178 NETWORK MODEL OF AUDITORY SPACE MAP IN BARN OWL ICX

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Abstract

In this study, we used neural networks to model the processing of interaural time difference (ITD) and interaural level difference (ILD) in barn owl's external nucleus of inferior colliculus (ICx). The inferior colliculus (IC) is a midbrain nucleus where different pathways of auditory processing converge. In barn owls, a nocturnal predator with precise sound localization, there are two separate parallel pathways processing ITD and ILD. The ITD pathway primarily encodes azimuth information and the ILD pathway mainly encodes elevation information. These two pathways converge in the lateral shell of central nucleus of inferior colliculus (ICcl), and ICcl projects to the ICx which contains a map of auditory space. Neurons in ICx are tuned to specific combinations of ITD and ILD cues, and unlike the neurons in the ICcl and other nuclei before ICcl in the ascending auditory pathway, ICx neurons have broadband frequency tuning. Our model consists of peripheral auditory filters, ITD and ILD processing units for each frequency band, and ITD/ILD interaction. A feed-forward model with topological information and non-linear ITD/ILD interaction captures broad-band properties of the ICx auditory space map. In addition, an extended version of this model is used to explore the plasticity of the auditory space map induced by visual feedback, and the roles of excitatory and inhibitory projections in the plasticity.

Model Description

Overview of the Model

- External nucleus of Inferior Colliculus (ICx) receives auditory signals from lateral shell of central nucleus of inferior colliculus (ICcl). In addition, ICx receives visual input from Optic tectum which is controlled by GABA-mediated inhibition. This signal is suggested to be the instructive signal guiding the plasticity the auditory map found in ICx (Gutfreund et al., 2002).

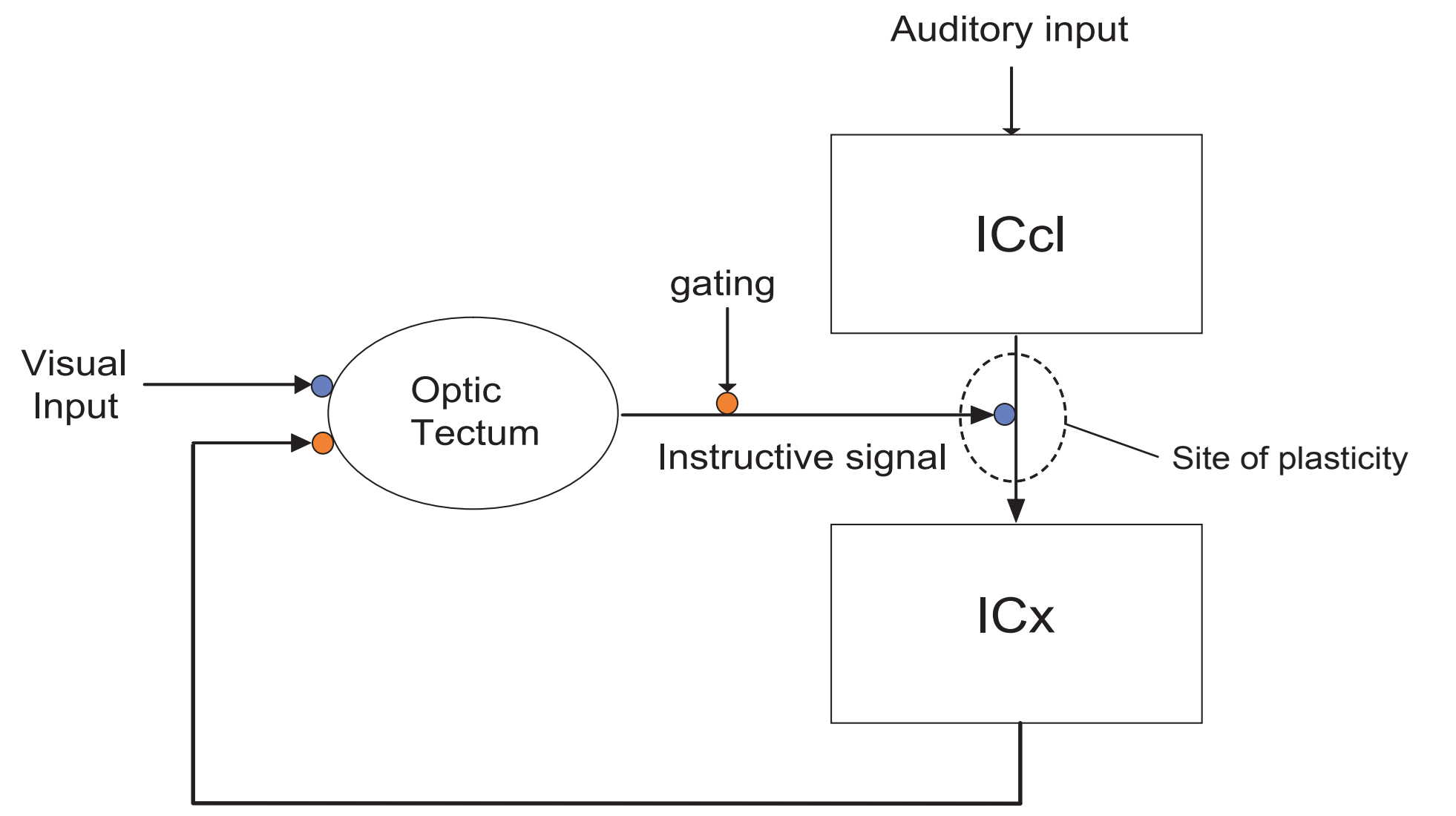

Figure1. Overview block diagram of the model. Optic tectum receives visual signal as well as ICx response. Plasticity is modeled as changes in synaptic strength between ICcl and ICx neurons.

ICcl

- Tonotopically organized.
- Independent ITD-tuned units and ILD-tuned units which encode azimuth information and elevation information.

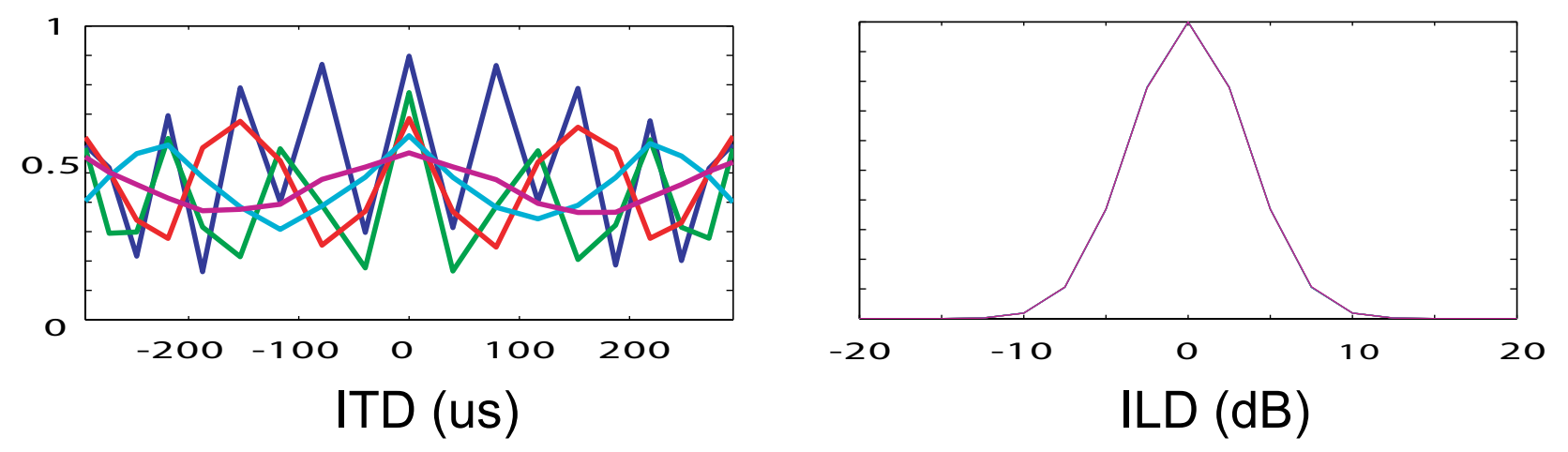

Figure2. (a) Activation of ITD tuned ICcl units. DIfferent colors indicate differenct characteristic frequencies. (b) Activation of ILD tuned ICcl units.

ICx auditory response A_k

- Weighted sums of ITD units and ILD units are multiplied (Pena and Konishi, 2001). Weights represent synaptic strengths from each ICcl neuron to ICx neuron. i and j are ICcl indices and k is ICx index.

$$A_k = \left(\sum w_{itd\ ij}\cdot ICC_{itd}(CF_i,\ \text{best } ITD_j)\right) \times \left(\sum w_{ild\ ij}\cdot ICC_{ild}(CF_i,\ \text{best } ILD_j)\right)$$

Learning rule

- Weights are updated according to to following rule at every training epoch.

$$w_{ijk} = w_{ijk} + \Delta w_{ijk}$$
$$\Delta w_{ijk} = (LR \times h_k + gate \times I_k) \times (ICC(i,j) - w_{ijk})$$

LR: exponentially decaying learning rate.
gate: gating parameter of instructive signal. 0 or 1.
h_{ij}: neighborhood function.
I_k: instructive signal.

At every training epoch, the ICx neuron with the largest response A_k to the presented stimulus is defined as the winning neuron. Then the neighborhood function is defined around the winning neuron.

- Neighborhood function: function of distance $d_{k\,k'}$ of the excited neuron k and the winning neuron k' of the training epoch.

$$h_k = \exp(-(d_{k\,k'})^2/sigma_d^2)$$

Visual response in ICx

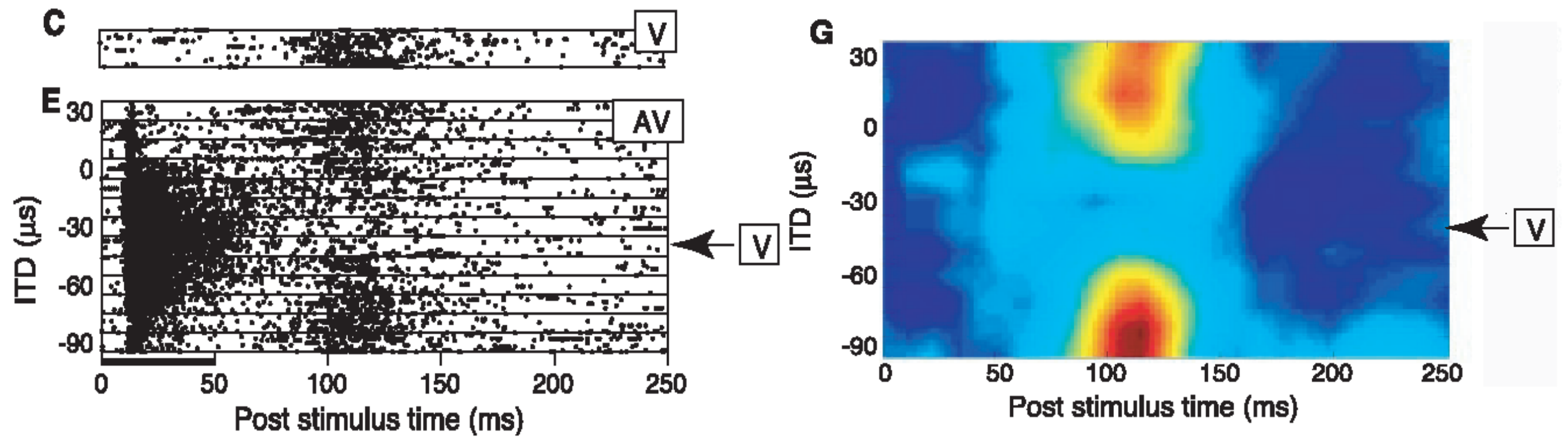

Figure2. The influence of auditory stimuli on visual response in the ICx. (From Gutfreund et al. 2002) Note strong auditory response reduces later visual response.

- Visual signal

$$V_k = \exp(-(\Phi_{signal} - \Phi_k))^2/(2\times sigma_{\Phi}^2))$$

Φ_{signal} is the azimuth/elevation angle of the signal and Φ_k is the best azimuth/elevation of the ICx neuron.

- Instructive signal

$$I_k = V_k - c\cdot A_k, \quad \text{if } V_k > c\cdot A_k$$
$$= 0, \quad \text{else}$$

Instructive signal is inhibited by the auditory response as shown in figure 2. c is a scaling factor.

When gate is 0, learning is dependent on the competitive process with topographical information provided by the neighborhood function.

When gate is 1, instructive signal guides the learning process. Instructive signal is large when the visual signal is in the visual receptive field and the auditory response is small.

When a bias in visual signal is introduced, this mismatch signal guides the network to learn a new auditory map.

Results:

1) Learning without the instructive signal

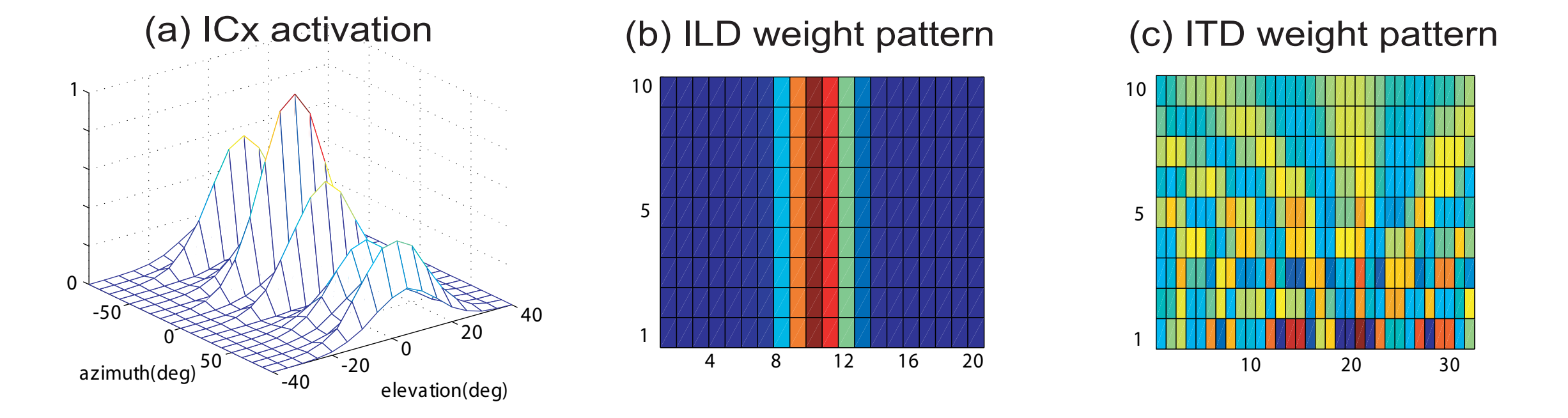

Figure 3. Activation and synaptic weight of a single ICx neuron in the network.
(a) Tuning profile of an ICx neuron after training without the instructive signal.
(b),(c) Patterns of synaptic strength connect the ICx neuron and ICcl neurons. Each block represents weight from the corresponding ICcl neuron, which is aligned by best ITD/ILD on the x axis and by CFs on the y axis.

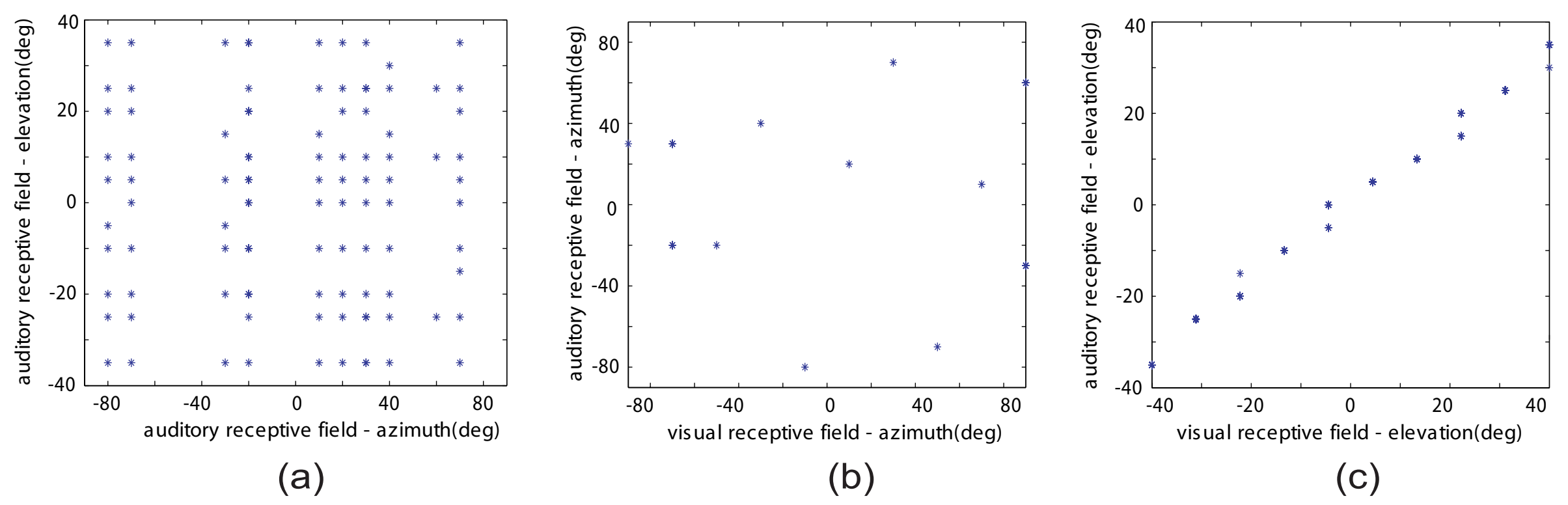

Figure 4. Overall characteristics of the ICx neuron population.
(a) Distribution of auditory receptive fields of ICx neurons. Each dot represents an ICx neuron with maximum response at the corresponding azimuth and elevation.
(b)(c) Alignment of visual receptive fields and auditory receptive fields.

2) Learning with the instructive signal

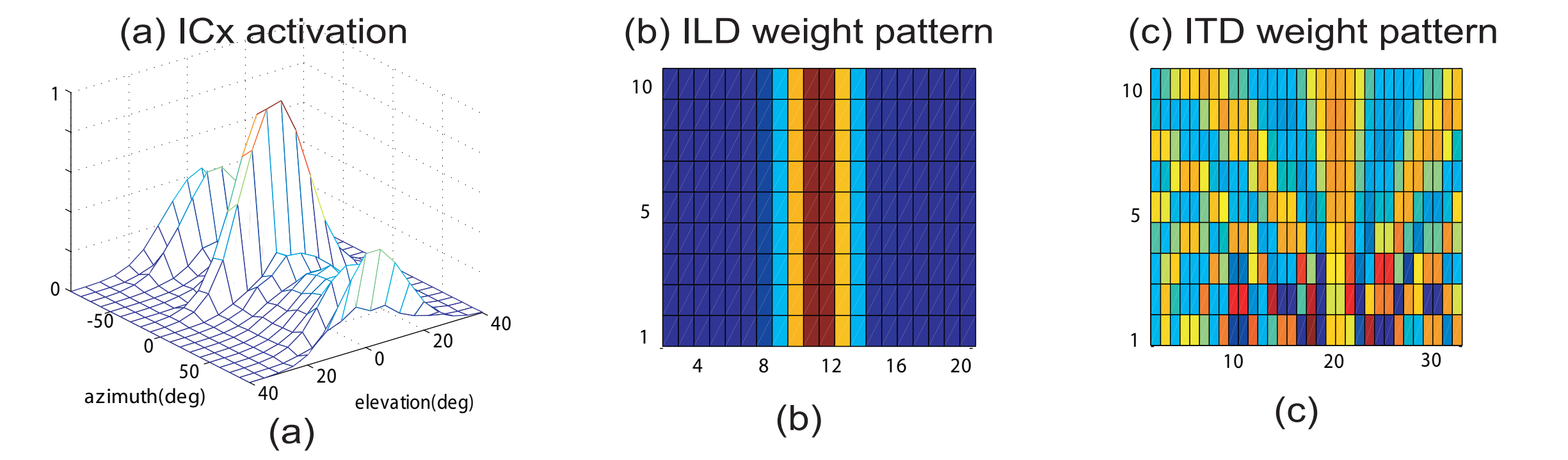

Figure 5. Activation and synaptic weight of an ICx neuron in the network.
(a) Tuning profile of an ICx neuron after learning with the instructive signal.
(b),(c) Patterns of synaptic strength connect the ICx neuron and ICcl neurons.

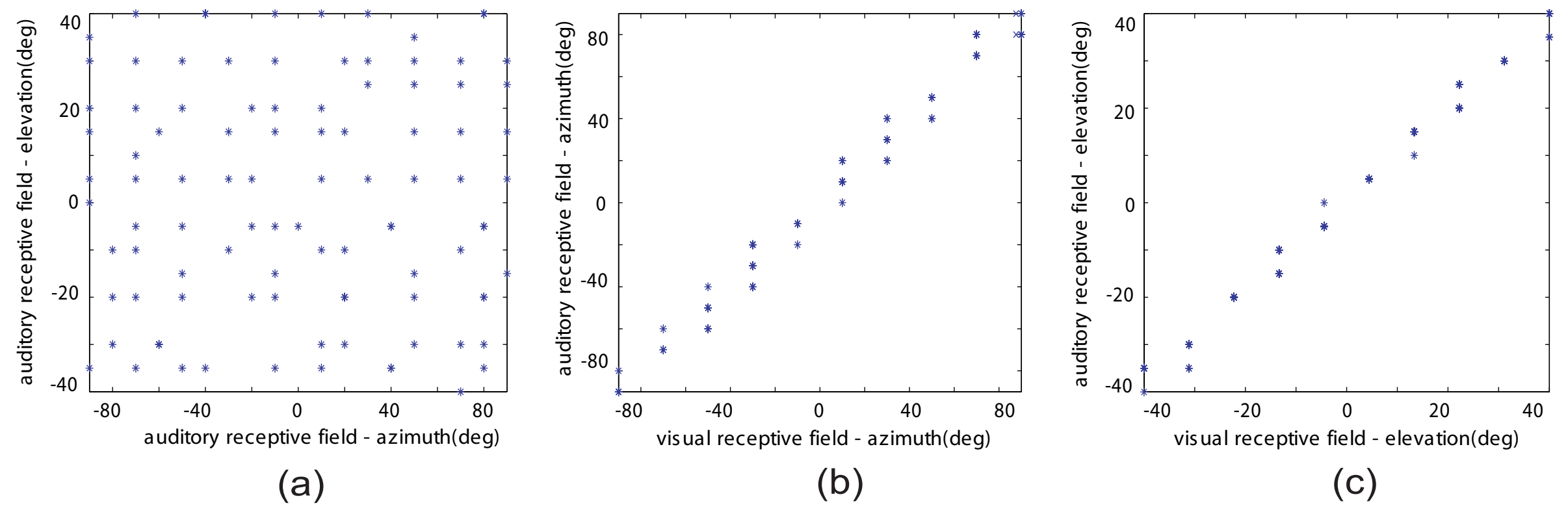

Figure 6. Overall characteristics of the ICx neurons after learning with the instructive signal.
(a) Distribution of auditory receptive fields of ICx neurons. Each dot represents an ICx neuron with maximum response at the corresponding azimuthe and elevation.
(b)(c) Alignment of visual receptive fields and auditory receptive fields.

In both cases, ICx is strongly connected from ICcl units with the tuned ITD and ILD of the ICx neuron. From ITD tuned ICcl neurons, ICx is also connected to the ICcl neurons which will have the side peaks at the tuned ITD.

Auditory receptive fields are more evenly distributed after the learning with instructive signal, and well aligned with visual receptive fields.

3) Learning with altered visual experience

Bias of 30deg in azimuth and 15deg in elevation was introduced to the previous network. The alignment of visual receptive fields and auditory receptive fields are shifted according to the bias.

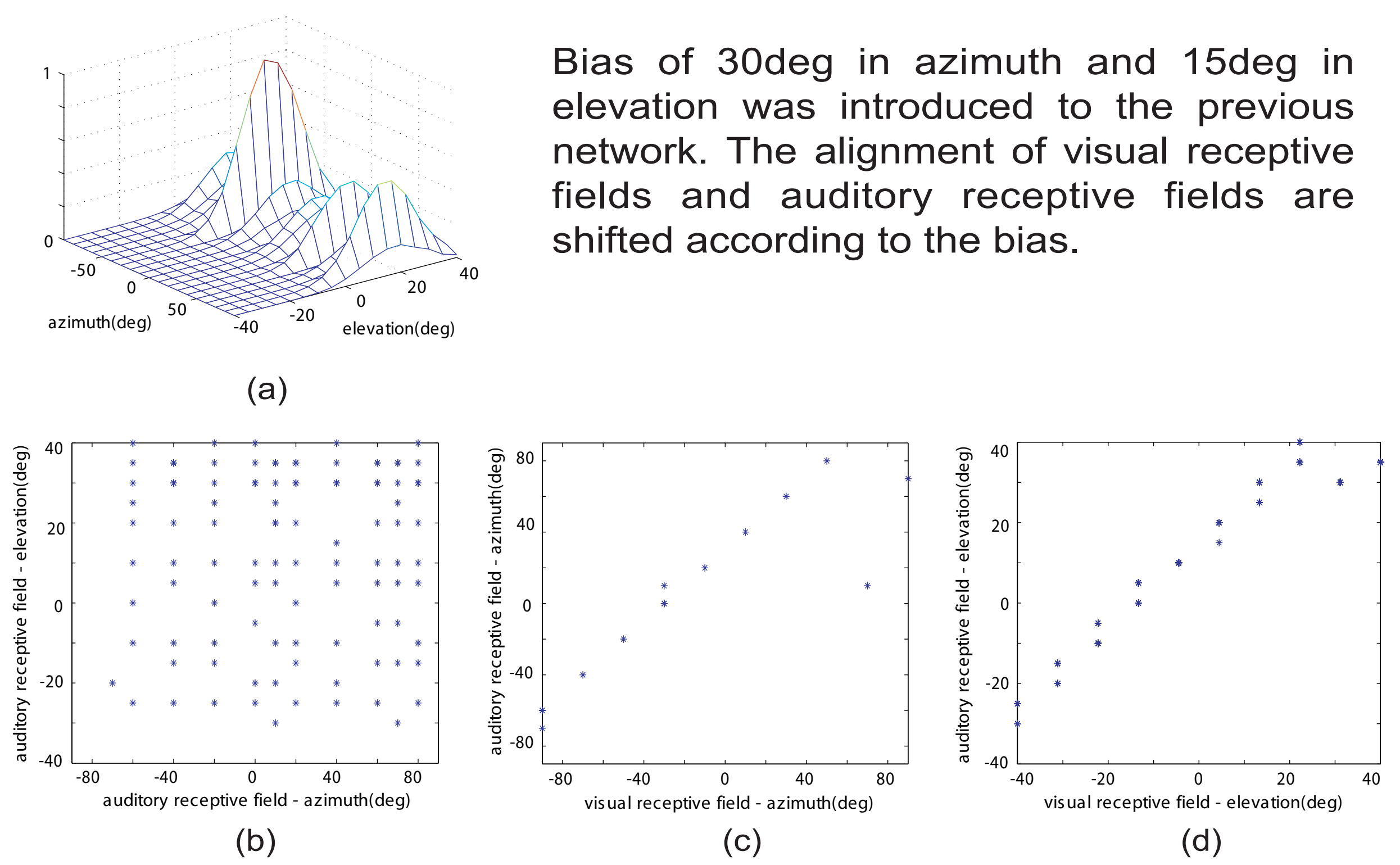

Figure 7. ICx response and auditory visual receptive field distribution after learning with altered visual experience.

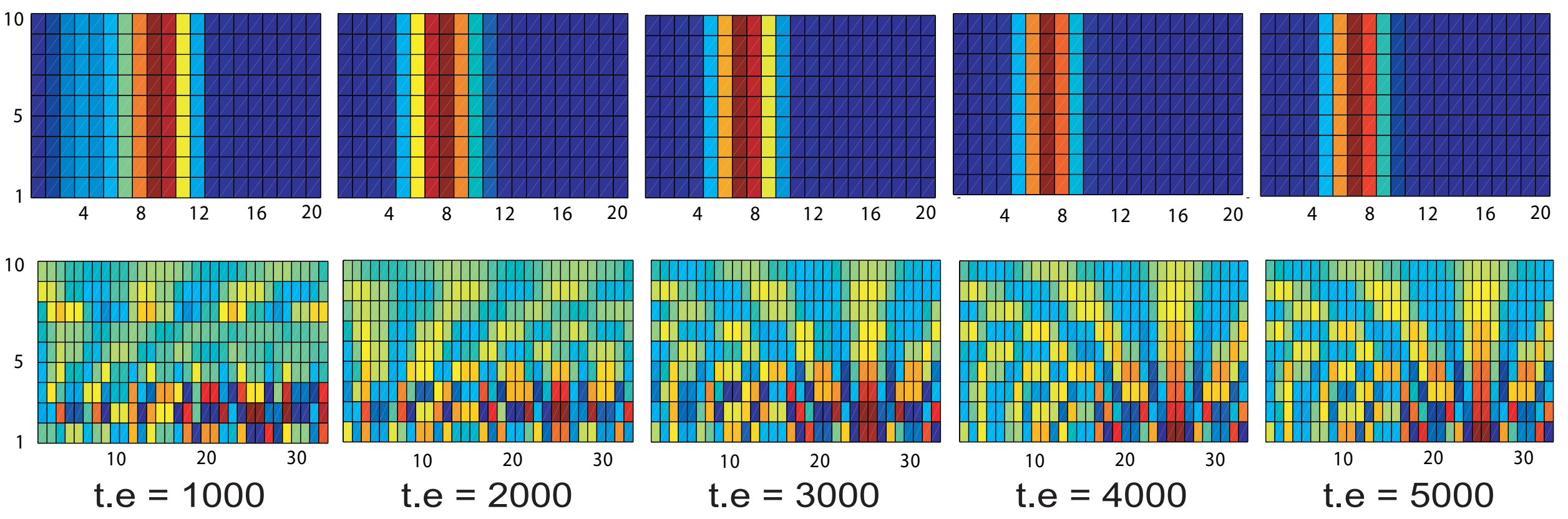

Figure 8. Change in synaptic strength patterns with altered experience across time. (t.e. is training epoch.)

Summary:

- ☐Gated visual input can guide auditory map learning in the ICx.
- ☐The modeling is consistent with the hypothesis that visual input is selectively active when it mismatches with auditory input and that this mechanism is adequite to instruct the learning with altered visual experience.

References:

Gutfreund Y, Zheng W, Knudsen EI. Gated visual input to the central auditory system. *Science*. 2002 Aug 30;297(5586):1556-9.

Pena JL, Konishi M. Auditory spatial receptive fields created by multiplication. *Science*. 2001 Apr 13;292(5515):249-52

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