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Rapid task-related plasticity of spectrotemporal receptive fields in primary auditory cortex

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We investigated the hypothesis that task performance can rapidly and adaptively reshape cortical receptive field properties in accord with specific task demands and salient sensory cues. We recorded neuronal responses in the primary auditory cortex of behaving ferrets that were trained to detect a target tone of any frequency. Cortical plasticity was quantified by measuring focal changes in each cell's spectrotemporal response field (STRF) in a series of passive and active behavioral conditions. STRF measurements were made simultaneously with task performance, providing multiple snapshots of the dynamic STRF during ongoing behavior. Attending to a specific target frequency during the detection task consistently induced localized facilitative changes in STRF shape, which were swift in onset. Such modulatory changes may enhance overall cortical responsiveness to the target tone and increase the likelihood of 'capturing' the attended target during the detection task. Some receptive field changes persisted for hours after the task was over and hence may contribute to long-term sensory memory.

Long-term auditory experience or learning can cause global cortical plasticity, such as the reshaping of tonotopic maps, as well as significant local plasticity at the cellular level, by transforming receptive field properties of neurons in the primary auditory cortex (A1)[1–8] and elsewhere in the auditory path. These long-term changes are shaped by the salient spectral and temporal characteristics of the inducing acoustic stimuli, and they can occur either by behavioral training or by specific forms of electrical brain stimulation[9–16], although the perceptual consequences of such induced plasticity are still obscure[17]. Convergent studies of plasticity in the visual[18,19] and motor systems[20–24] indicate that representational maps are dynamically modulated, and that cortical cells in these systems can undergo rapid, task-dependent and context-specific changes of their receptive field properties during attentive behavior. This form of adaptive plasticity has three key elements: (i) directed attention to salient task-related cues, which leads to (ii) selective functional reconfiguration of the underlying cortical circuitry during task performance and causes (iii) goal-related changes in receptive field properties of individual neurons and the cortical ensemble that may enhance task performance.

Here we describe a form of adaptive plasticity in A1 that can be rapidly induced by a change in the behavioral context of the animal. Specifically, we found that performing a tone-detection task, which requires attending to a target tone placed within the STRF, induced consistent and substantial facilitative change in the normalized shape of the STRF in most A1 neurons (>70%). This change usually takes the form of a frequency-domain-specific increase in excitation or reduction of inhibition. We propose that similar dynamic changes in the STRFs of many cortical neurons enhance the likelihood of 'capturing' the target, and thus improve task performance, by increasing the overall pattern of A1 activation to the target tone during the detection task.

RESULTS

Ferrets were trained to lick water from a spout during the presentation of reference sounds, and by aversive conditioning, they learned to refrain from licking after the presentation of target sounds[25] (experimental design shown in **Fig. 1**). Reference sounds were chosen from a set of 30 different broadband noise-like stimuli with spectrotemporally modulated envelopes called 'temporally orthogonal ripple combinations,' or TORCs[26] (see **Supplementary Audio 1–4** online). These stimuli were specifically designed to characterize the STRF of the cell under study in physiological experiments using the reverse-correlation method[26–29] (Methods). Target sounds were always tones. In each trial, a random number of different reference sounds (1–6) was presented, and these sounds were followed by a tonal target. During initial training, different target tones were randomly presented in sequential trials, and the ferrets learned to respond correctly to any tonal target during the detection task. Although we used multiple tonal targets during training trials, the tonal target frequency remained fixed during a given behavioral block within a physiological recording session, so that soon after the onset of a given block, the ferret quickly learned the relevant tonal target. In subsequent behavioral blocks, however, the target frequency could be changed so that the same neuronal STRF could be successively probed with different tonal targets.

In a typical experiment, the STRF of an isolated unit was measured using TORC stimuli while the animal was in a behaviorally passive resting state—there was no waterflow from the spout and no target was presented. This was followed by a series of STRF measurements while

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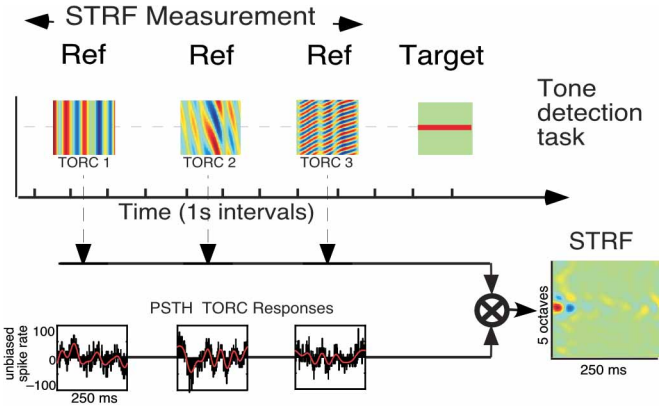

Figure 1 Experimental design. Two types of stimuli were used: broadband noise-like stimuli (TORCs) as reference signals, and pure tones as targets. On a given trial during a behavioral session, a random number of TORCs (1–6) was followed by a target tone (except on control 'catch' trials in which 7 reference TORCs were presented with no target tone). The target tone frequency was chosen as a suitable probe after inspection of the initial passive STRF of the cell, and was usually positioned in a specific excitatory or inhibitory region of interest in the receptive field. Top, spectrograms of three such TORCs and of the following target. Trials were repeated for 6–10 presentations of each of the 30 TORCs. Responses to each TORC were collected in post-stimulus time (PST) histograms that were cross-correlated with the TORC spectrograms to estimate the STRF (see Methods). Although the animal behaved in anticipation of the specific target, all of the spike measurements to derive the STRF were made during the presentation of the reference TORCs.

the animal performed the detection task, alternating with further STRF measurements in the passive state. By successively selecting different target frequencies, we could induce changes in multiple locations of the STRF and view them within a few minutes of their occurrence.

We recorded a total of 175 single units in A1, from two trained (141 units) and one naive (34 units) ferret. In the passive condition in all animals, the STRFs of most neurons were remarkably stable, showing few significant or consistent changes during multiple measurements over the course of one or more hours. Moreover, in control studies in the naive animal, the majority of STRFs (18/34) showed no significant change in response to presentation of the 'active task' stimuli (which included TORCs as well as target stimuli) in the absence of training and hence of behavioral performance. We did not observe consistent changes at a population level either. In the two trained animals, however, 72% of all cells tested (39/54) showed significant changes in STRF shape during the detection task, as compared with the passive pre-behavioral STRF. In two-thirds (67%) of these cases (26/39), the changes persisted in the post-behavior passive state. However, new STRF changes could still be induced in the same cell by subsequent behavioral tasks with novel targets. Our data did not indicate any laminar- or depth-dependence of the observed plasticity.

Facilitative plasticity in A1

The most common STRF shape change during task performance (that is, in comparison with the original passive STRF) was a facilitation at the target frequency caused by an enhancement of an excitatory field of the STRF or by a weakening of its inhibitory sidebands (**Fig. 2**). When the target was placed near an excitatory region of the STRF (arrow in **Fig. 2a**, middle panel), it created a new excitatory extension of the original region. To quantify this change, we calculated the difference between the normalized behavioral and passive STRFs ($STRF_{diff}$; **Fig. 2a**, right panel). We then extracted two measures from the $STRF_{diff}$: a local maximum difference within ±0.25 octaves around the frequency of the target (ΔA_{local}, asterisk) and a global maximum difference (ΔA_{global}; **Fig. 2**, circles) across all frequencies in the STRF. In subsequent figures, the location of these two maxima (ΔA_{local} and ΔA_{global}) are indicated on the behavioral STRF.

Placing the target in the excitatory region of an STRF resulted in an increase in the magnitude of the excitation (**Fig. 2b**). The opposite usually occurred when the target frequency coincided with STRF inhibitory sidebands (that is, it caused a reduction in the strength of the inhibition; **Fig. 2c**,**d**). In about half of all cases, STRF changes were local, restricted to the region of the target frequency, as evidenced by the coincidence of the local and global maxima in **Fig. 2a–c**. By contrast, the change depicted in **Fig. 2d** was global in that all inhibitory regions of the broad STRF were significantly reduced during the task, the nearby excitatory region was relatively enhanced, and the maximum change occurred away from the target tone frequency. We observed such global changes (specifically a knock-out of all inhibitory regions in the STRF, when the target was placed in one inhibitory area) in several other cases. Nevertheless, global STRF change was usually accompanied by a local facilitation—shown by an asterisk near the target frequency—although the local STRF change was less than the global maximum. In the units shown in **Figure 2b–d**, passive STRFs were measured again after the behavior, and they either reverted rapidly to their original shape (**Fig. 2b**,**d**) or at least partially recovered (**Fig. 2c**).

The distribution of ΔA_{local} in **Fig. 2e** summarizes the STRF changes observed in 54 single units in the two trained animals from which reliable passive and behavior STRFs were obtained. About 28% (15/54) did not show a significant STRF change. However, when a significant change in STRF shape did occur, a clear majority (79% or 31/39) showed a facilitative or positive STRF change, consisting of either enhancement of the excitatory fields or a reduction of the inhibitory sidebands during the tone detection task. This facilitation averaged +46% (median, +45%) of the maximum amplitude in the STRF. Furthermore, in about half of these units (16/31), the maximum change in the STRF occurred within 0.25 octave from the target frequency (*i.e.*, locations where ΔA_{local} and ΔA_{global} coincided).

Figure 2f provides a summary view of STRF changes over a broad range of frequencies around the target. This curve was calculated by taking spectral (vertical) cross sections through the local maxima (ΔA_{local}) of the $STRF_{diff}$, aligning them so that they were centered at their target frequencies and then summing over all cross sections (54 cells). The resulting curve (**Fig. 2f**) confirms the presence of significant facilitative STRF change near the target frequency. The curve also reveals suppressive side-band influences of the target on the STRF at distances greater than one octave from the target frequency, especially pronounced on the lower-frequency side of the target. The average spectrotemporal change derived by averaging the $STRF_{diff}$ aligned at the target frequency for all 54 neurons (**Fig. 2g**), gives another summary view of STRF change during the detection task. The figure shows the narrow range of spectral facilitation and the presence of suppressive surrounds in both the spectral and the temporal dimension.

STRF plasticity for multiple, sequential targets

In some experiments, STRFs were measured in a series of tone-detection tasks with different target frequencies, which were used to probe different excitatory and inhibitory regions of the same STRF. The rapid onset of STRF change during behavior, and the swift recov-

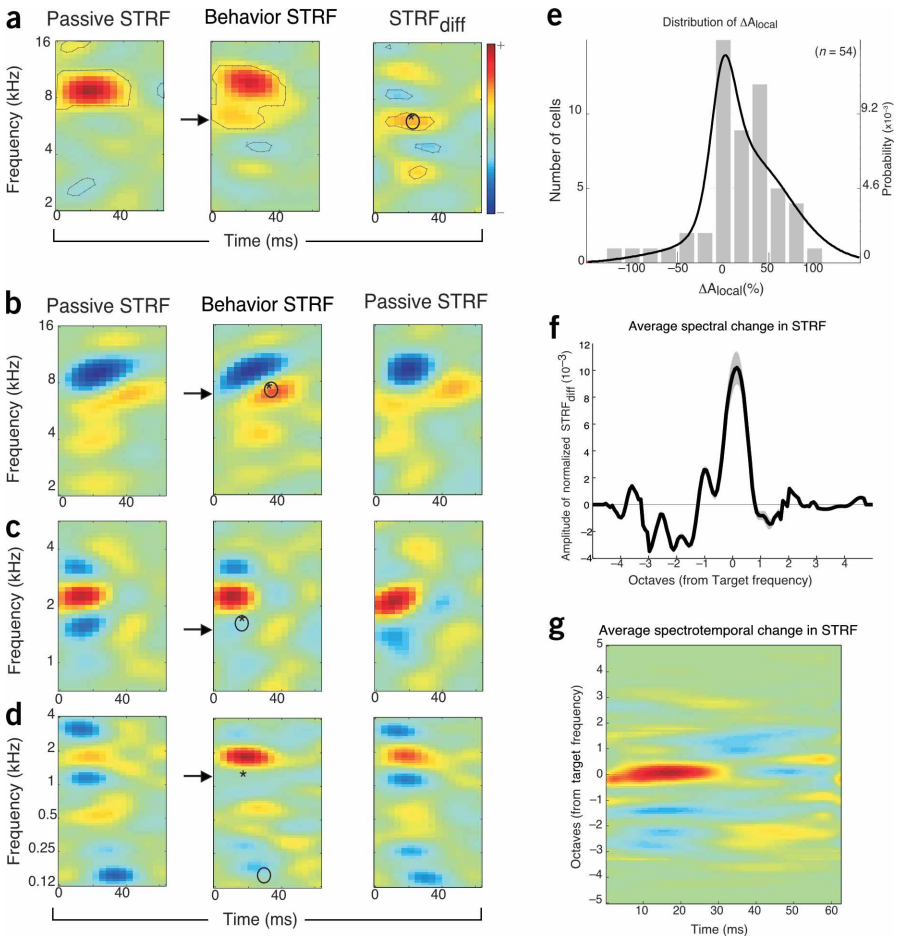

Figure 2 Facilitative STRF plasticity in A1. STRFs from four single units in A1 show typical changes observed during performance of the detection task. (**a**) Comparison of a pre-behavior passive STRF (left) and a behavioral STRF (middle). Color scale represents increased (red) to suppressed (blue) firing about the mean firing rate (green). The STRF in each panel was normalized, and all STRFs were then depicted on the same color scale. The contours in **a** demarcate the excitatory (red) and inhibitory (blue) regions with statistically significant fluctuations (± 3 s.d.) from the mean (see Methods). We do not draw these contours in subsequent STRFs to avoid cluttering the figures, but all excitatory and inhibitory features of the STRF or $STRF_{diff}$ discussed subsequently are statistically significant by this criterion. Black arrow, frequency of the target tone during the detection task. Right, the difference between the normalized passive and behavior STRF ($STRF_{diff}$). An asterisk marks the location of maximal local change (ΔA_{local}, 45%), and a circle marks the global change (ΔA_{global}, 45%) as defined in the text. The local and global maximal changes were both at target frequency in this case, as in about half of all cells. (**b**) Localized enhancement of an excitatory region in the STRF during behavior (left and middle). The post-behavior passive STRF (right) reverted immediately to its original shape (ΔA_{local}, 37%; ΔA_{global}, 42%). The two maxima were nearly coincident at the target frequency. (**c**) Local decrease or elimination of inhibitory sidebands in the behavior STRF. The inhibition recovered quickly afterwards, but the overall STRF shape was different (ΔA_{local}, 40%; ΔA_{global}, 40%; coincident maxima at target frequency). (**d**) A global weakening of inhibitory fields during behavior. Immediately following behavior, the STRF recovered its pre-behavior shape (ΔA_{local}, 64%; ΔA_{global}, 86%). In this example, the local maximum difference occurred at the target tone frequency, whereas the global maximum was located over a low-frequency inhibitory field (which was also knocked out during behavior). (**e**) Summary histogram and smoothed distribution of local STRF changes from all STRFs in the study (see Methods). The histogram (left ordinate) and distribution (right ordinate) are significantly skewed toward positive changes (overall mean, +20.2%). (**f**) Average spectral change in the STRF at all frequencies relative to the target frequency. This curve shows the average plastic change in STRF amplitude as a function of log-frequency distance from the target frequency (centered at 0 and marked by the red dot). The shaded region around the curve represents the variance around the mean. There was facilitation for about one octave around the target (half-width of ±0.5 octave) and asymmetric suppressive sidebands outside of this range. (**g**) Average spectrotemporal changes in the STRF derived from all units. This image was constructed by computing the $STRF_{diff}$ for each unit, centering it around its target frequency, and then averaging over all units. The facilitative and suppressive changes near the target frequency, as well as the relatively rapid onset of these STRF changes, can be seen here.

ery afterwards, is shown for two units (**Fig. 3**). In the first unit (**Fig. 3a**), the target was changed midway through the task from 2 kHz to 4 kHz, and the STRFs were constructed from three repetitions of the reference stimuli for each choice of target. As predicted, the first (2 kHz) target stretched the excitatory receptive field towards it (second panel), creating within 10 min a new excitatory area at the edge of the first passive STRF. The second (4 kHz) target equally rapidly reduced the local inhibition (third panel). Finally, the STRF quickly returned to its initial shape following behavior (last panel). The same kind of STRF changes and recovery are seen for the unit in **Fig. 3b**. Note that in both behavior STRFs measured in this unit, the maximum facilitative changes observed were global, that is, they occurred outside of the range of ±0.25 octaves from the target frequency. In some cases, as shown in **Fig. 3a**, we speculate that the non-local change may be partly due to an 'edge effect,' when the position of the target probe lies just outside the receptive field of the unit, leading to enhancement at the corresponding edge of the STRF.

Persistence and onset of STRF changes

The persistence of STRF changes following task completion was quantified for all units by taking the difference between passive pre- and post-behavioral STRFs. A third of all facilitated STRFs (13/39) reverted back to their original shape immediately after the behavior (**Fig. 2b,d** and **Fig. 3**). In the remainder, the STRF change persisted after the behavior, examples of which are shown in **Fig. 2c** and **Fig. 4**.

In 44 units in the trained ferrets, stable long-term recordings were maintained for many hours. This gave us sufficient time to carry out STRF measurements during performance of the detection task in multiple sessions using different target tones. We were also able to observe the time course of STRF recovery following behavior. For some cells (recordings from two units shown in **Figure 4a,b**), the STRF showed persistent changes after multiple sessions of the detection task in which the target tone was varied. In the first unit (**Fig. 4a**), the two post-behavior passive STRFs showed the predicted set of effects (reduction of inhibition and enhancement of excitation fol-

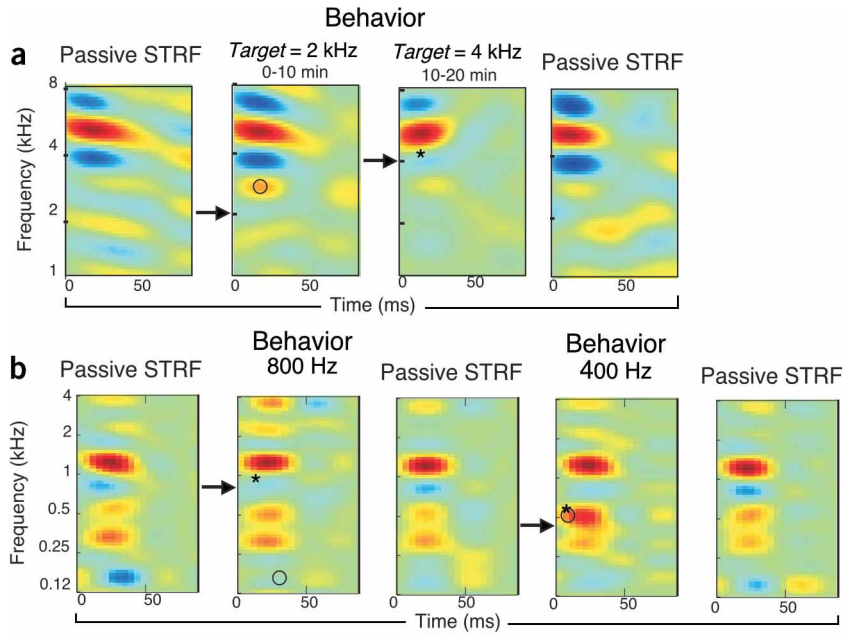

Figure 3 Receptive field plasticity in sequential contexts: STRF changes in moving from passive state to active detection tasks with changing targets. (**a**) A passive pre-behavior STRF (left panel), followed by two behavior STRFs (two middle panels) and ending with a passive post-behavior STRF (right panel). The target at 2 kHz enhanced an excitatory area at the lower edge of the receptive field, which disappeared together with the neighboring inhibitory sideband when the target shifted to 4 kHz (third panel). After behavior (right panel), the STRF reverted back to its original passive shape. (**b**) Three passive STRFs interleaved with two detection tasks. The target at 800 Hz reduced all four inhibitory sidebands of this STRF at a global level, as well as locally reducing inhibition at the target frequency (second panel, $\Delta A_{global} = 67\%$). The target at 400 Hz enhanced an adjacent excitatory field (fourth panel, $\Delta A_{global} = 36\%$). The STRF rapidly reverted to its original pre-behavior passive shape (first panel) in the post-behavior passive states (third and fifth panels).

lowing successive behavioral sessions with two tonal targets) that persisted following the behavior. In the second unit (**Fig. 4b**), a sequence of three separate detection tasks were carried out with three distinct tonal targets, as indicated by the gray arrows. Several post-behavior STRFs were subsequently measured at hourly intervals. Remarkably, these STRFs showed the build-up of a sensory 'memory' of the targets of prior behavioral sessions in the form of enhanced excitatory regions near 500 and 1,250 Hz in all post-behavior passive STRFs (see **Supplementary Note** online).

We compared the expression of STRF plasticity in multiunit clusters consisting of 5–20 neurons with that seen in single-unit recordings. Multiunit STRFs generally showed facilitative changes consistent with those seen in most of their associated single-unit records. They had the advantage, however, of being less 'noisy' (that is, higher signal-to-noise ratio) and often required no more than one presentation of the reference set of 30 TORC stimuli (which took about 2.5 min) to yield a clean STRF measurement. This allowed us to explore the onset of multi-unit STRF changes on a finer time scale after the start of the behavioral test. For example, the single-unit STRF of **Fig. 2d** closely resembled the STRF from the multiunit cluster shown in **Fig. 4c**, shown as it was progressively computed after one, three and five repetitions of the TORC set. After only one presentation of all of the TORCs (which included 6 target stimulus presentations), the multiunit STRF had already undergone a facilitative change relative to the passive STRF. In most cases thus examined, behavior-induced changes were already evident in the first clean multiunit STRF (typically after one or two TORC repetitions).

Behavior and STRF changes

To investigate the relationship between animal behavior and the expression of STRF change, we repeated the STRF measurements on a naive animal that was completely untrained on the detection task. To generate the 'detection' STRF, we simply exposed the naive ferret to the same stimulus sequence of TORC references and targets as was used for the trained ferrets in the detection task, but without training, water reward or aversive shock (that is, devoid of any learned behavioral meaning).

The distribution of the STRF changes (ΔA_{local}) for 34 cells in A1 in the naive ferret is shown in **Fig. 5a** (left), where 54% of cells remained unchanged. The distribution is approximately symmetric, centered at zero. The scatter around the midline may reflect intrinsic STRF instability (random jitter) or may be due to a combination of various experimental sources of error such as animal movement, other animal state changes between the two successive STRF measurements, or misclassification of sorted spikes across sessions because of changes in spike waveform. A similar symmetric distribution of ΔA_{local} was also found in data pooled from the two trained animals (12 units) when they passively listened to the 'detection' sounds, but without performing the detection task (**Fig. 5a**, right panel). These negative results, obtained in both naive and non-behaving trained animals, argue against the possibility that the facilitation we observed in the trained, behaving animals was due to an auditory 'oddball effect'[30] where the tone plays the role of a low probability narrowband 'oddball' stimulus (with ~25% likelihood of occurence in relation to the background of broadband TORCs). These negative results obtained in the control conditions emphasize the importance of behavior in mediating the plastic effects.

Fig. 5b directly compares the ΔA_{local} distributions in the behaving animals (**Fig. 2e**) against the non-behavioral baseline of the 'naive distribution' (**Fig. 5a**, left). The net effect of behavior can be seen in the difference between the two plots (**Fig. 5b**, right). The figure summarizes our finding that engaging in a detection task results in facilitated STRFs, with cells averaging 46% facilitative change between the passive and behaving states.

We examined the relationship between behavior and the pattern of STRF changes by comparing the distribution of ΔA_{local} derived from three distinct groups of cells, which were recorded during three different behavioral conditions in the two trained animals (**Fig. 5c**). Cells in the first group were recorded from while the animals listened passively to the stimuli (same 12 units as in **Fig. 5a**, right). The set of 54 units depicted in **Fig. 2e** were divided into a second group (11 units) recorded in sessions with poor performance (discrimination rate <0.3 and hit rate <80%; see Methods) and a third group (43 units) recorded in sessions with better per-

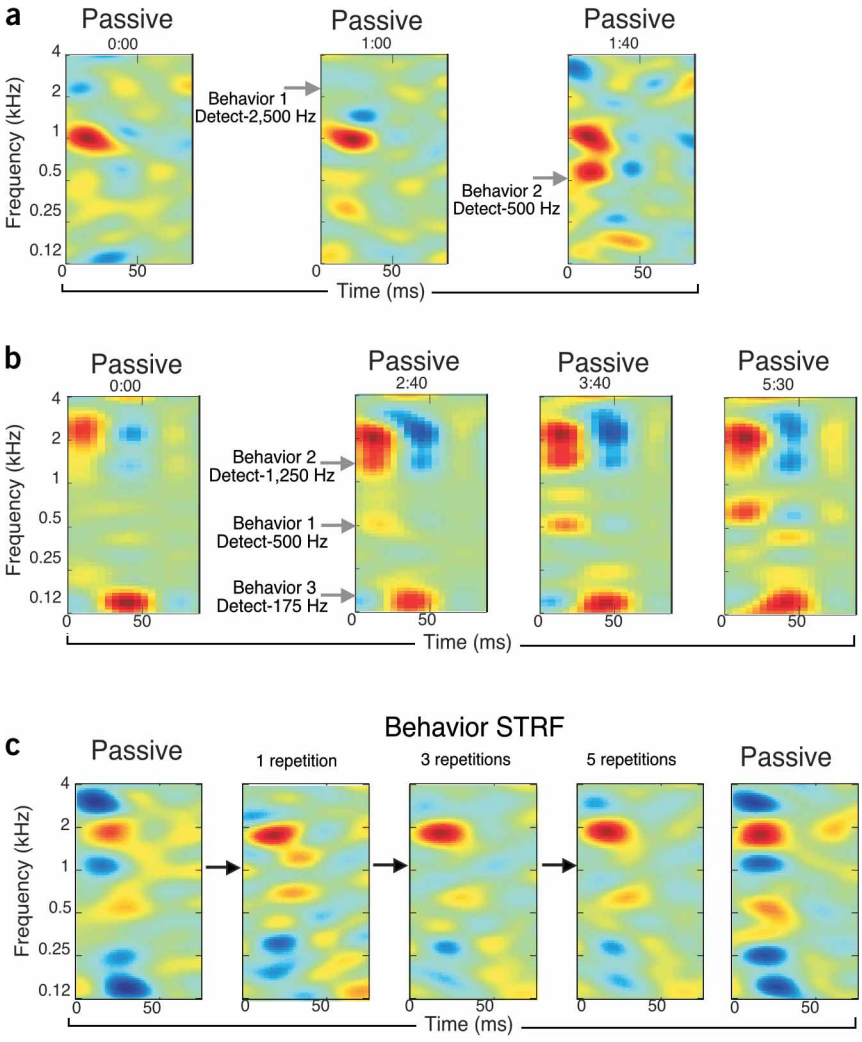

Figure 4 Onset and persistence of STRF plasticity. STRF changes induced by behavior could persist for many hours following task performance. (**a**) Passive STRFs recorded following intervening behavioral tasks (gray arrows indicate target tones used in the preceding detection task). The effects of the task can be seen to persist. After a detection task with a 2,500-Hz target, the inhibitory field at the target frequency was reduced (middle), and after a second detection task with a target at 500 Hz, the excitatory field at 500 Hz was enhanced (right). (**b**) Passive pre-behavioral STRF measured before (left), and post-behavioral STRFs (remaining panels) derived after a series of three detection tasks with different targets as indicated by the gray arrows. The STRF changes induced by the behavioral tasks persist, to varying extents, for several hours afterward (elapsed post-behavior time indicated above the STRF panels). (**c**) Onset of plasticity in a multiunit STRF. A pre-behavior passive multiunit STRF, followed by three multiunit STRFs that provide 'snapshots' of the evolving behavior STRF, analyzed after every two repetitions of the TORC stimuli (middle panels). The target in this detection task was 1 kHz, and clearly the behavior had the effect of changing the STRF by reducing the inhibitory field at the target frequency. Note that the onset of the STRF change occurred as quickly as it could be measured (*i.e.*, within 2.5 min of task onset; second panel). The post-behavior passive multiunit STRF is shown in the last panel.

formance (hit rate >80%). The superimposed ΔA_{local} distributions of the three groups (**Fig. 5c**) show that they become progressively more asymmetric (that is, more facilitatory) as behavior commences or improves, consistent with the idea that there is a causal relationship between the attentive behavior (as measured by performance) and the magnitude of facilitative changes of the STRF.

DISCUSSION

We have demonstrated the presence of a rapid form of plasticity in A1 spectrotemporal receptive fields that occurs when a trained animal engages in a behavioral detection task. The STRF changes, found in 72% of A1 single neurons during behavior, were generally facilitative and are consistent with the animal's goal of enhancing performance during the tone detection task. The STRF changes occurred quickly, in accord with the behavioral paradigm, in which the animal gained knowledge at task onset (following first target presentation) about the frequency of future tonal targets. Most of the facilitative changes observed were target-frequency specific, yet all were measured by analyzing neural responses to the reference TORCs and not to the target stimulus. As such, they represented a change in neuronal state while the animal was attentively poised in anticipation of target recurrence. These results may reflect a cortical role in simple auditory tasks, such as tone detection[31].

Attending to a salient stimulus selectively increases the ability to process it. During the detection task, the target tone was the primary focus of attention, and at the population level the observed STRF changes effectively increased sensitivity to this tone. At the single-unit level, we found that placing the attentional target tone in an excitatory region of the STRF led to an enhancement of the excitation (and an effective increase in contrast), whereas placing the target in an inhibitory area in the STRF led to a decrease in the inhibition (and a decrease in contrast). Therefore, the increased sensitivity to the target is not necessarily achieved by an increase in STRF contrast (*i.e.*, a constant multiplicative gain that would enhance both excitation and inhibition), but rather by an additive facilitative gain that reduces inhibition and increases excitation.

We conjecture that it may be the goal of the task that dictates the adaptive logic and direction of the STRF plasticity observed in our experiments. The same target stimulus could have differential effects on the STRF depending upon its behavioral meaning in the context of a specific task. In some tasks, attentional modulation may take the form of a gain change to increase sensitivity, whereas in others, the attentional target may differentially modulate specific features and regions of the receptive field. To fully explain receptive field modulation during behavior, it is also important to incorporate task-specific requirements and goals. A recent study[32] in A1 of owl monkeys trained on an instrumental learning paradigm supports this view by demonstrating enhancement of neural responses to the acoustic stimuli that were cues for rewarded motor responses. During training on our task, the ferrets learned how to selectively attend to narrowband target stimuli and link the appearance of a target to a set of motor

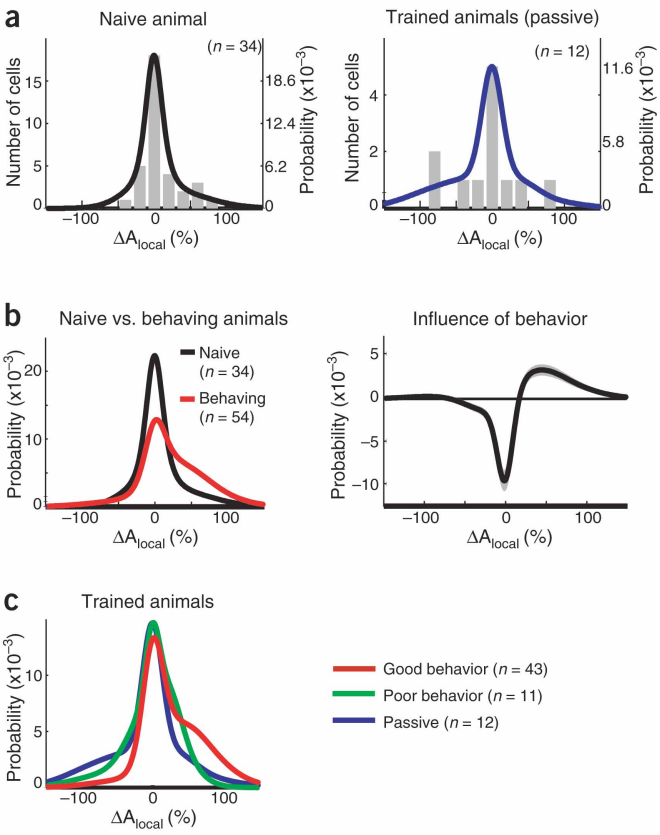

Figure 5 Relation of behavior to STRF plasticity. (**a**) Histogram and distributions from STRF measurements in a naive animal (left), and from trained but non-behaving animals (right). (**b**) Comparison of the baseline symmetric distribution of STRF changes in the naive animal (black; replotted from **Fig. 5a**) with the skewed distribution of STRF changes in the behaving animals (red; replotted from **Fig. 2e**). The difference between the two distributions (right) is equivalent to the net effect of the detection behavior, which is to decrease the probability of neutral STRFs ($\Delta A_{local} = 0$) and to increase the probability of facilitative changes near $\Delta A_{local} = 40\%$. (**c**) Distribution of STRF changes in the two trained animals under three behavioral conditions: passive listening (blue), poor behavior (green) or good behavior (red) (see Methods for details). The commencement and improvement of behavior correlates with progressive increase in distribution asymmetry toward facilitative changes.

responses (tongue withdrawal) which allowed the animal to reach a desirable goal (avoidance of shock). Our data, which include some evidence for a possible motor component in A1 responses, are consistent with the proposal[32] that the functional role of sensory cortex may include remapping of sensory contexts to motor acts that lead to reward (see **Supplementary Note** for alternate interpretations).

In some respects, the STRF plasticity found in our A1 experiments is remarkably similar to the neuronal plasticity resulting from dynamic motor adaptation to an artificial external force field recently described in monkey primary motor (M1) cortex[20,21]. In both studies, the receptive (movement) fields of about two-thirds of cortical neurons adapted rapidly and significantly during the task. In other investigations of behavior-induced plasticity in A1, albeit using different criteria and measurements, 63% or 70% of units showed plasticity[3,8]. This fraction may represent a cortical compromise in the trade-off between modifiability and stability of information processing. Furthermore, within the group of plastic neurons, there was a significant proportion of 'memory' cells recorded in our study (67%) and >40% in others[20,21] that showed persistent changes which may contribute to long-lasting, task-dependent sensory or motor memory[1,2,4,20,21,33,34]. In experiments with multiple, successive targets, some of the A1 memory cells appeared to retain a "cumulative" memory prior behavioral targets (see **Fig. 4**). An important issue to resolve is the time course for the retention of change in the "memory" cells of A1 and M1, to discover whether the immediate neural plasticity may represent an initial building block in the process of sensory and motor learning.

One intriguing difference between the results of our study as compared with previous reports[20,21] is the presence of two distinct classes of memory cells in primary motor cortex, which showed complementary onsets and opposite dynamic shifts in their movement fields, as compared to our observation of a single type of persistent STRF change or 'memory' cell following the detection task in A1. This may reflect differences in the behavioral methods used, which in the movement studies[20,21], involved switching between two distinct active motor states, and required motor learning for adaptation to the perturbed condition as well as active re-adaptation to the non-perturbed condition in order to maintain good motor performance. However, in our auditory study, the animal performed only one basic active task, which alternated with passive listening, and hence did not appear to require such neuronal re-adaptation in returning to the passive state (in which there were no behavioral demands).

During the training period, the ferrets in our study learned a 'general' or 'cognitive' version of the detection task, reaching a stable behavioral performance level in which they could perform equally well on any target frequency chosen during the experiment. The neural basis for the changes underlying this longer-term training may well have involved some of the circuits and neuromodulators[35] that are central to auditory cortical plasticity, such as the cholinergic and dopaminergic projections to auditory cortex from the nucleus basalis[9–13,16,36] and ventral tegmental nucleus[37]. However, the rapid time course of STRF modifications (seconds to minutes) observed during ongoing behavior in the present study (and other quick-onset receptive field changes observed in A1 in classical conditioning[38] and cortical microstimulation paradigms[15,16]) likely precludes some candidate mechanisms associated with longer-term synaptic plasticity, such as the formation of new functional connections through axonal sprouting, or long-term induction of changes in transmitter or receptor levels, all of which usually take place over a longer period of time (10 minutes to hours or more). Instead, we speculate that the rapid changes we found are more akin to a rapid attentive recall of pre-existing but normally silent programs, circuits and synapses. Such changes may be mediated by top-down control over local cortical circuitry in A1, operating by mechanisms such as STDP to rapidly modulate synaptic efficacy or dynamics[39], unmask silent synapses, alter neuronal gain or change the level of excitability[40,41]. An important arena for such rapid synaptic modulation may be the set of widespread subthreshold horizontal synaptic connections found in sensory and motor neocortex[42,43]. These connections show plasticity, and it is thought that their efficacy strengthens during procedural motor learning[44,45].

These findings suggest that cortical receptive fields are not fixed, but may be constantly adapting and reorganizing dynamically to meet the challenges of an ever-changing environment and new behavioral demands. The rapid receptive field modulation we have described can play an important role in information processing and storage. Each primary sensory cortical neuron participates in multiple behavioral contexts, and it is likely that its receptive field properties are differentially modified by a complex interaction of top-down

and bottom-up influences depending on the context[15,46]. A sensory neuron's network connectivity may also be reconfigured[47] in an immediate and reversible manner as the animal switches between behavioral states. In this way, the same neuronal ensemble can mediate entirely different perceptual functions. The basic adaptive mechanisms that underlie this plasticity may be similar in perceptual and motor learning, and, as in the present study, during optimal performance of a previously learned task.

METHODS

Behavioral training. All experimental procedures were approved by the University of Maryland Animal Care and Use Committee and were in accord with NIH Guidelines. Two adult ferrets were trained on a tone detection task using a conditioned avoidance procedure[25]. Ferrets licked water from a spout while listening to a sequence of reference stimuli (drawn from a set of 30 TORCs) until they heard a tonal target. When presented with a tone, the animal was trained to stop licking, in order to avoid a mild shock. A trial consisted of a sequence of reference stimuli (randomly ranging from 1–6 TORCs) followed by a tonal target (except on catch trials in which 7 reference stimuli were presented with no target). The ferrets were trained twice daily (100 trials/session) in a sound-attenuated test box until they reached criterion, defined as consistent performance[25] on the detection task for any tonal target (range, 125–8,000 Hz) for two sessions with >80% hit rate accuracy and >80% safe rate for a discrimination rate of >0.65. Initial training to criterion in the free-running test box took ~6 weeks for each ferret. After headpost implantation, the ferrets were retrained on the task while restrained in a holder, with head fixed in place.

Surgery. To secure stability for electrophysiological recording, a stainless steel headpost was surgically implanted on the skull. The ferrets were anesthetized with Nembutal (40 mg per kg body weight), and deep anesthesia was maintained throughout the surgery. Using sterile procedure, the skull was surgically exposed and the headpost was mounted using dental cement, leaving clear access to primary auditory cortex in both hemispheres. Antibiotics and post-surgery analgesics were administered as needed after surgery.

Neurophysiological recording. Experiments were conducted in a double-walled sound attenuation chamber. Small craniotomies (>1 mm in diameter) were made over primary auditory cortex prior to recording sessions, each of which lasted 6–8 h [**AU: OK?**]. Responses were recorded with tungsten microelectrodes (3–8 MΩ) and then stored, filtered and spike-sorted off-line. A typical recording yielded 1–4 simultaneously active single units. Multiunit records were constructed by responses from all spikes by triggering on a low-threshold level (2 standard deviations (s.d.) above baseline). Location was based on the presence of distinctive A1 physiological characteristics (*e.g.*, latency, tuning) and on the position of the neural recording relative to the cortical tonotopic map in A1 (ref. 48).

Stimuli. During training and active physiological measurements, the acoustic stimuli were 1.25 s in duration, 75 dB SPL and consisted of tones and TORCs[26] or temporally orthogonal ripple combinations (see **Supplementary Audio 1–4** online). All passive STRF measurements used TORC stimuli that were longer (3 s) in duration, which allowed for more rapid measurements. Each of the 30 TORCs was a broadband noise with a dynamic spectral profile that was the superposition of the envelopes of six ripples. A single ripple has a sinusoidal spectral profile, with peaks equally spaced at 0 (flat) to 1.4 peaks per octave; the envelope drifted temporally up or down the logarithmic frequency axis at a constant velocity of up to 24 Hz[26–29]. During physiological recording, the computer-generated stimuli were delivered through inserted earphones that were calibrated *in situ* at the beginning of each experiment. The amplitude of tone and TORC stimuli was set at 5 dB below neuronal best amplitude at best frequency during physiological recording.

STRF analysis. STRFs were measured using the reverse-correlation method[26–29]. Response variance (σ) was estimated using a bootstrap procedure[29,49], and an overall signal-to-noise ratio (SNR) was computed for each STRF. Most SNRs were >1, and those with an SNR <0.2 were excluded from further analysis. Each STRF plot is therefore associated with a particular variance (σ). Excitatory (positive) and inhibitory (negative) fluctuations from the (zero) mean of the STRF were deemed significant only if they exceeded 3 s.d. from the mean. Contours were drawn at this level to demarcate significant excitatory and inhibitory features. This analysis and criteria also apply in determining the significant changes between two STRFs, that is, as in the $STRF_{diff}$ of **Fig. 2a** (right). Thus, a significant STRF change refers to a suppressive or facilitative region in the $STRF_{diff}$ that exceeds the variance criterion.

To quantify the effect of the detection task on STRF shape, we independently normalized the passive and behavior STRFs by the Euclidean norm. The difference ($STRF_{diff}$) between the passive and behavior STRFs was used to extract measures of local and global STRF change. We defined the local difference (ΔA_{local}) as the maximum difference within ±0.25 octaves around target frequency. Global change was denoted by ΔA_{global} and corresponded to the global maximum of $STRF_{diff}$ over the entire frequency range spanned by the STRF. The values of ΔA_{local} and ΔA_{global} were reported as percentages relative to the maximum value of the passive STRF.

The smooth distributions of the ΔA_{local} changes shown in **Figs. 2** and **5** were derived from the histograms as follows: (i) We assumed that for each cell, the resulting ΔA_{local} was Gaussian distributed with a mean and variance computed using the bootstrap method. (ii) The probability that the ΔA_{local} fell within a bin of 1% around any specific ΔA_{local} value was calculated by summing over contributions from all STRFs. This gave the smooth distributions shown, which represent the mean of the probability of ΔA_{local} having any particular range of values. (iii) We used the jack-knife method[49] to compute the variance (shaded outline) of the difference in distributions of the behavior and naive animals (**Fig. 5b**).

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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