Version ML/2

EGT2
ENGINEERING TRIPOS PART IIA

Monday 10 May 2021   09:00 to 10:40

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 and at the top of each answer sheet.*

STATIONERY REQUIREMENTS
Write on single-sided paper.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

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

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

1 (a) Suppose a neuron is well described by an *integrate and fire model* with a fixed firing threshold, V_{thr}, and with sub-threshold membrane potential, V, modelled as a single passive compartment with capacitance C and Ohmic membrane conductances, g_i, with reversal potentials, E_i:

$$C\frac{dV}{dt} = \sum_i g_i\ (E_i - V)$$

(i) Write down expressions for the resting potential, V_{m}, of the neuron and the membrane time constant, τ. [5%]

(ii) An experimentalist applies a train of depolarising impulses to the neuron that cause the membrane potential to increase by an amplitude S, as shown in Fig. 1. Each pulse is separated by a time interval, T, equal to the membrane time constant, τ. Assuming the neuron remains below firing threshold, V_{thr}, derive an expression for the peak membrane potential, V_{p}. What is the minimum impulse amplitude, $S = S_0$, that will eventually cause the neuron to reach the threshold? [20%]

(iii) The experimentalist next applies a drug that introduces an additional conductance, g_{m}, with reversal potential E_{m}. Suppose g_{m} is equal to the pre-drug membrane conductance, $\sum_i g_i$. Assuming the impulses are kept at the same amplitude, $S = S_0$, derive an expression for the minimum value of E_{m} that will allow the neuron to fire. Write your expression in terms of V_{thr} and V_{m}. [20%]

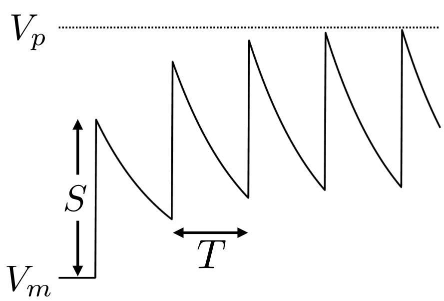

Fig. 1

(b) Explain why perception can be thought of as probabilistic inference, and why it relies on prior knowledge and prior expectations. [15%]

(c) The left panel of Fig. 2 depicts a checkerboard, with dark and light squares, and a cylinder casting a shadow on the checkerboard. Square A is commonly perceived darker than square B, even though the pixels in these two regions of the image have exactly the same physical colour. (To check that squares A and B indeed have the same physical colour, the right panel of Fig. 2 shows the same image as the left panel but with two superimposed vertical bars that have uniform colours.)

Explain the following aspects of this visual illusion using the probabilistic inference model of perception. (Think of the pixel colours as the sensory inputs/variables, s.)

(i) Specify the following components (by reference to features of the objects or object-parts depicted in the left panel of Fig. 2, or to the rules and regularities governing them) and briefly justify your answer in each case:

A. the variable(s) inferred by perception; [10%]

B. a variable that plays a causal role in determining s, but is (partially) discarded or compensated for by perception; [10%]

C. key pieces of prior knowledge/expectations. [10%]

(ii) Describe how the components you described above come together to explain the illusion. [10%]

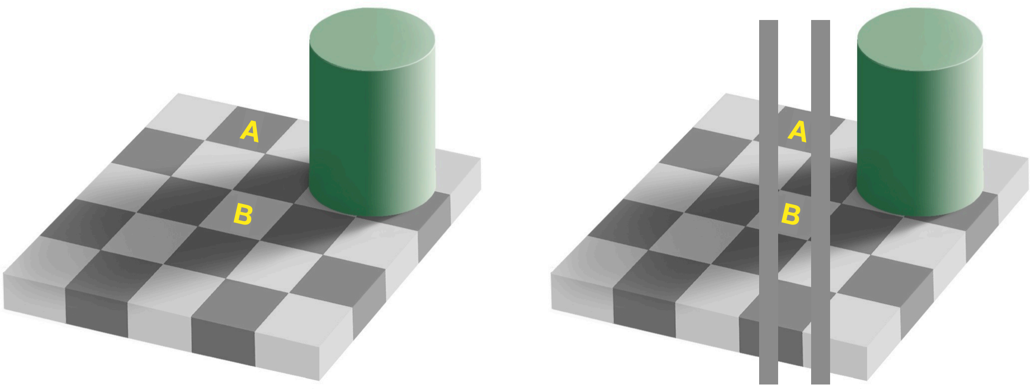

Fig. 2

2 (a) Do conductances that depolarise the neuronal membrane potential always increase the likelihood of an action potential? Explain your reasoning. [10%]

(b) This question is about the drift-diffusion model of decision making, whereby a decision variable, x_t, starts at $x_0 = 0$ and evolves according to the stochastic differential equation

$$dx_t = \mu \, dt + dW_t$$

until it reaches one of the two bounds at $\pm B$. (Note that here we have fixed the coefficient of dW_t to 1, but allow B to be a free model parameter.) Explain, with reasons, how increasing B affects the decision maker's speed and accuracy, and thus the speed-accuracy trade-off. [20%]

(c) Crickets have two "cerci" (Fig. 3, left, rear appendages in black), each covered with hairs that are deflected by air currents, thus providing information about the wind direction θ (relative to heading direction). For low air velocity, only four sensory neurons relay information about θ to the brain. Specifically, the firing rate f_i of the i^{th} neuron is a half-wave rectified cosine function of θ (Fig. 3, right), $f_i(\theta) = 40\,[\cos(\theta - \theta_i)]_+$, where θ_i is the neuron's preferred wind direction and $[x]_+$ equals x if $x > 0$ and 0 otherwise.

(i) Show that $f_i(\theta) = 40\,[\vec{v} \cdot \vec{c}_i]_+$, where $\vec{v}$ is the normalised air velocity vector and $\vec{c}_i$ is the normalised preferred direction vector of neuron i (Fig. 3, left). [10%]

(ii) Assume the wind direction is constant. Give an expression for the reconstruction (or "decoding") of $\vec{v}$ from the firing rates of these four neurons, assuming a sufficiently long time window is used to obtain near-perfect rate estimates. Explain why you think this system uses four neurons. [30%]

(iii) Now, assume that firing rate estimates are noisy, e.g. based on a finite time window. What mathematical approach would you use to formalise optimal decoding of the wind direction? [30%]

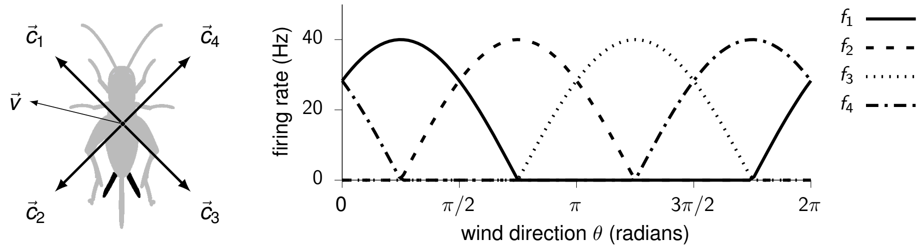

Fig. 3

3 (a) Write short notes on the following:

(i) Dale's principle; [5%]

(ii) ionotropic receptor; [5%]

(iii) spaced training; [5%]

(iv) conditioned stimulus; [5%]

(v) Mg^{2+} block. [5%]

(b) This question is about the role of hippocampal learning in spatial navigation.

(i) Describe an experimental approach for studying how navigation depends on information stored in the hippocampus depending on the amount of experience. In your answer, describe the following:

A. the apparatus; [5%]

B. the behavioural paradigm for training and testing; [10%]

C. the key behavioural measure of learning; [10%]

D. the pharmacological interventions that need to be used in the experiment: the drug(s), the time at which they are applied, and the brain structure(s) to which they are applied. [10%]

(ii) Describe the results you expect from the experiment you specified above, and what these results tell us about the kind of information that is and is not stored in the hippocampus, and when that information is used for navigation. [20%]

(iii) Explain how you would extend the experimental approach above to show that the hippocampal information used for navigation is stored by LTP. In your answer, include any changes to the behavioural paradigm or any additional drugs that you may use, as well as the results you would expect from the experiment and the interpretation of those results. Make sure that your proposed experiment controls for potential effects of LTP on retrieval, and the effects of hippocampal LTP on storing other kinds of information. [20%]

 (TURN OVER

4 (a) This question is about classical conditioning in the *Aplysia*.

(i) Name three different neurotransmitters that are involved in the induction of classical conditioning. For each neurotransmitter, explain which cell releases it, on which cell it exerts its effects, the kind of molecules the target cell uses to bind it, and the effects binding has on the target cell. [30%]

(ii) Describe the differences between the training protocols used to induce (short-term) sensitisation and conditioning, and the resulting differences in the behavioural effects of these two forms of learning. In addition, explain the mechanisms by which differences in training lead to the differences in behaviour. [20%]

(b) The activity of GABAergic neurons in the ventral tegmental area has been shown to strongly correlate with reward prediction.

(i) Describe how you expect the activity of such a neuron to vary over time during the course of a classical conditioning trial (using a single CS) before and after training. [20%]

(ii) Based on their main neurotransmitter, what effect do you expect these neurons to have on dopaminergic neurons in the VTA, and how would you interpret this effect in the context of the Rescorla-Wagner learning theory of dopaminergic activity? [30%]

END OF PAPER

Answers

1(a)(i)

$\tau = \frac{C}{\sum_i g_i}$.

1(a)(ii)

$S_0 > (V_{\mathrm{thr}} - V_m)(1 - \mathrm{e}^{-1})$

1(a)(iii)

$E_m > \frac{1-\mathrm{e}^{-1}}{1+\mathrm{e}^{-1}} V_m + \frac{2\mathrm{e}^{-1}}{1+\mathrm{e}^{-1}} V_{\mathrm{thr}}$. or $E_m > V_m$

2(c)(ii)

$\vec{v} = \frac{1}{40} \sum_i r_i \vec{c}_i$