Version GH/3

EGT2
ENGINEERING TRIPOS PART IIA

Tuesday 6 May 2025 14:00 to 15:40

Module 3G3

INTRODUCTION TO NEUROSCIENCE

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book
Supplementary page: one extra copy of Fig. 2 (Question 1)

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

1 A neuron's membrane is approximated by a sphere of radius r. The neuron's specific membrane capacitance (capacitance per unit area of membrane) is estimated to be $c_\mathrm{m} = 1\,\mu\mathrm{F}\cdot\mathrm{cm}^{-2}$. A scientist proposes the following model for how the neuron's membrane potential, $V(t)$, responds to the injection of a small current, I_ext, measured in pA:

$$C\frac{dV}{dt} = -g(V - E) + I_\mathrm{ext} \tag{1}$$

where C, g and E are constants.

(a) What does C represent, and what properties of the membrane determine its value? [10%]

(b) What does g represent, and what properties of the membrane determine its value? [10%]

(c) What does E represent, and what properties of the membrane determine its value? [10%]

(d) Explain why Eq. (1) is unlikely to be a good description of the neuron's response when I_ext is large. [10%]

(e) The scientist injects a current step of 1 pA and records the voltage response $V(t)$ shown in Fig. 1. Using the model of Eq. (1), estimate the neuron's radius r, and explain your derivation. [30%]

(f) The Hodgkin-Huxley equations, as presented in lectures, are used to model the response of another neuron to a step of hyperpolarising current (Fig. 2, left; the grey box marks the stimulation period). The voltage dependence of the model's three gate variables (sodium activation m, sodium inactivation h, and potassium activation n) is shown in Fig. 2 (right, showing voltage-dependent steady-states and time constants).

(i) On the additional copy of Fig. 2 provided at the end of this paper, complete the legend by writing m, h, or n in front of the relevant line style. Do not forget to hand in your completed copy of Fig. 2 with your answer to this question. [10%]

(ii) Somewhat paradoxically, this hyperpolarising stimulus ends up eliciting an action potential. Based on Fig. 2, describe two potential mechanisms by which this action potential might arise (no need to explain the shape of the action potential itself). Which of these two mechanisms is likely to be the largest contributor, and why? [20%]

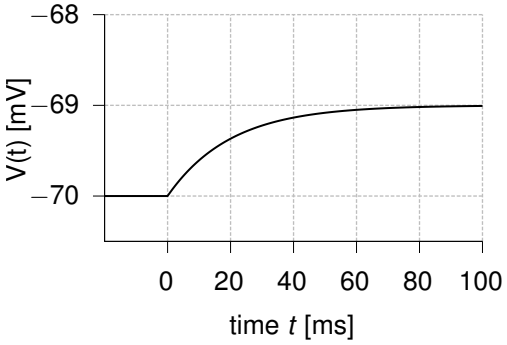
−68
−69
−70
V(t) [mV]
0
20
40
60
80
100
time *t* [ms]

Fig. 1

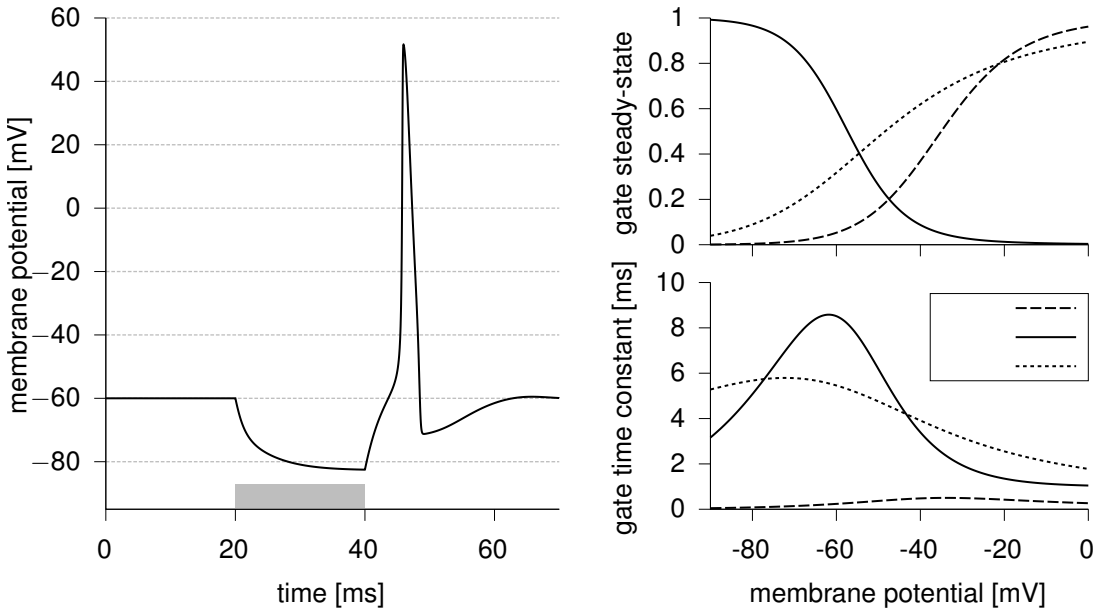
60
40
20
0
−20
−40
−60
−80
membrane potential [mV]
0
20
40
60
time [ms]
1
0.8
0.6
0.4
0.2
0
gate steady-state
10
8
6
4
2
0
gate time constant [ms]
-80
-60
-40
-20
0
membrane potential [mV]

Fig. 2

2 In a multisensory integration experiment, a subject is asked to gaze at the center of a multimodal panel, which can deliver a brief visual and/or auditory stimulus at an arbitrary yaw location θ within the binocular visual field. Here, the yaw angle θ is measured in degrees relative to the center of the panel (with $\theta > 0$ on the right, by convention). Visual stimuli take the form of circular dot clouds ('blobs'), with the location of each dot drawn from an isotropic Gaussian distribution of variance α^2 (which the experimenter can control) around the desired location θ. Auditory stimuli are single clicks.

(a) Suppose that a visual stimulus is shown at angular position θ, with no sound. According to the statistical perception framework discussed in lectures, the visual sensory evidence can be summarised by a likelihood function $p(\text{'evidence from eyes'} \mid \theta)$. Up to a multiplicative factor, this function has the same shape as the probability density function of a Gaussian random variable with mean $\hat{\theta}_\text{v}$ ('maximum-likelihood estimate') and constant standard deviation σ_v.

(i) Does $\hat{\theta}_\text{v}$ equal θ? If yes, under what assumption? If no, why? [10%]

(ii) Describe a 2AFC task that could be used to estimate the subject's σ_v without ever asking them to output precise localisation judgments. Explain what you would measure, how you would analyse the data to extract an estimate of σ_v, and what key assumption you need for this. [30%]

(b) The subject is now presented with coincident visual *and* auditory stimuli, presented simultaneously at the same location θ.

(i) Derive an expression for the maximum-likelihood estimate, $\hat{\theta}_\text{va}$, of the stimulus location, and for the corresponding spread σ_va. Express your answers in terms of $\hat{\theta}_\text{v}$, $\hat{\theta}_\text{a}$, σ_v and σ_a, where $\hat{\theta}_\text{a}$ and σ_a, defined analogously to their $(\cdot)_\text{v}$ counterparts, are the parameters of the (Gaussian) likelihood function arising from the auditory stimulus. State and justify any key assumption(s) in your derivation. [20%]

(ii) Based on your answer to part (a)(ii), describe an experimental protocol and associated analysis that could be used to test the hypothesis that subjects combine vision and hearing optimally in their perception of stimulus locations? [30%]

(c) A ventriloquist can trick their audience into thinking that their own vocalizations originate from a puppet whose mouth they move at the same time. Based on your answers to previous parts, give a possible explanation for this effect, and what it says about the relative precision of location encoding in the visual and auditory domains in humans. [10%]

3 (a) This question is about excitatory and inhibitory synaptic signalling.

(i) Describe the difference between an excitatory and an inhibitory synapse. [5%]

(ii) Describe the difference between an EPSP and an IPSP. [10%]

(iii) Explain with reasons if an excitatory synapse can generate an IPSP under physiological conditions. [5%]

(iv) Explain with reasons if an inhibitory synapse can generate an EPSP under physiological conditions. [10%]

(v) Explain with reasons if an excitatory neuron can lead to the inhibition of an other neuron. [10%]

(vi) Explain with reasons if an inhibitory neuron can lead to the excitation of an other neuron. [10%]

(b) This question is about synaptic plasticity in the Aplysia gill withdrawal reflex. For each of the following pharmacological manipulations during training (but not testing), describe their effects on habituation, sensitisation, and conditioning, in terms of how the animal's gill withdrawal response (for any relevant stimulus) compares to those of naïve animals after training:

(i) Local application of lidocaine to the sensory neurons. [10%]

(ii) Local application of a potassium channel blocker to the sensory neurons (of the siphon). [20%]

(iii) Selective serotonin re-uptake inhibitors (SSRIs). [Hint: normally, serotonin molecules are actively taken up by the presynaptic cell from the synaptic cleft. This process is inhibited by SSRIs.] [20%]

4 (a) Explain what changes at the cellular level underlie the following three aspects of LTP as measured in extracellular recordings:

(i) increased amplitude of the population EPSP; [10%]

(ii) increased amplitude of the population spike; [20%]

(iii) decreased latency of the population spike. [20%]

(b) This question is about dopaminergic cells and the temporal difference error.

(i) Describe three different experimental conditions in a simple classical conditioning experiment in which it can be shown that the activity of dopaminergic cells is consistent with a temporal difference error signal. [30%]

(ii) Describe the activity of dopaminergic cells as a function of within-trial time in a secondary conditioning paradigm at each stage of training: before the first phase of training, after the first but before the second phase of training, and after the second phase of training. [20%]

END OF PAPER

Version GH/3 Candidate Number:

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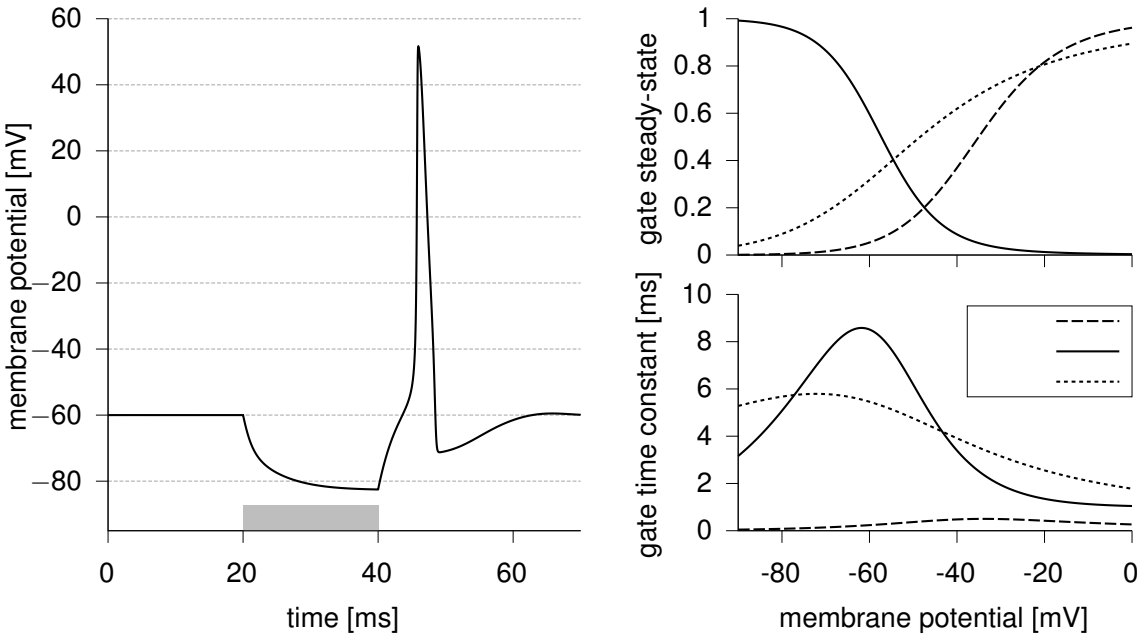
ENGINEERING TRIPOS PART IIA
Tuesday 6 May 2025, Module 3G3, Question 1.



Additional copy of Fig. 2. It should be annotated as specified in Question 1, and handed in with your answers to that question.