

Hebbian Reverberations in an Insect's Brain

Roberto Fernández Galán^{1,3}, Marcel Weidert², Randolf Menzel², Andreas Herz³, Giovanni Galizia⁴

¹Carnegie Mellon University and Center for the Neural Basis of Cognition

²Free University, Berlin ³Humboldt University, Berlin ⁴University of California, Riverside

Over half a century ago Donald Hebb formulated his theory of learning and memory and postulated that a synapse between two neurons should increase its efficacy if both cells were simultaneously active. According to Hebb, this synaptic change needed not occur instantaneously but rather would be preceded by a short-lived **memory trace** - or "reverberation" - that mediates between perception and memory consolidation via synaptic plasticity.

Hebb's ideas to explain memory formation and associative learning have been successfully tested in theoretical models that illustrate how neural networks can process and store sensory information. The common feature of these models is "learning through correlations", a modern reformulation of Hebb's postulate, known as **Hebbian learning rule**: pairs of neural units that are excited by the stimulus should increase their correlation after stimulation; pairs of neural units that are inhibited by the stimulus should also increase their correlation; pairs of neural units, where one is excited and the other inhibited should decrease their correlation; pairs of units where at least one does not respond to the stimulus should not change their correlated activity.

We demonstrate that the neural units (olfactory glomeruli in the antennal lobe of honeybee) that respond to a given stimulus (odor) change their correlated spontaneous activity in a stimulus-specific manner. During a few minutes after stimulation these correlations enable the **retrieval of the stimulus from the spontaneous activity** of the network (antennal lobe) with a principal-component analysis. We expect our methodological approach to help uncover this form of memory trace in other neural systems.

Complementary information available at:
www.andrew.cmu.edu/user/rfgalan/home.htm

Fig. 1: Neural activity in the antennal lobe of the honeybee recorded with calcium imaging. During stimulation (time 0) a set of odor-specific glomeruli are activated. Some of them are excited (red) and others inhibited (blue). The majority do not respond (green). Even in the absence of stimulation the neural activity in this neural network is considerable high (typically one order of magnitude lower than during stimulation). This spontaneous activity allows us to estimate statistical correlations between glomeruli, as well as its changes after stimulation.

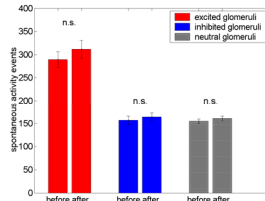
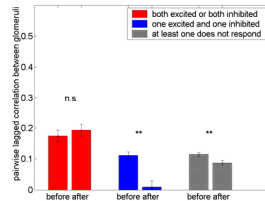
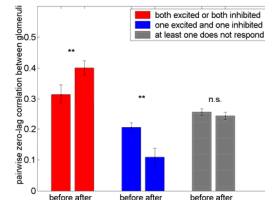
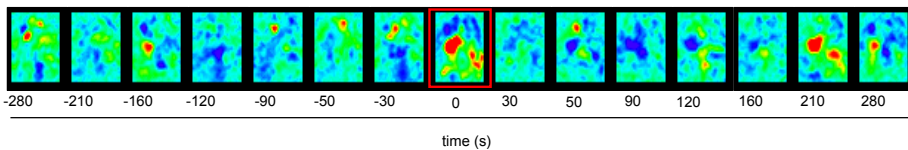


Fig. 2: Biological evidence of the Hebbian learning rule. (top) As predicted by Hebb, pairs of glomeruli that were both excited or both inhibited by the odor significantly increased their correlated activity after stimulation; glomerular pairs where one glomerulus was excited and the other inhibited decreased their correlation; glomerular pairs where at least one glomerulus did not respond to the odor did not change their correlation. By shifting the signals of the glomeruli with respect to each other by a small time lag this correlation structure was destroyed (middle). In addition, activity events in calcium imaging data, defined as the spontaneous events in a single glomerulus beyond its standard deviation, were not significantly affected after stimulation (bottom). These results indicate that odor exposure does not increase the overall spontaneous activity in the antennal lobe, but rather changes their correlation structure.

Fig. 3: Stimulus retrieval from the spontaneous Activity. (left) Matrices of pairwise correlations of glomerular activity before and after stimulation, as well as the correlation changes, ΔC , and the corresponding dominant eigenvectors or first principal components (PCs, right). The estimation of correlations and their changes was improved by applying bootstrap methods. Non-significant entries of the ΔC matrix have been set to zero and are shown in white; the diagonal elements equal zero by definition and are depicted in grey. Stimulus reconstruction significantly succeeded from the principal component of the spontaneous activity after stimulation, as well as from the dominant eigenvector of ΔC .

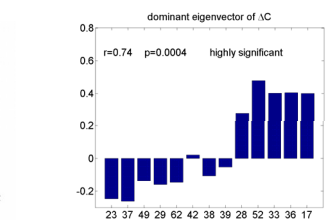
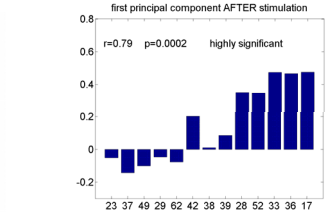
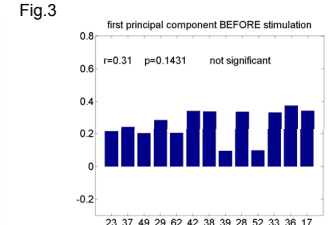
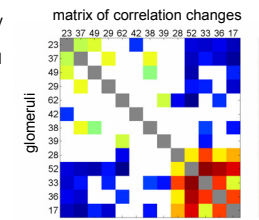
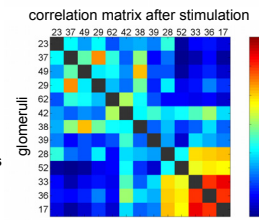
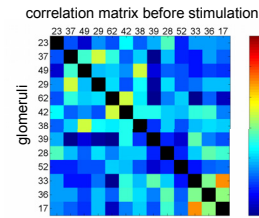


Fig. 4: Statistics across animals and memory dynamics. (left) Box-plot of the similarity (estimated as Kendall's nonparametric correlation) between the actual odor-evoked response and the reconstructed response as dominant eigenvector of the correlation matrix 2 minutes and 1 minute before and after stimulus presentation. Numbers above the box-plots indicate in how many animals stimulus retrieval succeeded (significant similarity between the first PC and the odor response). (right) Actual activity pattern elicited by the odor (2-octanol). Glomeruli are arranged according to their activity strength. Compare this pattern with the ones obtained by the principal-component analysis.

