CCN assignment 1: How the brain represents space around the body (peri-personal space)

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1 Introduction

Deadline is Friday 14th 2020 at 4 pm (standard late policies apply). Please submit the pdf of your report to ITO using the command submit. Please name your document using yourname-assign1-ccn20.pdf. Please also submit the *paper copy* to ITO by the deadline or just after (it will be the time of the submit command that will matter).

Your report should look like a scientific report – no need to include any code. Report your findings. Particularly well-researched answers can receive additional points. Plots should always include axes labels and units. Figures should always have a caption and be referenced in the text. The presentation and format will count in the final mark. Be concise and precise in how you report your results. Don't include a million graphs: you can superimpose different graphs in the same plot. The maximum length for the report is **8 pages**.

Copying results is not allowed. It's OK to ask for help from your friends. However, this help must not extend to copying code or written text that your friend has written, or that you and your friend have written together. I assess you on the basis of what you are able to do by yourself. It's OK to help a friend. However, this help must not extend to providing your friend with code or written text. If you are found to have done so, a penalty will be assessed against you as well.

Email me (pseries@inf.ed.ac.uk) and Frank Karvelis (s1532046@sms.ed.ac.uk) the **Matlab script** that you used. We will not assess the programming style, but we might check them if results are unexpected. We will also run plagiarism detectors on them.

2 Background Information : what is the peri-personal space (PPS)?

This assignment explores a model of peri-personal space. The network that we are going to re-implement is described in the article of [Serino et al., 2015], which itself is inspired from [Magosso et al., 2010].

*Inspired by the work of Renato Paredes, Informatics MSc dissertation 2019

The brain encodes the space that surrounds the body to be able to interact with the environment. These space representations are split into regions according to their distance from the body: peri-personal space (PPS) (i.e. roughly the space reachable by hand) and extrapersonal space (EPS) (i.e. the space that cannot be reached by hand). This classification is supported by evidence of frontoparietal neurons of macaques and humans responding stronger to visual and auditory stimulation that occurs near the body. Maintaining a representation of the PPS is thought to allow animals to respond faster to stimuli near the body as a mechanism against threats from the environment. More recently, it has been proposed that PPS representation is crucial in the causal inference process involved in bodily self consciousness. In mental illness, such as schizophrenia, differences in how the PPS is represented are found [Di Cosmo et al., 2017] and might play a crucial role in the abnormal experiences of the self.

There are different ways to measure the PPS in behavioural experiments with humans. One way is to use an audio-tactile interaction task. Briefly, participants need to report when they feel an electric stimulation on their hand, while concurrent sounds are presented at different distances. It is found that the presence of sounds speed up the reaction time (RT) to the tactile stimulus only when they are administered within a limited distance from the hand. Such a protocol can be used to calculate the critical distance where sounds affect tactile RT, thus estimating the boundary of the PPS.

In this assignment, we reimplement the model of [Serino et al., 2015] to explore how peri-personal space is represented in the brain, and how differences in mental disorders could be accounted for. By doing so, you will learn how a relatively complex neural model of multi-sensory integration is constructed and can serve as a basis for forming new predictions related to mental illness and plasticity.

3 Neural model

The model is composed of two recurrently connected unisensory areas (auditory and tactile) interacting with one multisensory area, as shown in Figure 1. In the following the superscript t, a, m will indicate quantities referring to tactile auditory and multisensory neurons, respectively. The subscripts i, j or h, k will reprsent the spatial position of individual neurons.

3.1 Setting up the tactile and auditory (unisensory) neurons (15 points)

In this section, we start constructing the network by defining the receptive field of neurons in the tactile and auditory areas.

The tactile area is composed of an array of $(M_t = 40)$x$(N_t = 20) = 800$ neurons. The distance between the center of the receptive fields (RFs) of adjacent tactile neurons is 0.5 cm along both dimensions, so the array of neurons code for a portion of skin of 20 cm x 10 cm. The center of the RF of each neuron is thus $x_i^t = 0.5i$ cm and $y_j^t = 0.5j$ cm.

The auditory area is composed of an array of $(M_a = 20)$x$(N_a = 3)$=60 neurons. The distance between the center of the receptive fields (RFs) of adjacent auditory neurons is 10 cm along both dimensions, so the array of neurons code for a portion of space of 200 cm x 30 cm on and around the hand. If we consider a reference frame rigidly connected to the hand, the center of the RF of each neuron is thus $x_i^a = 10i - 5$ and $y_j^a = 10j - 15$ cm (the area corresponding to the hand is represented in 20 x 10 cm of the auditory space, see Figure 1).

The tactile and auditory stimuli $I^s(x,y,t)$ are described as Gaussian "blobs" in auditory and/or tactile space, i.e. a Gaussian function with amplitude I_0^s and spatial extension σ_I^s centered on x_o, y_o.[1]

$$I^s(x,y,t) = I_0^s \exp(-\frac{(x-x_o)^2 + (y-y_o)^2}{2\sigma_I^2}) \tag{1}$$

if $t \geq t_{o.}$where t_o is the time when the input is given, and where $s = t, a$. We will assume they are constant in time and last 200 msec.

The receptive field (RFs) of each unisensory neurons (which defines what portion of space each neuron is sensitive to) is also described by a Gaussian function. The RF of neuron i, j is described by:

$$\Phi_{ij}^s(x,y) = \Phi_0^s \cdot exp\left(-\frac{\left(x-x_i^s\right)^2 + \left(y-y_j^s\right)^2}{2\cdot\left(\sigma_\Phi^s\right)^2}\right), \qquad s = t, a \tag{2}$$

The input to each neuron is defined by the convolution between the input and the receptive field where we discretize the x and y domain:

$$\phi_{ij}^s(t) = \sum_l \sum_n \Phi_{ij}^s(x_l, y_n) I^s(x_l, y_n, t)\Delta x_l \Delta y_n \tag{3}$$

Here, Δx_l =Δy_n = 0.2 cm can be used. All other parameters can be found on Table 1.

- Implement and plot the input $\phi_{ij}^t(t)$ received by the tactile area neurons for a tactile stimulus placed at the center of the skin area ($x_0^t = 10, y_0^t = 5$). (5 points)
- Implement and plot the input $\phi_{ij}^a(t)$ received by the auditory area neurons when the auditory stimulus is at coordinates ($x_0^a = 100, y_0^a = 15$). (5 points)

3.2 Setting up the connections between neurons (15 points)

3.2.1 Lateral (recurrent) connectivity in the unisensory areas

Neurons in each unisensory area are all connected to each other symmetrically by lateral connections. The strength of the synaptic connections depends on their relative distance and follows a "Mexican-hat" function (i.e. neurons next to each other excite each other, neurons further apart inhibit each other). This function is here described by a difference between two Gaussian functions. We denote $L_{ij,kk}^s$ strength of the synaptic connection from the neuron at position hk to neuron at position ij. defined according to equation 4.

$$L_{ij,hk}^s = \begin{cases} L_{ex}^s \cdot exp\left(-\frac{(D_x^s)^2 + \left(D_y^s\right)^2}{2\cdot(\sigma_{ex}^s)^2}\right) - L_{in}^s \cdot exp\left(-\frac{(D_x^s)^2 + \left(D_y^s\right)^2}{2\cdot\left(\sigma_{in}^s\right)^2}\right), & ij \neq hk \\ 0, & ij = hk \end{cases} \tag{4}$$

D_x^s and D_y^s indicate the distances between the pre-synaptic neuron and the post-synaptic neurons along the horizontal and vertical axis of the unisensory area. The excitatory Gaussian function is defined by parameters L_{ex}^s and σ_{ex}^s, whereas the inhibitory is defined parameters by L_{in}^s and σ_{in}^s. The bottom line in equation 4 means that auto-excitation from one neuron to itself is not allowed.

[1]Unlike Serino et al (2015), we here ignore noise in the sensory input

- Implement those connectivity matrices. To verify that the implementation is correct, show the pattern of lateral connections from one neuron located in the center of the tactile area to the other neurons in this area. (7 points)

3.2.2 Setting up the feedforward and feedback connectivity with the multisensory area

The tactile and auditory areas are both connected to a multisensory neuron (Figure 1). The synaptic strength between the multisensory neuron and the unisensory neurons are different according to each modality. The weights of the synapses that connect the tactile neurons and the multisensory neuron are independent of the position of the neuron in the tactile area. W^t_{ij} and B^t_{ij} denote the weight of the feedforward and feeedback tactile synapses, we have:

$$W^t_{ij} = W^t_0 \tag{5}$$

$$B^t_{ij} = B^t_0 \tag{6}$$

In contrast, the weights of the synapses that connect the auditory neurons and the multisensory neuron depend on the distance that the auditory neurons encode relative to the hand: the synapses hold a constant weight for the space on and near the hand, covering 65 cm of the auditory space (20 cm for the hand and 45 cm for the space close to the hand). The synaptic weights outside this boundary ($Lim = 65$) are described by a bi-exponential function decreasing with the distance between the neurons' RF and the hand, as shown by Equations 8 and 7. W^a_{ij} and B^a_{ij} denote the weight of the feedforward and feeedback auditory synapses respectively

$$W^a_{ij} = \alpha \cdot W^a_0 \cdot exp\left(-\frac{D_{ij}}{k_1}\right) + (1-\alpha) \cdot W^a_0 \cdot exp\left(-\frac{D_{ij}}{k_2}\right) \tag{7}$$

$$B^a_{ij} = \alpha \cdot B^a_0 \cdot exp\left(-\frac{D_{ij}}{k_1}\right) + (1-\alpha) \cdot B^a_0 \cdot exp\left(-\frac{D_{ij}}{k_2}\right) \tag{8}$$

In both equations, the distance D_{ij} is equal to zero for the auditory neurons that encode the first 65 cm of the auditory space, whilst for the neurons outside this boundary D_{ij} is the Euclidean distance between the RF centre and the boundary. W^a_0 and B^a_0 denote the value of the feedback and feedforward synapses respectively when D_{ij} is equal to zero. k_1, k_2 and α are parameters governing the exponential decay of synaptic weights of auditory neurons encoding regions outside the near space of the hand.

- Implement these connectivities. Plot the feedforward and feedback weights between the auditory region and the multisensory neuron. (8 points)

3.3 Responses of neurons : putting everything together (25 points)

Unisensory neurons activity The output of each neuron z^s_{ij} is a continuous variable representing the neuron's firing rate. These quantities are defined in two steps. First, each neuron is defined by its dynamic state variable $q^s_{ij}(t)$:

$$\tau \frac{dq^s_{ij}(t)}{dt} = -q^s_{ij}(t) + u^s_{ij}(t), \qquad s = t, a \tag{9}$$

where τ is the time constant and $u_{ij}^{s}(t)$ denotes the overall input of a neuron at a given time step, i.e. the sum of the external stimulation received convolved with its RF, the recurrent input received from other neurons of its same area and the feedback input of the multisensory area (see below for the exact expression for $u_{ij}^{s}(t)$). Second, the rates z_{ij}^{s} are computed by passing the state variable $q_{ij}^{s}(t)$ rhrough a sigmoidal activation function F:

$$z_{ij}^{s}(t) = \left[F\left(q_{ij}^{s}(t)\right)\right]_{+}, \qquad s = t, a \tag{10}$$

$$F\left(q_{ij}^{s}(t)\right) = \frac{f_{min}^{s} + f_{max}^{s} \cdot e^{\left(q_{ij}^{s} - q_{c}^{s}\right) \cdot r^{s}}}{1 + e^{\left(q_{ij}^{s} - q_{c}^{s}\right) \cdot r^{s}}}, \qquad s = t, a \tag{11}$$

The notation [.]+ means that all negative values will be rectified to 0 (rates can't be negative). Here, f_{min}^{s} and f_{max}^{s} are the lower and upper boundaries of the sigmoid function, q_{c}^{s} is the central point of the sigmoid and r^{s} denotes the slope of the curve at the central point.

The inputs $u_{ij}^{s}(t)$ to each neuron are defined by:

$$u_{ij}^{s}(t) = \varphi_{ij}^{s} + I_{ij}^{s}(t) + b_{ij}^{s}(t), \qquad s = t, a \tag{12}$$

where φ_{ij}^{s} represents the external input (eq. 3), and the lateral inputs $I_{ij}^{s}(t)$ are defined by:

$$I_{ij}^{s} = \sum_{h=1}^{N^{s}} \sum_{k=1}^{M^{s}} L_{ij,hk}^{s} \cdot z_{hk}^{s}(t), \qquad s = t, a \tag{13}$$

The feedback input $b_{ij}^{s}(t)$ follows:

$$b_{ij}^{s}(t) = B_{ij}^{s} \cdot z^{m}(t), \qquad s = t, a \tag{14}$$

Multisensory unit activity The multisensory neuron activity is defined by an analogous set of equations:

$$\tau \frac{dq^{m}(t)}{dt} = -q^{m}(t) + u^{m}(t) \tag{15}$$

$$z^{m}(t) = \left[G\left(q^{m}(t)\right)\right]_{+} \tag{16}$$

where:

$$G\left(q^{m}(t)\right) = \frac{f_{min}^{m} + f_{max}^{m} \cdot e^{\left(q^{m} - q_{c}\right) \cdot r^{m}}}{1 + e^{\left(q^{m} - q_{c}\right) \cdot r^{m}}} \tag{17}$$

and the input $u^{m}(t)$ received by the multisensory neuron is composed of the sum of the feedforward inputs from both auditory and tactile areas, as presented in equation 18.

$$u^{m}(t) = \sum_{i=1}^{N^{t}} \sum_{j=1}^{M^{t}} W_{ij}^{t} \cdot z_{ij}^{t}(t) + \sum_{i=1}^{N^{a}} \sum_{j=1}^{M^{a}} W_{ij}^{a} \cdot z_{ij}^{a}(t) \tag{18}$$

- Using Euler integration method with a discrete time step of 0.4 ms, plot the response of the tactile area neurons for a tactile stimulus placed at the center of the skin area ($x_0^t = 10, y_0^t = 5$) at the last step of the simulation (stead-state), i.e. 200 msec after the tactile stimulus is shown (5 points)
- Plot the response of auditory area neurons when the auditory stimulus is at coordinates ($x_0^a = 100, y_0^a = 15$) at the last step of the simulation (5 points)
- By running simulations with different parameters for L_{ex} and L_{in}, comment on the role of the lateral connections in each unisensory area. (5 points)
- By running simulations with different parameters for the auditory stimulus location, comment on the role of the feedforward connection to the multisensory neuron. How does the activity of the multisensory neuron depend on the distance of the auditory stimulus? (5 points)
- Comment on the role of the feedback connections from the multisensory neurons. (5 points)

3.4 Influence of the distance of the auditory stimulus on the Reaction Times (RTs) (20 points)

The reaction times $RT^{90\%}$are defined as the time at which the tactile neurons reach 90% of their final (steady-state) activity. To obtain realistic values of RT in msec, we further use:

$$RT = 3RT^{90\%} + 60$$

The tactile stimuli is always applied at coordinate $x^t = 10$ cm and $y^t = 5$ cm. In contrast, the auditory stimuli is always applied at coordinate $\mathrm{y^a} = 5$ cm but the x^a coordinate changes across trials to simulate the presentation of the sound stimuli at different distances from the hand.

- Plot the activity of the multisensory neuron as a function of time, when the auditory stimulus is presented with $x^a = 19, 34, 55, 76, 91$ cm. (6 points)
- Plot the reaction times as a function of distance, when the auditory stimulus is presented with x^a varying from 10 to 110 cm in steps of 10 cm. (7 points)
- In experiments, the PPS boundary is defined as the central point of the sigmoidal function that best fits the RTs as a function of auditory stimulus distance, while the slope of that function captures how steep the boundary is. What would be the PPS boundary here? Explain how you obtain this number. (7 points)

3.5 Differences in mental illness (25 points)

In schizophrenia, it is found that the PPS are narrower, and the slope is sharper [Di Cosmo et al., 2017]. This is believed to play a crucial role in the abnormal experiences of the self observed in schizophrenia. Similar differences have been found in autism. The mechanisms explaining this are not clear but it has been proposed that they could be related to either an imbalance of excitation and inhibition (E/I) in unisensory neurons and/or an impairment of bottom-up and top-down connectivity between unisensory and multisensory neurons (i.e. a destruction of some connections, also called "pruning"). The first mechanism could be modelled either as a bias in the excitability of neurons (see for example [Hoffman et al., 1995, Hoffman and McGlashan, 2006]), or changes in the lateral weights (amplitude and/or spread of the "mexican-hat") in the unisensory areas. The second mechanism could be modelled by a systematic destruction of the weakest feedforward and/or feedback connections with the multisensory neuron (see e.g. [Hoffman and Dobscha, 1989]).

- Can you explain a change in the PPS center (a narrowing) and slope (steepening) by modifying the network according to one or several of these hypotheses? Explain how you implement the model(s), what changes could account for differences observed in schizophrenia and plot your results. What are the predictions of such model(s)?

3.6 Plasticity of the PPS with tool use (20 bonus points[2])

A critical property of the PPS representation is that it is dynamically modified through experience. Using a tool (e.g. a rake) to reach objects in the far space extends the boundaries of PPS representation. Taking inspiration from [Serino et al., 2015], explain qualitatively how this could possibly be accounted for in the network (5 points). Can you simulate it? (15 points).

References

[Di Cosmo et al., 2017] Di Cosmo, G., Costantini, M., Salone, A., Martinotti, G., Di Iorio, G., Di Giannantonio, M., and Ferri, F. (2017). Peripersonal space boundary in schizotypy and schizophrenia. *Schizophrenia research*, 197:589–590.

[Hoffman and McGlashan, 2006] Hoffman, R. and McGlashan, T. (2006). Using a speech perception neural network computer simulation to contrast neuroanatomic versus neuromodulatory models of auditory hallucinations. *Pharmacopsychiatry*, 39(S 1):54–64.

[Hoffman and Dobscha, 1989] Hoffman, R. E. and Dobscha, S. K. (1989). Cortical pruning and the development of schizophrenia: a computer model. *Schizophrenia bulletin*, 15(3):477–490.

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[Magosso et al., 2010] Magosso, E., Zavaglia, M., Serino, A., Di Pellegrino, G., and Ursino, M. (2010). Visuotactile representation of peripersonal space: a neural network study. *Neural computation*, 22(1):190–243.

[Serino et al., 2015] Serino, A., Canzoneri, E., Marzolla, M., Di Pellegrino, G., and Magosso, E. (2015). Extending peripersonal space representation without tool-use: evidence from a combined behavioral-computational approach. *Frontiers in behavioral neuroscience*, 9:4.

[2] This means your final mark will be counted out of 120%, but marks above 100%, if any, will be clipped at 100%.

Unisensory receptive fields			
$\phi_0^t = 1$	$\sigma_\phi^t = 1$	$\phi_0^a = 1$	$\sigma_\phi^a = 10$
External stimuli			
$I_0^t = 2.5$	$\sigma_I^t = 0.3$ cm	$I_0^a = 3.6$	$\sigma_I^a = 0.3$ cm
Lateral synapses in unisensory areas			
$L_{ex}^t = 0.15$	$L_{in}^t = 0.05$	$\sigma_{ex}^t = 1$ cm	$\sigma_{in}^t = 1$ cm
$L_{ex}^a = 0.15$	$L_{in}^a = 0.05$	$\sigma_{ex}^a = 20$ cm	$\sigma_{in}^a = 80$ cm
Feedforward and feedback synapses			
$W_0^t = 6.5$	$W_0^a = 6.5$	$B_0^t = 2.5$	$B_0^a = 2.5$
$k_1 = 15$ cm	$k_2 = 800$ cm	$\alpha = 0.9$	Lim = 65 cm
Input-output relationship of unisensory neurons			
f_{mim}^t = -0.12	$f_{max}^t = 1$	$q_c^t = 19.43$	r^t= 0.34
f_{mim}^a = -0.12	$f_{max}^a = 1$	$q_c^a = 19.43$	$r^a = 0.34$
$\tau = 20$ ms			
Input-output relationship of the multisensory neuron			
$f_{mim}^m = 0$	$f_{max}^m = 1$	$q_c^m = 12$	$r^m = 0.6$
$\tau = 20$ ms			

Table 1: Values of the model parameters.

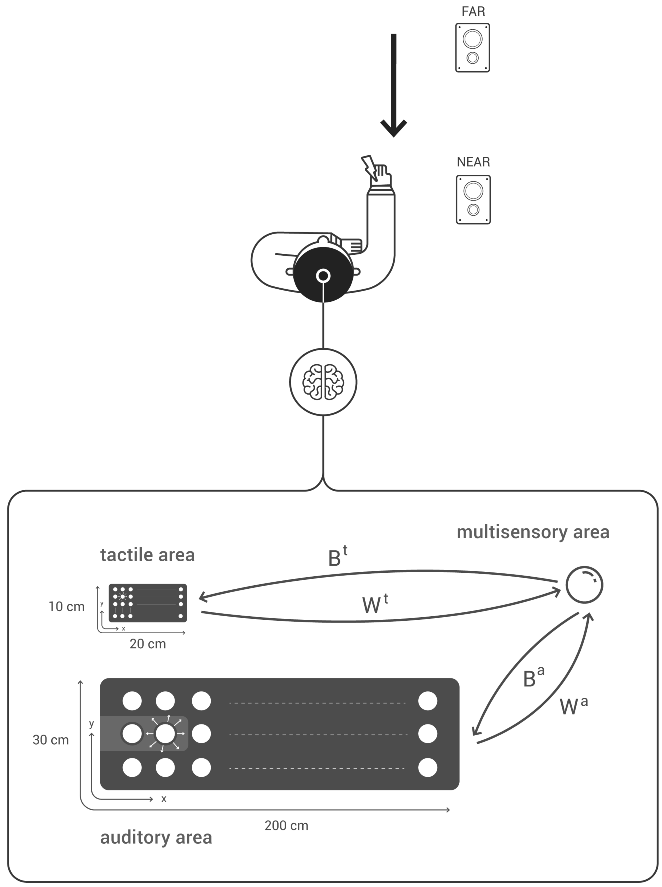

Figure 1: Audio-tactile experimental paradigm and model of PPS audio-tactile representation. In this experimental setup, two speakers are placed in front of the participant and an electrode is fit on his right hand. Sounds are presented at difference distances from the participant. At every trial, participants were required to respond as fast as possible to the tactile stimulation by pressing a button with their left index finger. The network model is composed of two unisensory areas (tactile and auditory) connected with a multisensory area. Each unisensory area is arranged according to a specific topological organisation to encode the external space.