal animals (2.75 ± 0.33 pinwheel centers per mm^2).

The observed imbalance in cortical representation of orientations could have different causes: it could be due either to 'respecification' of the orientation preferences of single cells^{9,20} or to loss of tuning or responsiveness of cells tuned to orientations other than the experienced one¹⁴. To test whether loss of tuning could account for our results, we electrophysiologically assessed the response properties of single neurons in supragranular layers (Fig. 3). Orientation preference and tuning width were determined quantitatively. We purposely targeted our electrode penetrations to sample roughly equal numbers of neurons preferring either the experienced orientation or one of the other orientations used in the imaging experiment. There were no significant differences among these four populations of cells with respect to either tuning width (Fig. 3b) or response magnitude at the preferred orientation (data not shown). The half width at half height (HWHH) of tuning of 17 neurons preferring the experienced orientation was $27.4^\circ \pm 2.2^\circ$ (mean ± s.e.); for non-experienced orientations, HWHH ranged from 23.5° to 26.5° (s.e. from 1.3° to 2.8° ; Fig. 3c). For the whole population of 81 cells, HWHH was $25.6^\circ \pm 1.1^\circ$, similar to the values reported for cats with normal contour experience^{21,22}. The results from single-neuron recordings thus suggest that stripe rearing does not cause a

noticeable loss in orientation selectivity of individual cells that are biased toward orientations other than the experienced one⁹.

It is much harder to rule out by electrophysiology that a subset of neurons originally preferring the non-experienced orientation became less responsive or even unresponsive to visual stimulation. In this case, the apparent decrease in number of cells preferring non-experienced orientations previously reported^{9,13–17} would be the result of sampling bias toward the more responsive cells rather than a respecification of orientation preference in single cells.

To distinguish between an 'active' role of visual experience in recruiting neurons for the experienced orientation by shifting their orientation tuning curves and a 'passive' role in which neurons not tuned to the experienced orientation fail to develop normally, we considered how the two alternatives would affect orientation maps (Fig. 4a–c). If neurons shifted their orientation preference toward the experienced orientation, domains of orientations not present in the environment would shrink, but maximum responses would not decrease (Fig. 4c). On the other hand, if responses of neurons preferring non-experienced orientations degraded, then signal strength would be reduced in the centers of the corresponding domains (Fig. 4b); in other words, domains preferring the experienced orientation would exhibit high responsiveness, whereas regions preferring other orientations would be less responsive. For both scenarios, the analysis applied so far would yield identical results, as images were analyzed for orientation preference only, not for response strength. To distinguish

Fig. 3. Results of single-neuron recordings in an animal (C16) that had been exposed to stripes of 90°. **(a)** Polar map of orientation preference in the visual cortex of the right hemisphere, with overrepresentation of the experienced orientation (see Fig. 2a). Sites of 12 electrode tracks are marked by asterisks and numbers. **(b)** Orientation preference and half width at half height (HWHH) of tuning of 81 neurons recorded in 18 tracks in both hemispheres. Numbers next to data points denote some of the sites in **(a)** where representative neurons were recorded. There is good correspondence between tuning preferences of neurons and the imaged orientation map, although scatter of both preferred orientations and width of tuning can be observed at individual recording sites. **(c)** HWHH (mean ± s.e.) of orientation tuning of all neurons grouped in four classes centered on the orientations that were used in the imaging experiment. Cells preferring non-experienced orientations do not show enlarged orientation tuning width. Numbers of cells in each class are given within the bars.

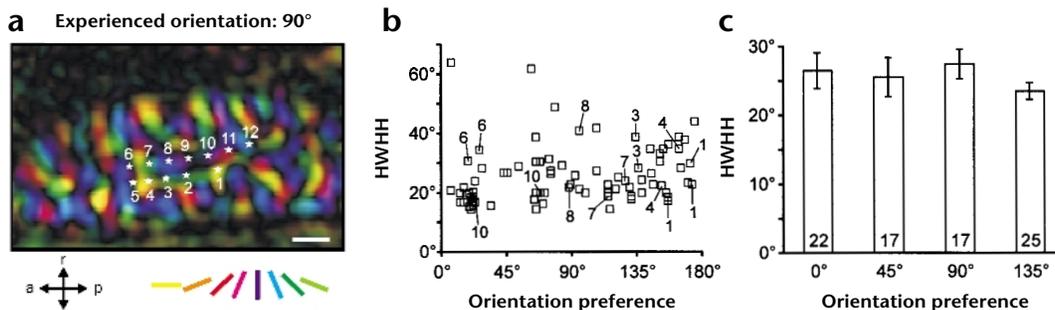
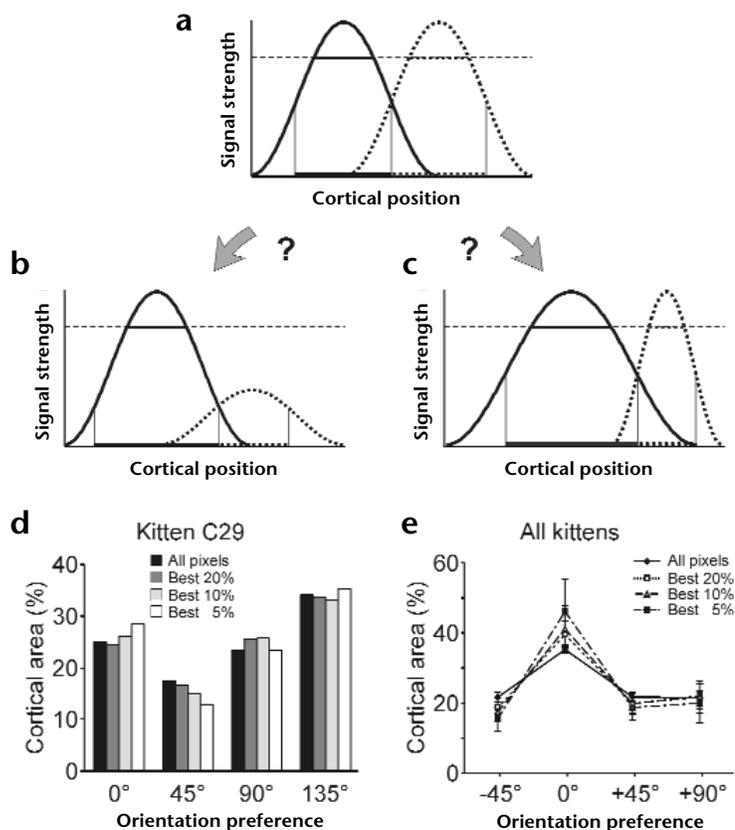


Fig. 4. Evidence for an instructive role of visual experience.

(a–c) Models illustrate how, starting from an equal representation of all orientations **(a)**, exposure to contours of a single orientation would affect the intensity profiles of intrinsic signals across the cortical surface for the experienced orientation (solid lines) and the orthogonal orientation (dotted lines). A selective reduction of responses of those neurons whose initial preferred orientation is not present in the environment would lead to a reduction of response magnitude in the respective orientation domains **(b)**. These domains would then not fulfill a high criterion of responsiveness (signal strength) indicated by the thin dashed line. In contrast, a true shift in orientation preference toward the experienced orientation would lead to a narrowing of domains responding to the orthogonal one without a loss of maximum response strength **(c)**. In this case, the relative size of these domains would not change with the criterion level of responsiveness. Note that the position and distance of the centers of domains responding to exposed and orthogonal orientations do not change in either of these scenarios. **(d, e)** Experimental results. **(d)** Relative cortical areas preferring each of the 4 orientations tested for animal C29, which had been exposed to stripes of 135° orientation (see Fig. 1). The distributions obtained were virtually identical, whether all pixels or just the 5%, 10% or 20% most responsive ones were considered, demonstrating that scenario **(c)** applies. **(e)** Relative representation of orientations averaged across all six stripe-reared kittens. The overrepresentation of the experienced orientation is not significantly higher for the 5%, 10% or 20% most responsive pixels than for all pixels ($p > 0.3$). Data are mean \pm s.e.



between these alternatives, we re-analyzed the imaging data for different response criterion levels. (See ref. 23 for a similar argument.) We considered, for example, only the 20% of pixels that were most responsive in any of the four iso-orientation maps. These pixels will be found mainly in and near the centers of iso-orientation columns; in an animal with equal representation of all orientations, they would constitute 5% of the cortical area in each of the four maps, corresponding to an 'orientation column' that covers a 9° range of orientations, centered on 0°, 45°, 90° and 135°, respectively. (This range approximates the smallest difference in orientation preference between two 'orientation columns' that can be measured electrophysiologically.) An active role of visual experience would yield the same relative distribution of these 20% of pixels across the four orientations as the one obtained above for the entire population (compare relative widths of solid and dotted horizontal lines at the different criterion levels in Fig. 4c), whereas with a passive role, the distribution would change dramatically because responses to non-experienced orientations would be too weak to reach the higher criterion (Fig. 4b). Applying this analysis, we found that the distributions of orientation preferences were not significantly different ($p > 0.3$, t -test) for the two criteria of response strength (Fig. 4d and e). The same was true when only the 5% or 10% most responsive pixels were analyzed ($p > 0.3$, Fig. 4d and e). However, with the highest response criterion level, a much larger variability of the data across the six animals was observed, as only a very small number of pixels (1–2% of the total) was analyzed in each iso-orientation map. Notably, in all animals even at that criterion level, regions of cortex were found that responded best to non-experienced orientations. This result then strongly suggests that cells tuned to orientations not present in the environment have large-

ly maintained their normal responsiveness. Therefore, a loss in response strength cannot (or can only to a very small extent) account for the observed gain in cortical territory for the experienced orientation. In further support of this conclusion, the sum of responses to all four orientations tested was uniform across the visual cortex (data not shown), indicating that there were no regions of cortex that responded less to visual stimulation.

DISCUSSION

In the past, single-neuron recording studies on stripe-reared cats varied widely in their results, ranging from very pronounced biases⁹ to no representational imbalance whatsoever¹¹, even among different animals within a single study²⁴. Variations in experimental procedure and sampling bias, as well as genuine differences among individual animals, probably account for this diversity. Optical imaging provides an objective and quantitative measure of the overrepresentation of the experienced orientation in the visual cortex of stripe-reared kittens. We, too, observed differences in the degree of overrepresentation of the exposed orientation among animals (Fig. 2a), but such a bias never failed to develop, even though it is likely that, if anything, we underestimated the degree of overrepresentation. We aimed at imaging lower supragranular layers, but cannot rule out that part of the signal was obtained from layer 4 where the modifiability of orientation columns by selective experience is rather small²⁵. Our study therefore proves the potency of rearing in a striped environment to modify cortical orientation preference⁹.

In single-neuron recording studies, rearing with goggles that contain lines of a single orientation consistently produces a preponderance of neurons responsive to that orientation^{13,14,24}, and also results in an unusually large proportion of neurons that

are either unresponsive or poorly tuned for orientation¹⁴. Based on that finding, it was suggested that early visual experience primarily serves to maintain the responsiveness and stimulus selectivity of those neurons for which stimuli present in the environment match their intrinsic stimulus preference. Our results do not support this conclusion, as rearing in a striped environment decreased neither orientation selectivity nor responsiveness of neurons (Figs. 3 and 4). Some of the effects of goggle-rearing may result from severe interference with visuomotor integration because of the retinal image stabilization during head and body movements²⁶.

Our data imply that the relative number of neurons preferring the experienced orientation increases upon rearing in a single-orientation environment. An alternative—albeit, in our view, much less likely—explanation for our results would be a selective growth of somata and/or dendritic arbors of neurons responding to the experienced orientation. Although stripe-rearing may cause asymmetry in the shape of dendritic trees, there is no change in the average length and number of dendrites^{27,28}. An increase in soma size has not been reported either, and it would seem quite unlikely, as not even the much more severe visual deprivation caused by monocular lid suture causes differences in the soma size of cortical neurons. This leads us to conclude that visual experience must have modified the orientation preference of individual neurons.

Orientation selective neurons are present at the time of natural eye opening^{29,30}, and quite normal maps of orientation preference form in the visual cortex of young kittens that have been visually deprived by binocular lid suture^{31,32} (but see also K. Krug & I. D. Thompson, *Eur. J. Neurosci. Suppl.* 10, 325, 1998). In light of this evidence, it seems unlikely that the role of contour experience is to make initially silent or non-selective neurons acquire orientation selectivity for the experienced orientation. This is further underlined by our finding that over half of the visual cortex responded best to orientations never seen by the animal, demonstrating again that visual experience is certainly not the only determinant of cortical orientation selectivity^{29,30,32,33}. However, our results are also consistent with an 'instructive' role of visual experience whereby the orientation preference of neurons shifts from the original toward the experienced one. This instructive effect might have even been greater if dark rearing before selective visual exposure had lasted beyond five or six weeks of age, when cells initially selective for orientation without visual experience lose their intrinsic selectivity and/or responsiveness^{29,32}.

The modification of neuronal orientation preference could be explained by a Hebbian mechanism. In very young kittens, less than half of the cells in area 17 are actually orientation biased or selective^{30,34}. Moreover, orientation tuning is broad among the selective cells, with a half width at half height of $\sim 30^\circ$ in two-week-old normal kittens, and slightly more in dark-reared animals²³. Therefore, at the time at which selective exposure to a single orientation started in our study, a large proportion of the visually driven neurons would have already responded to the experienced orientation. Afferent connections conveying activity elicited by that orientation could therefore be strengthened, whereas synaptic efficacy of unstimulated connections would decrease²². This would then lead to an instructive change in orientation preference of only those neurons whose initial response range included the experienced orientation. The shift of orientation preferences we observed therefore implies a competition of different orientations for cortical territory similar to the competition of thalamocortical afferents from the two eyes for terminal space in the primary visual cortex.

Taken together, our results show that there is a delicate balance between a considerable intrinsic component in determining the layout of orientation preference maps and environmental factors that can modify neuronal response properties such as orientation preference.

METHODS

Animals. All experimental procedures were approved by local government authorities. From the day of birth, kittens and their mothers were housed in a dark room. Starting at P16/17 (P22 in the case of kittens that wore goggles), the kittens were placed in cylinders (2 m tall, 65 cm in diameter), which were painted with evenly spaced black and white stripes (3 or 4 cm wide) of a single orientation (0° , 45° , 90° or 135°). Animals spent 3–5 hours a day (increasing with age) in this visual environment and the rest of the time in the dark. At P37–54, when the imaging experiment was done, they had had a total exposure of 75 to 120 hours.

Imaging and data analysis. Anesthesia was induced with an i.m. injection of ketamine (20–40 mg per kg) and xylazine (2–4 mg per kg). Animals were intubated and artificially ventilated (50–60% N₂O, 40–50% O₂, 0.9–1.2% halothane). ECG, end-tidal CO₂ and rectal temperature were monitored continuously. Optical imaging of primary visual cortex was done as described¹⁹. The camera was focused approximately 500 μ m below the cortical surface. Animals were presented with moving square-wave gratings (0.2 to 0.4 cycles per degree) of 4 different orientations, interleaved with blank-screen presentations. Single-condition responses (averages of 128–192 trials) were divided by responses to the blank screen, or by the sum of responses to all 4 orientations ('cocktail blank'; see ref. 19). Twelve-bit digitized camera data were range-fitted such that for the iso-orientation map with the largest signal amplitude, the 1.5% most responsive pixels (least responsive pixels) were set to black (white). Signal amplitude was displayed on an 8-bit gray scale. The same absolute signal amplitude values were also used to clip and display the other three iso-orientation maps.

Measures of the area of cortical surface responding preferentially to a particular orientation were based on the gray-scale values of pixels in the images obtained after high-pass filtering. Importantly, quantitative analysis was only done on images obtained with the blank-correction procedure, as it does not make assumptions about the distribution of responsiveness across the cortical surface.

Pixels that were darker in any of the four iso-orientation maps than in the blank response map (dark regions representing high activity) were considered to fulfill the threshold criterion of responsiveness. Each pixel was then allocated to the orientation where it was darkest. Histograms of pixels per orientation were obtained and normalized to the total number of pixels in the analyzed region.

Electrophysiology. In one animal, we made 18 electrode penetrations and recorded quantitative orientation and direction tuning curves of 81 single neurons discriminated by their spike shapes (Brainware, Oxford, UK). Responses to drifting gratings of 16 different directions were averaged over 5 trials. Smooth tuning curves were fitted to the data points based on Fourier analysis³⁵, and preferred orientation and half width of tuning at half height were determined for these curves.

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