CAAM/NEUR 415: EXAMINATION #2

April 06, 2007

1 Answer the following questions (total 25 points):

1. Explain the relation between the binomial and Poisson distribution. Explain why one of these distributions does not usually work well to describe synaptic release at central synapses and why it does work well at the neuromuscular junction. (3 points)
2. What is the typical coefficient of variation and Fano factor observed in visual cortical neurons in vivo? Are the observed values consistent with the hypothesis that these neurons act as neural integrators of the approx. 10000 synaptic inputs they typically receive? Explain why/why not. (2 points)
3. Explain under which assumptions synaptic inhibition acts divisively on excitatory synaptic inputs. Name and briefly describe the properties of typical inhibitory conductances (neurotransmitter, reversal potential, preferred charge carrier). (3 points)
4. You have designed an experimental setup that allows you to stimulate two individual excitatory synapses onto a neuron separated by a brief (few tens of milliseconds) time interval. You are planning to do this experiment before and after blocking the background spontaneous activity that the neuron receives. If the resting membrane potential does not change after the block (i.e. spontaneous activity consists of excitatory and inhibitory synaptic inputs roughly in equal proportion) do you expect the two stimulated excitatory inputs to summate better or less well after the block? Briefly explain why. (2 points)
5. Make a sketch of (or describe in words) the gain and phase for the subthreshold Green's function of a leaky integrate-and-fire neuron. Explain the significance of these graphs when sinusoidal currents of various temporal frequencies are injected into the model neuron. (3 points)
6. How does an ON-center retinal ganglion cell (RGC) respond to a bright spot of light flashed in the center of its receptive field? How about a dark spot (darker than the background) at the same location? What are the corresponding responses (same stimuli) of an OFF-center RCG in its surround? (2 points)
7. You record the responses of a neuron in visual cortex to a stationary counterphasing grating optimally oriented in its receptive field. You systematically vary the phase of the grating relative to the receptive field center of the neuron. Can you from this data decide whether the cell is simple or complex? If yes, how? If no, why? (2 points)

8. Briefly explain how orientation selectivity arises in simple cortical cells according to the Hubel and Wiesel model. A sketch would be useful. (2 points)
9. Briefly explain what the reverse-correlation method is and how it works. (3 points)
10. Explain what a two-alternative forced choice experiment is. From an experimentalist's point of view, what is the advantage of such a psychophysical experiment compared to a yes-no rating experiment ? (3 points)

2 Theory and practice of Fourier transforms (total 20 points)

1. Your computer has an analog-to-digital board (A/D) with a maximal sampling rate of 1kHz. What is the maximal frequency that an analog signal can have if you want to acquire it without distorsions ? (2 points)
2. You sample 2048 points of an analog signal at the maximal rate of your A/D board, and you fast Fourier transform it using fft in Matlab. What frequency values does the corresponding fft-transformed vector contain? (2 points)
3. How are the frequency components arranged in your Matlab output vector in terms of positive and negative frequencies (below the Nyquist frequency)? (5 points)
4. The Fourier transform vector turns out to have only two non-zero components at positive frequencies $f_{Nyquist}/4$ and $f_{Nyquist}/8$. The corresponding values of these components are purely imaginary, i.e. $\alpha\, i$ and $\beta\, i$ with α, β real. Furthermore, the only two other non-zero components are at frequencies $-f_{Nyquist}/4$ and $-f_{Nyquist}/8$ with values $-\alpha\, i$ and $-\beta\, i$, respectively. What does this information tell you on the properties of the corresponding original time vector (symmetry, ...)? (3 points)
5. You want to model the time vector. Given the information of point 4 above, how would you chose your model function? Briefly explain why or give an explicit formula. (3 points)
6. You now want to compare the model function's Fourier transform computed analytically with the discrete Fourier transform that you computed using fft. How do you have to scale these functions for the comparison to be meaningful? (2 points)
7. Briefly explain the convolution theorem and its significance. (3 points)

3 LIF model of spike frequency adaptation (total 35 points)

Spike-frequency adaptation is a phenomenon by which the firing rate of a neuron decreases during a current injection pulse. It is often mediated by a potassium conductance, g_{AHP}, that is calcium-dependent. We want to study a model of spike frequency adaptation based on a modification of the leaky integrate-and-fire model. We assume that the subthreshold membrane potential satisfies the following differential equation:

$$C\frac{dV}{dt} = -\frac{(V(t) - V_r)}{R} + I - g_{AHP}\,[Ca^{2+}](t)\,(V(t) - V_K).$$

In this equation $C = 0.5\,nF$ is the membrane capacitance, $R = 40\,M\Omega$ is the membrane resistance, $V_r = -70\,mV$ is the resting membrane potential, $V_K = -80\,mV$ is the potassium reversal potential, I is the injected current, $g_{AHP} = 0.015\,\mu S/\mu M$ is the calcium-dependent potasium conductance and $[Ca^{2+}]$ is the intracellular calcium concentration (μM). Once the membrane potential reaches threshold, $V_{th} = -54\,mV$, a spike is generated, the membrane potential is reset to its resting value and the intracellular calcium concentration is incremented by $0.2\,\mu M$:

$$\text{if} \quad V(t) = V_{th} \quad \text{then} \quad V \to V_r \quad \text{and} \quad [Ca^{2+}] \to [Ca^{2+}] + 0.2.$$

Between spikes, the calcium concentration relaxes exponentially towards 0 with a time constant $\tau_{Ca} = 150\,ms$:

$$\frac{d[Ca^{2+}]}{dt} = -\frac{[Ca^{2+}]}{\tau_{Ca}}.$$

The initial values of $V(t)$ and $[Ca^{2+}]$ are V_r and 0, respectively.

1. Assume first that $g_{AHP} = 0$ (i.e., **passive model** without spike frequency adaptation) and compute the membrane time constant from the parameters given above. (2 points)

2. Derive from the formula for the firing rate of the leaky integrate-and-fire neuron given in the lecture notes the minimum current (I_{thres}) needed for the passive model to fire and the current required for the passive model to fire at 200 spk/s (I_{max}). (3 points)

3. Plot the $f - I$ curve for the passive model between I_{thres} and I_{max}. (2 points)

4. Simulate current injection in the passive model during 1 second for 10 equally spaced current values between I_{thres} and I_{max}. Compute the corresponding mean firing rate (total number of spikes during the 1 second current pulse) and compare with the value obtained in 3 above. Use your preferred integration method (for example forward Euler with a small time step, 0.05 milliseconds). (3 points)

5. Add the adaptation conductance (g_{AHP} and the calcium dynamics to the model and repeat the simulations of the previous step. Plot the resulting spike trains for three current values. (15 points)

6. Plot the mean firing rate (total number of spikes during the 1 second current pulse) and the initial firing rate (the inverse of $(t_2 - t_1)$ where t_2 is the time of the second spike and t_1 the time of the first spike) as a function of current between I_{thres} and I_{max}. Plot also the final firing rate (the inverse of $(t_{last} - t_{last-1})$, where t_{last} is the time of the last spike and t_{last-1} the time of the next to last spike). (10 points)

4 Temporal and frequency characteristic of LGN neurons (total 20 points)

In this exercise you will reproduce the graphs shown on the next page. The top panel depicts the temporal weighting function of a typical LGN cell, given by

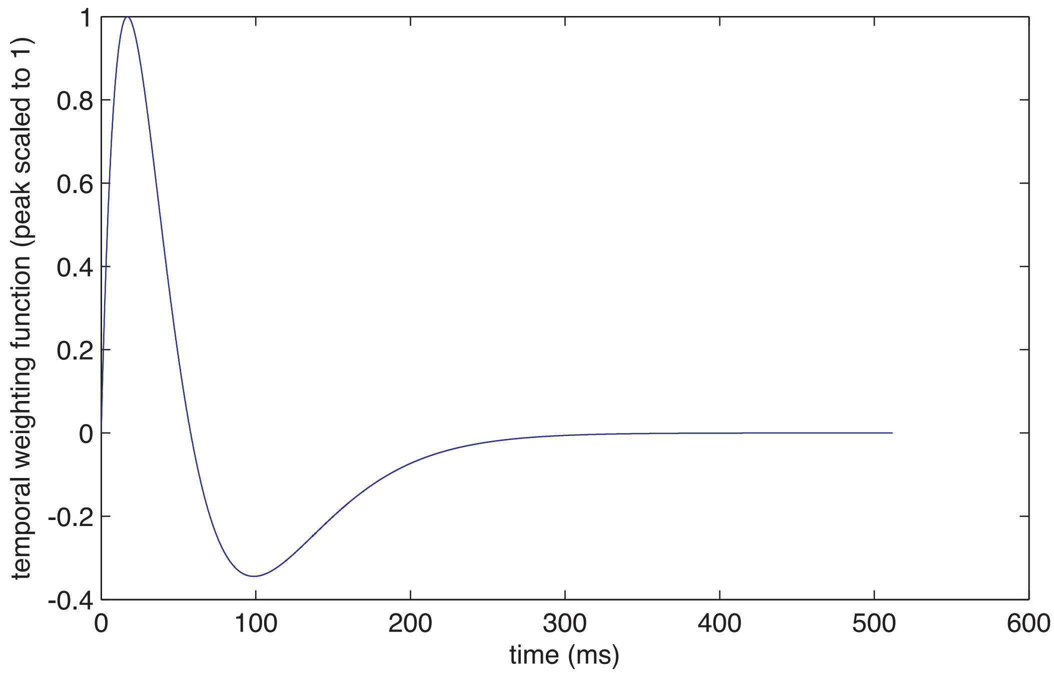
$$w_{temp}(t) = C_1\, t(1 - \frac{\alpha}{2}t)e^{-\alpha t},$$

with $\alpha = 2\pi\nu_c$, $\nu_c = 5.5$ Hz and the constant C_1 is used to scale the peak response to 1. The bottom graph depicts the gain of the Fourier transformed weighting function. The blue line is the gain obtained from the modulus of the Fourier transform of w_{temp} calculated analytically,

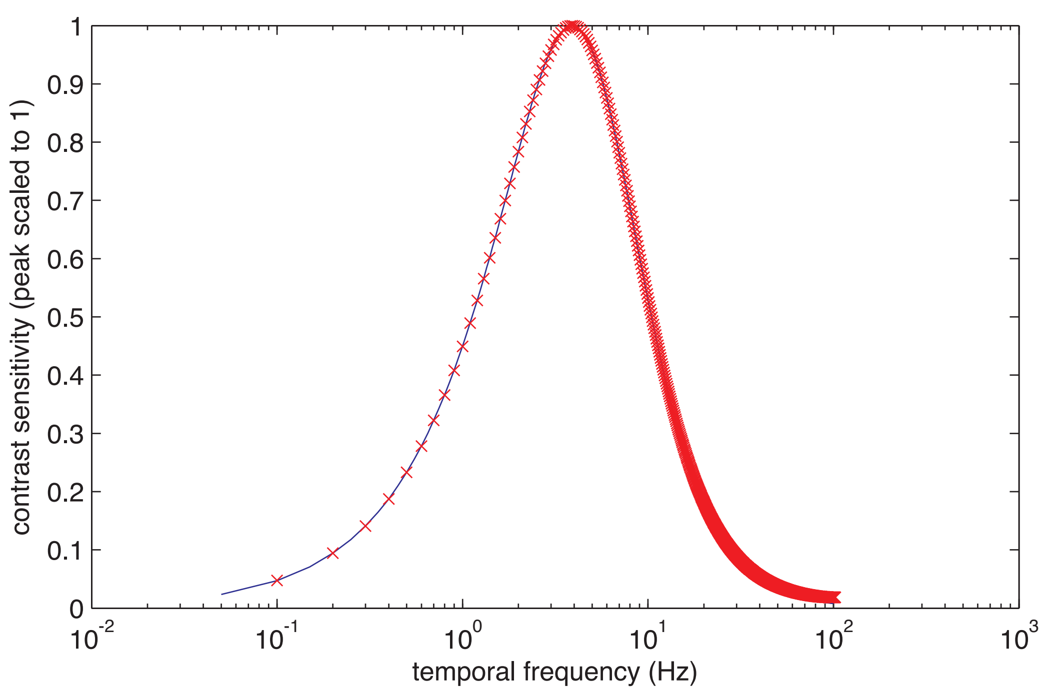
$$|\hat{w}_{temp}(\omega_t)| = C_2\, \frac{\omega_t}{(\alpha^2 + \omega_t^2)^{3/2}},$$

for non-negative frequencies $\omega_t \geq 0$. The constant C_2 is used to scale the peak response to 1. The red crosses are the values obtained by a numerical Fourier transform of $w_{temp}(t)$.

Hints. Use the MATLAB function `semilogx` to plot the frequency response. Sampling in the frequency domain should be around $\Delta f = 0.1\, Hz$.



temporal weighting function (peak scaled to 1)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
100
200
300
400
500
600
time (ms)



contrast sensitivity (peak scaled to 1)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
temporal frequency (Hz)