Exploring the Interaction between Peri-Personal Space and Multisensory Integration through Computational Neural Modeling: A Study on the Impact of Mental Illness and Plasticity Use

Ahmed Al-Ali, *MSc. in Operational Research with Data Science,*

***Abstract*—Our study aims to investigate the interplay between peri-personal space and multisensory integration. In particular, we focus on determining the effects of stimulus applied at different locations on unisensory and multisensory responses and activities, as well as the lateral connections between unisensory areas and their influence on feed-forward and feed-back connections to the multisensory area. Furthermore, we aim to investigate the difference in reaction times due to the presence of mental illness and the use of plasticity.**

To answer those questions, we will mimic the brain processes involved in multisensory integration and peri-personal space using a computational neural model. By manipulating the model parameters, we will be able to examine how different factors impact the processing of sensory information and ultimately our perception of the world around us.

The findings of this study will help us better understand the intricate relationships between multisensory integration and peri-personal space, as well as the ramifications of those relationships for both healthy and clinical populations. In the end, our discoveries will have significant effects on improving the use of plasticity in people with brain injuries or diseases as well as the creation of more effective therapies for mental illness.

I. Introduction

THe human brain can integrate sensory information from multiple senses such as touch, hearing, and vision to form a coherent perception of the world. The peri-personal space surrounding the body is believed to play a role in this multi-sensory integration process, by integrating sensory information from different modalities and helping us understand the objects in our surroundings. The peri-personal space is represented by a network of sensory, motor, and higher-order cognitive areas in the brain, including the parietal cortex, premotor cortex, and inferior temporal cortex. This network helps guide our movements and interactions with objects in our environment, by integrating information about an object's texture, location, and appearance. The understanding of the peri-personal space network's role in multi-sensory integration and interaction with our surroundings is crucial, and further research in this area is expected to provide insights into the complex mechanisms of this integration in the human brain.

A. Background

Peri-personal space (PPS) and multisensory integration (MSI) are two critical components of sensory processing that are fundamental to how we interact with our surroundings. The complicated interactions between PPS and MSI, as well as how these interactions are affected by mental disorders like schizophrenia and autism, as well as the use of plasticity tools are all understood using computational neural modelling, which is a potent tool. The purpose of this article is to evaluate the effects of mental illness and plasticity tools on the interaction between PPS and MSI using computational neural modelling. By doing this, we seek to illuminate the fundamental processes underpinning sensory perception and pinpoint possible therapeutic targets for the management of mental illness. Peri-personal space (PPS) refers to the area surrounding the body that is within reach of the limbs, and is defined by both visual and somatosensory inputs. The process through which the brain mixes data from several sensory modalities to produce a cogent and significant perceptual experience is known as Multisensory integration (MSI). According to research, PPS and Multisensory integration work together to influence neuronal activity and guide behaviour. By selectively boosting or inhibiting neural responses to stimuli in many sensory modalities, PPS can alter multisensory integration, which in turn can affect behaviour.It has been demonstrated that this contact is essential for a number of functions, including reaching and grasping, planning movements, and even social interactions.

B. Postulate Statement

An essential component of cognitive neuroscience is the interaction between MSI and PPS. To know how these processes alter in the presence of mental illness and in the presence of plasticity, it is necessary to explore the interaction by the use of computational neural modelling to shed light on the underlying mechanisms of these processes and how they may be altered in people with mental illnesses like schizophrenia.To Explore how the stimuli applied at different locations with respect to the unisensory and multisenso ry responses and activities affect the lateral connections between the unisensory areas and how they influence the feedforward and feedbackward connections to the multisensory area. Additionally, we aim to investigate the impacts of mental illness and the use of plasticity on multisensory integration in the peri-personal space. We will use a computational neural model method, which enables the modelling of intricate neural networks and the analysis of their

dynamics, to accomplish these goals. We will employ a model that includes lateral connections within the unisensory areas as well as feedforward and feedbackward connections between unisensory and multisensory areas.We want to elucidate on the mechanisms behind multisensory integration and personal space perception by altering the placement of stimuli and examining the subsequent brain activity. Overall, this study has significant ramifications for our comprehension of the intricate relationships that exist between sensory integration and personal space. It may also pave the way for the creation of novel treatments for people who suffer from mental illness or other conditions that impair multisensory integration. We postulate that a narrower PPS representation in SCZ spectrum disorders is a result of an E/I imbalance in recurrent synapses among unisensory neurons. Moreover, we expect that PPS boundaries sharpening in SCZ may be explained in terms of an impairment of recurrent feed-forward and feed-backward connection between unisensory and multisensory neurons.

II. Literature Review

Computational modeling has been used to investigate the neural mechanisms underlying PPS and MSI, as well as their alterations in various neuropsychiatric disorders. One study by (Serino et al. ,2015) used a computational neural model to investigate the neural mechanisms underlying PPS representation in the brain. The model showed that PPS representation is mediated by both bottom-up and top-down processes, and that multisensory integration plays a key role in the formation of PPS representation. In terms of schizophrenia, several computational modeling studies have investigated the role of E/I (excitation/inhibition) imbalance and decreased synaptic density in the pathophysiology of the disorder. For example, a study by (Murray et al.,2014)used a biophysical neural network model to investigate the effects of decreased synaptic density in the prefrontal cortex on cognitive functioning in schizophrenia. The model showed that decreased synaptic density leads to a reduction in the ability to perform working memory tasks. Similarly, in autism, computational modeling studies have investigated the role of E/I imbalance in the disorder. A study by (Rubenstein and Merzenich, 2003) proposed that an imbalance between excitation and inhibition in the brain may underlie the pathophysiology of autism. The authors developed a computational model of the brain's cortical circuitry, which showed that an increase in excitation or a decrease in inhibition could lead to the behavioral and cognitive deficits seen in autism. Self-disturbances are seen as an early indicator of schizophrenia (Nelson et al., 2013), although it is unclear what brain processes underlie this characteristic. According to the predictive coding explanation, sensory attenuation issues brought on by incorrect Bayesian conclusions may be to blame for self-disturbances like thought insertions and external control (Fletcher and Frith, 2009). This theory, however, does not take into account recent theoretical and experimental developments in the research of human peri-personal space (PPS) representation, physical self-consciousness, and their possible effects on self-disturbances (Tsakiris et al., 2011). It is also uncertain whether particular brain mechanisms underlie the observed PPS representation in schizophrenia patients and others with schizotypal features (Farnè and Làdavas, 2002). There is a lack of a thorough justification for why the PPS is narrower and the limits are well defined in schizophrenia patients and those with schizotypal features (Martn-Rodrguez et al., 2017). Furthermore, it is not quite obvious why changes in both PPS and personal space are associated with worse schizophrenia symptoms (Häfner et al., 2005). It is still unclear what common brain defect in schizophrenia causes the changes to PPS, personal space, unpleasant symptoms, and social cognitive deficiencies (Oorschot et al., 2020). A limited and well defined PPS representation, a tendency for patients to exhibit bodily self-aberrations, and positive sensations linked to self-disturbances are all indicators of a shared faulty mechanism that are unknown (Vogeley and Kupke, 2007).

III. Proposed Method

A. Technical Backcgorund

Computational modeling is a useful tool in investigating the mechanisms underlying sensory processing and perception. In recent years, researchers have used computational modeling to study the neural basis of peri-personal space (PPS) representation, which plays a crucial role in the processing of sensory information and the regulation of bodily movements. One such model is the multisensory integration (MSI) model, which proposes that the PPS is represented by a set of multisensory neurons that integrate information from different sensory modalities, such as vision, touch, and audition (Farnè and Làdavas, 2002).

Computational modeling has also been used to study the neural basis of schizophrenia, a debilitating psychiatric disorder characterized by disturbances in perception, thought, and behavior. One prominent theory proposes that the imbalance of excitation (E) and inhibition (I) in cortical microcircuits may underlie the cognitive deficits observed in schizophrenia (Murray et al., 2014). This theory suggests that decreased synaptic density in the feedback and feedforward connections leads to a reduction in inhibitory activity, which in turn causes excessive excitation and destabilization of cortical networks. This imbalance of E/I is thought to contribute to the disorganization of sensory information processing and the emergence of positive symptoms, such as hallucinations and delusions (Nelson et al., 2013).

In plasticity use, the ability of the brain to change and adapt in response to experience, plays a crucial role in the development and maintenance of sensory processing and perception. Recent research has shown that plasticity can be harnessed to enhance peri-personal space (PPS) representation and multisensory integration (MSI) in both healthy individuals and those with sensory and cognitive impairments. For example, neurofeedback training, which involves giving real-time feedback on neural activity in the PPS network, has been shown to enhance PPS representation and improve multisensory integration in healthy adults (Kuehn et al., 2017).

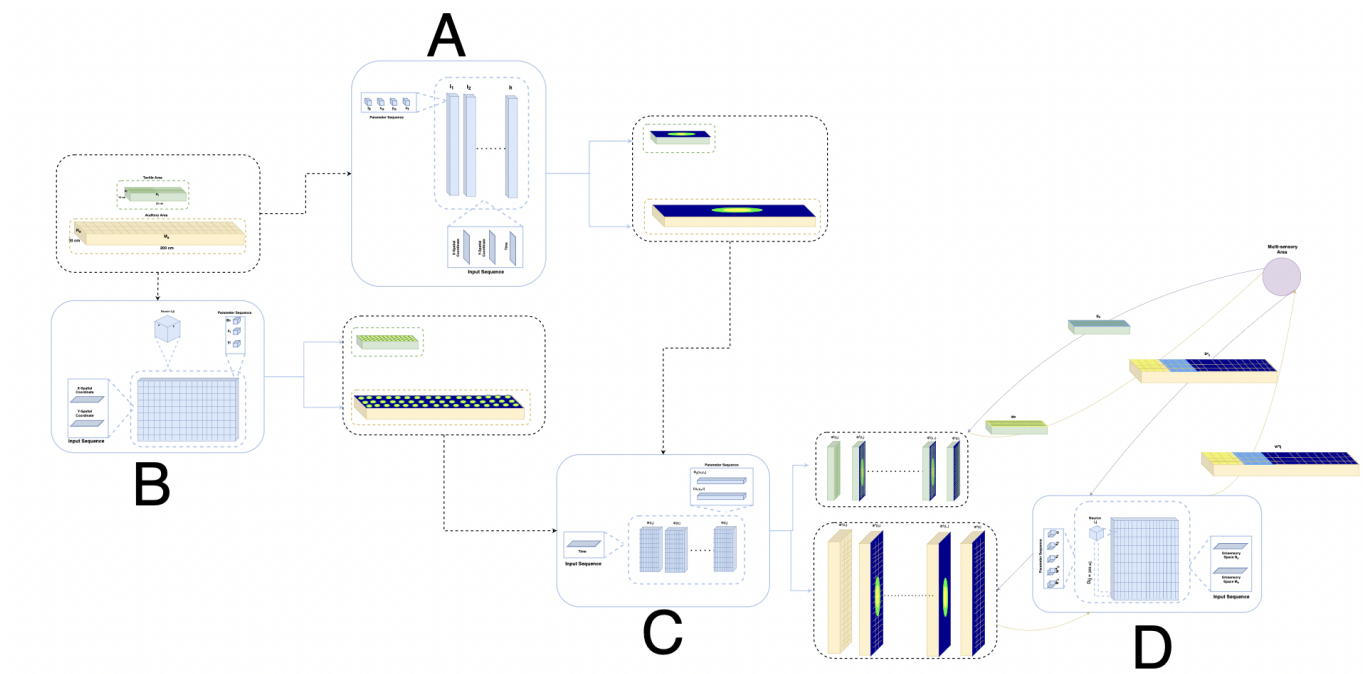


Fig. 1: PPS and MSI Model
Network Architecture

B. PPS Representation Neural Network Heuristics

The Network is composed of three main areas: the two recurrently connected unisensory areas for touch (tactile) and hearing (auditory) interacting with one multisensory area. Structure of each unisensory area is composed of dimensions of the encoded space, number of neurons in the space and the receptive fields (RF) centres, which refers to the specific area of a sensory receptor that is activated by a particular stimulus. The RF center can be thought of as the "center of attention" for a sensory receptor, as it is the location where the neuron is most responsive to.

1) ***Structure:*** In the unisensory area, the tactile space encodes to 20 cm by 10 cm skin portion encapsulating $(M_t = 40) * (N_t = 20) = 800$ Neurons. The receptive fields (RF) centres are defined by

$$x_i^t = 0.5i \;\; and \;\; y_i^t = 0.5j \;\; \forall\, i, j \in M_t, N_t \tag{1}$$

Similarly, the auditory space encodes to 200 cm by 30 cm skin portion encapsulating $(M_a = 20) * (N_a = 3) = 60$ Neurons.The receptive fields (RF) centres are defined by

$$x_i^a = 10i - 5 \;\; and \;\; y_i^a = 10j - 15 \;\; \forall\, i, j \in M_a, N_a \tag{2}$$

In the multisensory area it is composed of a single neuron that is connected to all neurons in both auditory and tactile areas.

The unisensory area receives input from the corresponding sensory modality (i.e., tactile for the tactile area, and auditory for the auditory area). The network considers two types of external stimuli: a visual stimulus and a tactile stimulus. The visual stimulus is presented in the form of a white Gaussian blob centered on the x-axis of the visual space, and the size of the stimulus is controlled by the standard deviation of the Gaussian distribution. The tactile stimulus is presented in the form of a rectangular pulse centered on the x-axis of the tactile space, and the size of the stimulus is controlled by the width of the rectangular pulse. Both stimuli are discretized on a grid of spatial coordinates, and their external input to the neural network is computed as a convolution with the receptive fields of the sensory areas.

2) ***Stimuli, Receptive Field and Input:*** In unisensory areas, the stimuli is what causes the spiking response of neurons, the centres of both auditory and tactile sensations were positioned at a particular coordinate in each unisensory area for the tactile and aduitory space, respectivley. As shown in Fig. 1, Part A.The equation below defines the input stimuli in which we seek to omit the random noise added to the stimulus intensity as opposed to the original approach (Serino et al. ,2015) to minimise unknown variability, beside that we adapted several parameters for Eq (3,4,5) listed in Appendix A.

$$I^s(x, y, t) = I_0^s exp(-\frac{(x - x_o)^2 - (y - y_o)^2}{2(\sigma_I^s)^2}) \;\; s = t, a \tag{3}$$

Relative to each sensory neuron, the measure of sensitivity to an external stimuli applied at (x_o, y_o).Which is modelled as two-dimensional Gaussian's known as Receptive Field (RFs) given in Eq (4). Illustrated in Fig. 1B.

$$\Phi_{ij}^s(x, y) = \Phi_0^s exp(-\frac{(x - x_i^s)^2 - (y - y_j^s)^2}{2(\sigma_\phi^s)^2}) \;\; s = t, a \tag{4}$$

The inputs to the unisensory areas are computed as the convolution between the external stimuli and the RFs given in Eq (5) of the corresponding area. The x and y domain are

discretized, and the convolution process involves integrating the product of the stimulus and the receptive field over the x-y plane, which results in a scalar value that represents the input to the neuron. Note that, The RFs play a crucial role in shaping the neural activity of the multisensory neurons, which is computed by integrating the inputs from both sensory areas. The neural activity is then used to drive the multisensory neuron that integrates the information from both sensory areas, enabling multisensory processing. As Shown in in Fig. 1C.

$$\Phi_{ij}^{s}(t) = \sum_{l}\sum_{n} \Phi_{ij}^{s}(x_l, y_n) I^{s}(x_l, y_n, t) \quad s = t, a \tag{5}$$

The input to each neuron is defined by the convolution between the stimulus and the receptive field. The x and y domain are discretized, and the convolution process involves integrating the product of the stimulus and the receptive field over the x-y plane, which results in a scalar value that represents the input to the neuron. Then the computation of the convolution is done using the discretized x and y values and the corresponding receptive field values for each x and y coordinate, which gives a map of the input to each neuron in the network. This process of computing the input to each neuron is essential for determining the neural activity in response to external stimuli and is a critical step in building a functioning network.

*3) **Synapses and Connections**:* Transmitting information from stimuli between the sensory neurons in the tactile and auditory areas is carried by the synaptic connections. The strength of the synaptic connections is determined by two different weight functions: the recurrent synaptic weight function ($L_{ij.hk}^{s}$) in each unisensory Area and the feedforward/feedback synaptic weight function (W_{ij}^{s}, B_{ij}^{s}) to the multisensory area.

$$L_{ij,hk}^{s} = \begin{cases} L_{ex}^{s} \cdot \exp\left(-\frac{(D_x^s)^2 + (D_y^s)^2}{2(\sigma_{ex}^s)^2}\right) - \\ L_{in}^{s} \cdot \exp\left(-\frac{(D_x^s)^2 + (D_y^s)^2}{2(\sigma_{in}^s)^2}\right) & , ij \neq hk \\ 0 & , ij = hk \end{cases} \tag{6}$$

The lateral (recurrent) connectivity in the unisensory areas allows the neurons to communicate with each other and send feedback signals $L_{ij.hk}^{s}$ calculates the recurrent synaptic weights in the tactile and auditory areas by taking into account the excitatory and inhibitory synapses' amplitudes and extensions in which neurons closer to a neuron tend to excite each other but further neurons tend to inhibit each other, which increases or decreases the synaptic strength along the unisensory areas space, give by Eq (6).

Feedforward and feedback connectivity between the multisensory neuron and the unisensory neurons is implemented as follows, the feedforward weight W_{ij}^{s} and the feedback weight B_{ij}^{s} are used to determine the synaptic weights for each connection. Together, these two types of connectivity facilitate the integration of multisensory information in the brain, allowing for more comprehensive and accurate perception of the environment.

$$\begin{aligned} W_{ij}^{t} &= W_0^{t} \\ B_{ij}^{t} &= B_0^{t} \end{aligned} \tag{7}$$

The weights of the synapses connecting the tactile neurons to the multisensory neuron are independent of the neuron's position in the tactile area given in Eq (7).

$$W_{ij}^{a} = \alpha \cdot W_0^{a} \cdot \exp\left(-\frac{D_{ij}}{k_1}\right) + (1-\alpha) \cdot W_0^{a} \cdot \exp\left(-\frac{D_{ij}}{k_2}\right) \tag{8}$$

$$B_{ij}^{a} = \alpha \cdot B_0^{a} \cdot \exp\left(-\frac{D_{ij}}{k_1}\right) + (1-\alpha) \cdot B_0^{a} \cdot \exp\left(-\frac{D_{ij}}{k_2}\right) \tag{9}$$

While the weights of the synapses connecting the auditory neurons to the multisensory neuron are dependent on the neuron's position in the auditory area, given by the bi-exponential functions given in Eq (8) and Eq (9). Parameters of the feedforward and feedback synapses and decay rates are defined in Appendix A. Illustrated in Fig. 1D.

*4) **Activity in Unisensory and Multisensory Areas**:* The output of each unisensory neuron is a continuous variable representing its firing rate. The firing rate is determined by the input that the neuron receives, which is defined by the convolution of the external stimulus with the neuron's receptive field. This input is then integrated over time and passed through a sigmoidal activation function to produce the firing rate. The sigmoidal function acts as a threshold, such that the neuron's firing rate increases rapidly once its input exceeds a certain threshold value. The firing rate is also modulated by lateral connections between neurons in the same unisensory area, which can facilitate or inhibit the activity of neighboring neurons. Overall, the firing rates of unisensory neurons reflect the processing of sensory information within a particular modality, and play an important role in the perception of the external world.

$$\tau \frac{dq_{ij}^{s}(t)}{dt} = -q_{ij}^{s}(t) + u_{ij}^{s}(t), \quad s = t, a \tag{10}$$

Unisensory neuron activity is defined by the dynamic state variable $q_{ij}^{s}(t)$, the time constant τ is used to describe the rate at which the state variable $q_{ij}^{s}(t)$ changes over time., which is a continuous variable representing the neuron's firing rate given in Eq (10).

$$I_{ij}^{s} = \sum_{h=1}^{N^s}\sum_{k=1}^{M^s} L_{ij,hk}^{s} \cdot z_{hk}^{s}(t), \quad s = t, a \tag{11}$$

$$b_{ij}^{s}(t) = B_{ij}^{s} \cdot z^{m}(t), \quad s = t, a \tag{12}$$

$$u_{ij}^{s}(t) = \varphi_{ij}^{s} + I_{ij}^{s}(t) + b_{ij}^{s}(t), \quad s = t, a \tag{13}$$

The lateral input $I_{ij}^{s}(t)$ given in Eq (11) is defined as the sum of the firing rates of other neurons in the same area, multiplied by their corresponding weights $L_{ij,hk}^{s}$. The feedback input $b_i^s j(t)$ given in Eq (12) is defined by the product of the feedback matrix $B_i^s j$ and the multisensory firing rate $z^m(t)$. The overall input $us_i j(t)$ to each neuron is the sum of the external input ϕ_{ij}^{s} given in Eq (5) , the lateral input, and the

feedback input.

$$z_{ij}^{s}(t) = \left[F\left(q_{ij}^{s}(t)\right)\right]_{+}, \quad s = t, a$$
$$F\left(q_{ij}^{s}(t)\right) = \frac{f_{\min}^{s} + f_{\max}^{s} \cdot e^{\left(q_{ij}^{s} - q_{c}^{s}\right)\cdot r^{s}}}{1 + e^{\left(q_{ij}^{s} - q_{c}^{s}\right)\cdot r^{s}}}, \quad s = t, a \tag{14}$$

The sigmoidal activation function $F(q_{ij}^{s}(t))$ is applied to the state variable $q_{ij}^{s}(t)$ to compute the firing rate of the neuron $z_{ij}^{s}(t)$, with f_{min}^{s} and f_{max}^{s} representing the lower and upper boundaries of the sigmoid function, q_{c}^{s} representing the central point of the sigmoid, and r^{s} representing the slope of the curve at the central point, the notation [·]+ means that all negative values will be rectified to 0, as firing rates can't be negative. Paraemters og given equations are found in Appendix A.

Multisensory neuron activity is defined by the dynamic state variable $q^{m}(t)$, which represents the neuron's firing rate.

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

The time constant τ is used to describe the rate at which the state variable $q^{m}(t)$ changes over time, and the input from the unisensory areas as $u^{m}(t)$ give in Eq(15).

$$z^{m}(t) = \left[G\left(q^{m}(t)\right)\right]_{+}$$
$$F\left(q^{m}(t)\right) = \frac{f_{\min}^{m} + f_{\max}^{m} \cdot e^{(q^{m} - q_{c}^{m})\cdot r^{m}}}{1 + e^{(q^{m} - q_{c}^{m})\cdot r^{m}}} \tag{16}$$

The sigmoidal function $G(q^{m}(t))$ is used to transform the state variable $q^{m}(t)$ into the firing rate $z^{m}(t)$ of the multisensory neuron, with the lower and upper boundaries of the sigmoid function represented by $f_{m}^{m}in$ and $f_{m}^{m}ax$, the central point of the sigmoid represented by q_{c}^{m}, and the slope of the curve at the central point represented by r^{m}.

$$z_{ij}^{s}(t) = \left[F\left(q_{ij}^{s}(t)\right)\right]_{+}, \quad s = t, a$$
$$F\left(q_{ij}^{s}(t)\right) = \frac{f_{\min}^{s} + f_{\max}^{s} \cdot e^{\left(q_{ij}^{s} - q_{c}^{s}\right)\cdot r^{s}}}{1 + e^{\left(q_{ij}^{s} - q_{c}^{s}\right)\cdot r^{s}}}, \quad s = t, a \tag{17}$$

The feedforward input $I_{m}^{a}(t)$ from the auditory area and the feedforward input $I_{m}^{t}(t)$ from the tactile area are defined as the sum of the firing rates of the neurons in the corresponding area, multiplied by their corresponding weights defined as the overall feedforward input $u^{m}(t)$ to the multisensory neuron is the sum of the feedforward inputs from both the auditory and tactile areas. as given in Eq (17).

C. Modelling of Schizophrenia Network Heuristics

To modify the network to account for changes in schizophrenia , we can consider an impairment of bottom-up and top-down connectivity between unisensory and multisensory neurons, Which corresponds to the the feed-forward (W) and feed-backward (B) connectivity. To model the mechanism, we can systematically destroy the weakest feedforward and feedback connections with the multisensory neuron. To implement this, we can randomly remove a certain percentage of the weakest feedforward and feedback connections to the multisensory neuron during the connection forming of the network. The percentage can be varied to see the effect on the model.

Let $K_{i,j}^{s}$ be the weight of neuron (i,j) in the unisensory area. Then a modified weight, $K^{s\prime}{}_{i,j}$, can be given by:

$$K^{s\prime}{}_{i,j} = K_{i,j}^{s} * M_{i,j}, \quad s = t, a \quad k = W, B \tag{18}$$

where $M_{i,j}$ is a binary mask that the weight is under a certain level then 0 if the weight is above then 1 and it should be kept. This is a modified version of the original mechanism called pruning mechanism as introduced by (Hoffman and Dobscha et al., 1989)

D. Modelling Use of Plasticity Network Heuristics

The PPS representation, according to (Serino et al. ,2015), is dynamically altered by experience, and utilising a tool to access objects in a distant region expands the PPS representation's bounds. The weights of the connections between the multisensory and unisensory neurons can be adjusted in the network to accommodate for this depending on the tool being used. The borders of the PPS representation grow when a tool is used to reach distant objects, hence the weights of the synapses between the auditory neurons and the multisensory neuron must be adjusted to reflect this expansion. The synapses corresponding to the area near the hand will be heavier than those related to the area distant from the hand. To simulate the dynamic modification of the PPS representation through experience, we can modify the weights of the synapses between the auditory neurons and the multisensory neuron based on the use of a tool. This can be done by introducing a tool to the network and simulating the effect of the tool on the network's responses. Specifically, we can modify the weights of the synapses based on the distance of the tool from the hand. When the tool is close to the hand, the synapses corresponding to the space close to the hand will have a stronger weight, while the synapses corresponding to the space far from the hand will have a weaker weight. This will mimic the PPS representation's borders expanding as a result of employing a tool to reach things in distant space.

We introduce a Hebbian learning rule that modifies the strength of the connections between the unisensory neurons and the multisensory area based on the correlation between their responses. Specifically, the strength of the feedforward connection from unisensory neuron (i,j) to multisensory area can be modified as follows:

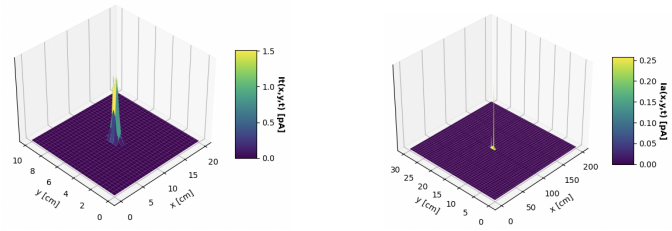
$$K_{ij}^{s}(t+1) = K_{ij}^{s}(t) + (\eta * \frac{z_{ij}^{s}(t)}{z^{m}(t)}) \quad s = t, a \quad k = W, B \tag{19}$$

where K_{ij}^{s} is the strength of the connection from neuron (i,j) at time t, η is a learning rate, $z_{i,j}^{s}(t)$ is the response of neuron (i,j) at time t, and $z^{m}(t)$ is the response of multisensory area at time t.

IV. Experimentation

A. Experimental Settings

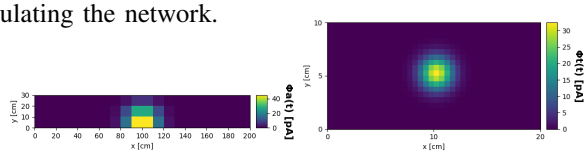
*1) **External Stimuli and Input**:* The external stimuli and input used in this study were based on previous experimental studies. These settings were chosen to simulate realistic external sensory stimuli and input to the neural field model, allowing for a more accurate simulation of neural activity in response



(a) Tactile (b) Auditory

Fig. 2: External Stimuli
Applied to Unisensory Areas

The center of each stimulus was placed at a specific coordinate in the corresponding unisensory area, shown in Fig. 2 the tactile and auditory stimuli on each area with the gradient being shown, tactile external stimuli ranges from (0-0.25) pA Unlike and the auditory ranges from (0-1.5) pA the original implementation, which included random noise in the stimulus intensity and resulted in unexplained network variability, we chose to exclude this element. Although in the original implementation by (Serino et. al,2015) external stimulus were low, we ought to increase them to increase the responses when simulating the network.

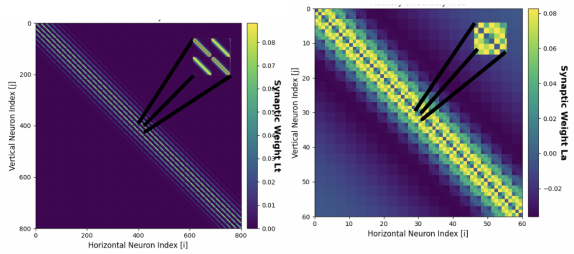


(a) Tactile (b) Auditory

Fig. 3: External Input
Received by Unisensory Areas

The External Input is the measure that neurons receive based on their RF centres in each unisensory area shown in Fig 3, the external input for tactile and auditroy areas ranges in (0-40) pA and (0-30) pA, resepcitvley.

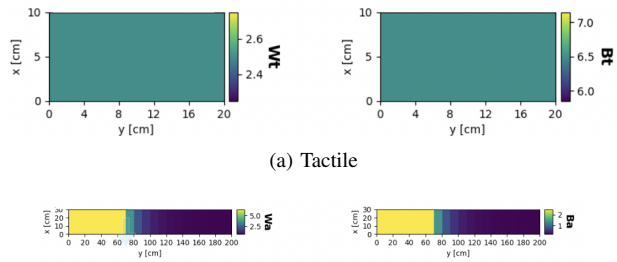
*2) **Synaptic Connectivity** :* The design aims to capture the observation that a multisensory stimulus reinforces the perception of unimodal stimuli in unisensory areas. Consequently, the synapses retain a constant weight for the space on and near the hand, which covers 65 cm of the auditory space (20 cm for the hand and 45 cm for the area near the hand).



(a) Tactile (b) Auditory

Fig. 4: Lateral Connections
in Unisensory Areas

In the tactile area, (Serino et al. ,2015) reported a ”Mexican hat” pattern of lateral connections, where neighboring neurons excite each other and more distant neurons inhibit each other. This is consistent with the patterns found as shown in Fig 4, it specifies the synaptic strength between neuron i to neuron j, where there is a repeating pattern of synaptic weights around each neuron, and the weights decrease as you move outward, the range of synaptic weights (0.00-0.08) also is in the same order of magnitude as the synaptic weights reported in the paper. In the auditory area, (Serino et al. ,2015) reported a ”center-surround” pattern of lateral connections, where neurons within a certain distance of the center neuron excite it, and neurons further away inhibit it. This is consistent with the diagonal pattern of zero weights we found described, where neurons that are further away have lower weights. We found that there were stronger connections between the tactile and multisensory areas compared to the auditory and multisensory areas, and that the strength of these connections decreased with distance from the hand in the auditory area. Similarly, in (Serino et. al,2015) model, the feedforward and feedback weights between the tactile area and multisensory neuron are both constant, while the weights between the auditory area and multisensory neuron decrease with distance from the hand.



(a) Tactile

(b) Auditory

Fig. 5: Forward and Backward Connections

We found that there were stronger connections between the tactile and multisensory areas compared to the auditory and multisensory areas, and that the strength of these connections decreased with distance from the hand in the auditory area. Similarly, in your model, the feedforward and feedback weights between the tactile area and multisensory neuron are both constant and strong, while the weights between the auditory area and multisensory neuron decrease with distance from the hand.

B. Experimental Simulations

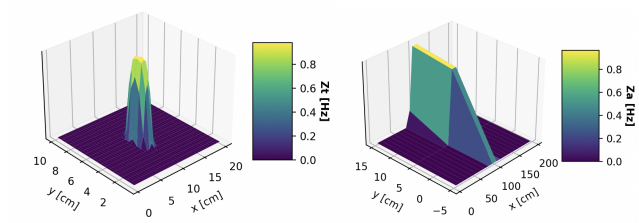
Simulations will run for a total of t = 400 ms , with a time step of 0.4 ms. External stimulus will be applied t = 100 ms, which will last for t = 200 ms. Consequently, any time below t = 100 ms or over t = 300 ms will receive zero external stimulus. The experimental setup was first evaluated using unisensory auditory and unisensory tactile simulations independently to examine the effects of the experimental settings within each unisensory area and between multisesnory area , followed by integrating it with the audio-tactile experiment, similar to the original implementation (Serino et al., 2015). The external stimuli was stimulated onto the unisensory areas at $x_0^t = 10cm$ and $y_0^t = 5\ cm$ for the tactile area , $x_0^a = 100\ cm$ and

$y_0^a = 15\ cm$ for the auditory area independent trials, and $x_0^a = \#\ cm$ and $y_0^a = 5\ cm$, when simulating the (audio-tactile) simulation trial.

V. Analysis

A. Unisensory Areas Simulations

1) ***Response to External Stimuli:*** After applying an external stimuli neurons mechanisms and settings mentioned previously come into action where the recurrent connectivity's and the Input received interweave to produce the resposne.

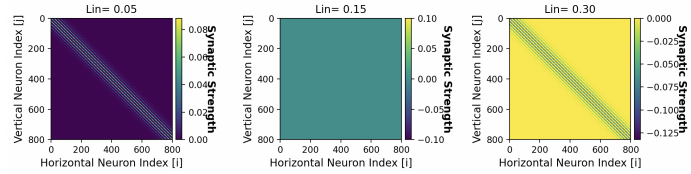


(a) Tactile Area (b) Auditory Area

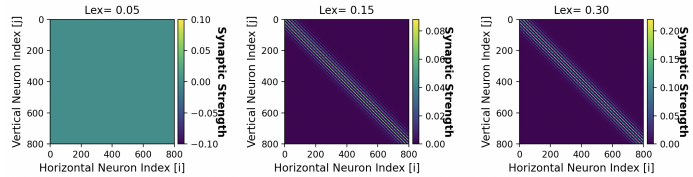
Fig. 6: Response at Steady State t = 300 ms

In their paper (Serino et. al, 2015), they found that the response of unisensory areas neurons to the respective stimulius was strongest in the vicinity of the stimulated area, which is consistent with Fig.6 For the tactile area the highest response is observed at the location of the stimulus, and the response decreases gradually with increasing distance from the stimulus. For the auditory area responses near the center of the auditory stimulus were the highest and a decrease in response towards the edges however, our response pattern is complex and included multiple peaks and troughs, which is in alignment with their observation. this is due to the neural connectivity structure being in a "Mexican hat" pattern as opposed to "Central surrounded" pattern for the tactile area, as in Fig.4 .

2) ***Influence of Excitation and Inhibitory Parameters of lateral connections on Unisensory Areas:*** The lateral connections connect to lateral inputs, which then connect to sending responses based on these values. The lateral connections and inputs provide a feedback mechanism that modulates the response of the neurons. To investigate the affects of L_{in} and L_{ex} parameters we ran a sensitivity analysis to determine what affects the parameters have on Synaptic weight of lateral connections , Lateral Inputs and Response. It's worth noting that we are isolating the effect of each stimulus by setting the parameters related to the other space to zero. This will allow us to focus specifically on the response of the intended area and observe how the lateral connections contribute to the processing of each unisensory area information.



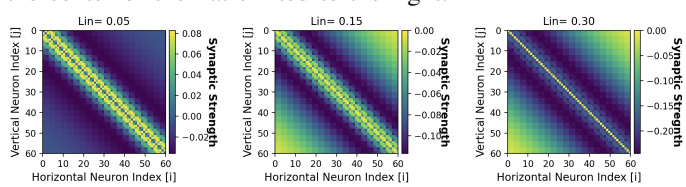
(a) Fixed Lex = 0.15



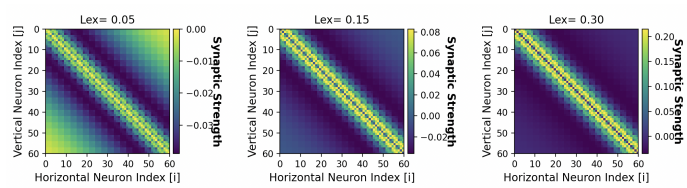
(b) Fixed Lin = 0.05

Fig. 7: Tactile Lateral Connections

As shown in Fig. 7, When we iterate through values of L_{in} and L_{ex}, we observe different lateral connectivity measures. If both parameters match we get a net zero of synaptic strength which means that lateral connections inhibit responses in transmitting the input , if $L_{ex} > L_{in}$ excitatory connections dominate leading to an net-increase in neural activity between neurons and it amplifies as we increase L_{ex}, but if $L_{in} > L_{ex}$ inhibitory connections dominate leading to a net-decrease in neural activity and it amplifies as we increase L_{in}. Increasing the value of L_{ex} (with L_{in} held constant) leads to an increase in the strength of lateral connections between neurons, resulting in a Mexican hat-shaped pattern of synaptic strength. Similarly, increasing L_{in} (with L_{ex} held constant) also leads to a Mexican hat-shaped pattern of synaptic strength, but with the center of the hat shifted to the right.



(a) Fixed Lex = 0.15

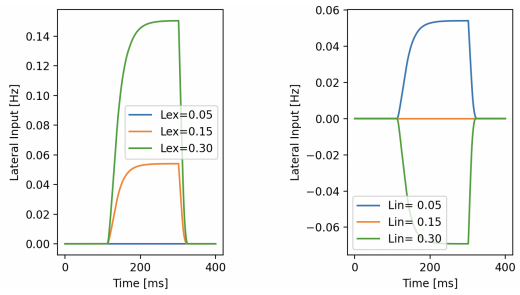


(b) Fixed Lin = 0.05

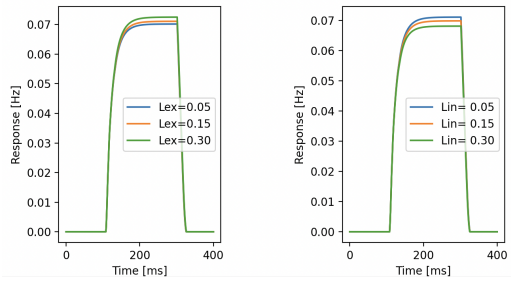
Fig. 8: Auditory Lateral Connections

As shown in Fig. 8, When we iterate through values of L_{in} and L_{ex}, we observe different lateral connectivity measures. If both parameters match we get a net-decrease in synaptic strength which means that neurons far-away dominant inhibitory connections,if $L_{ex} > L_{in}$ synaptic strength is zero at the center then increases between the central and near-surroundings neuron and then decreases for neurons far away from center, exciting the response of the neurons note that the strength amplifies as we increase L_{ex}. But if $L_{in} \geq L_{ex}$ inhibitory connections dominate leading to a net-decrease in neural activity even between the central neurons and near-surrounding neurons.increasing L_{ex} (with L_{in} held constant)

leads to a Mexican hat-shaped pattern of synaptic strength, but with a negative value at the center of the hat. Similarly, increasing Lin (with L_{ex} held constant) also leads to a Mexican hat-shaped pattern of synaptic strength, but with a negative value in the surround.



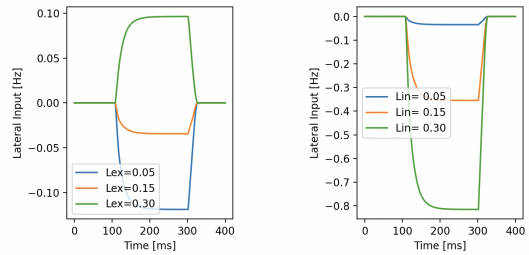
(a) Lateral Inputs



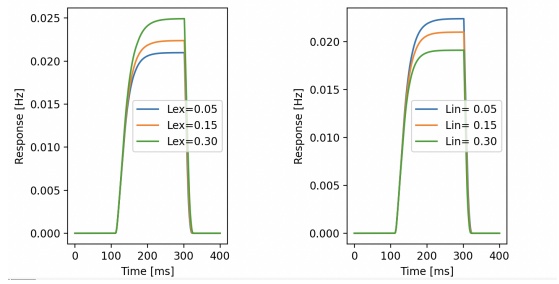
(b) Tactile Response

Fig. 9: Effects on Tactile Area

The increase in steady-state response with increasing L_{ex} is consistent with the idea that increasing the lateral excitatory connections enhances the spatial summation of input signals, leading to an increase in neural activity, as shown in Fig. 9. This trend is also observed in the lateral inputs to neurons, where an increase in L_{ex} leads to an increase in lateral input strength. The trend observed in response and lateral input strength with increasing L_{in} is a bit more complex. The increase in steady-state response with increasing L_{in} suggests that the inhibitory lateral connections are playing a role in shaping neural activity by limiting the spatial summation of input signals. The negative values observed in the synaptic strengths for some neurons when $L_{in} = 0.3$ indicate that the inhibitory connections are dominating the excitatory connections, leading to a net decrease in neural activity. This effect is also reflected in the negative steady-state response and lateral input strength observed. Additionally, the increase in steady-state response with increasing L_{ex} is consistent with the idea that increasing the lateral excitatory connections enhances the spatial summation of input signals, leading to an increase in neural activity. The study's findings also suggest that inhibitory lateral connections play a critical role in limiting the spatial summation of input signals, leading to a decrease in neural activity, as per (Serino et. al, 2015).



(a) Lateral Inputs



(b) Auditory Response

Fig. 10: Effects on Auditory Area

As shown in Fig. 10, Both L_{ex} and L_{in} have an effect on the steady-state firing rate of the neurons in the auditory area, with higher values of L_{ex}(with $L_{in} = 0.05$ held constant) leading to a higher steady-state firing, and vice versa for L_{in}(with $L_{ex} = 0.15$ held constant). However, the effect is more pronounced for L_{in} than for L_{ex}. While in comparison the effects are more complex for the lateral inputs when $L_{in} = 0.05$ is held constant, adn L_{ex} increases from 0.05 to 0.30 we can observe that the Lateral Input to each neuron increases this translates to that when further neurons attain a higher excitatory values the response transmitted amplifies rather than being inhibited by nearby neurons.

*3) **Influence of Stimulus Location on Feed-forward connection to Multisnesory Activity**:* The feedforward connection for auditory stimuli appears to play a crucial role in the delivery of multisensory activity in the unisensory area. However, the strength and timing of this connection are location-dependent, and this could explain the different patterns and values of feedforward inputs and response observed in the simulations.

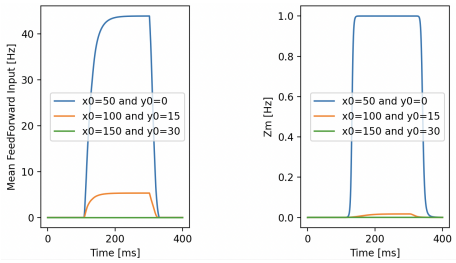
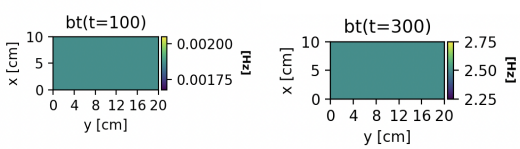


Fig. 11: Effects of Distance on FeedBack from Auditory Area

As shown in Fig. 11, the feedforward connection for auditory stimuli appears to play a crucial role in the delivery of multisensory activity in the unisensory area. However, the strength and timing of this connection are location-dependent, and this could explain the different patterns and values of feedforward inputs and response observed in the simulations.The mean feedforward input for the auditory

stimuli at $x = 50\ cm$ and $y = 5\ cm$ and $x = 100\ cm$ and $y = 15$ showed a similar pattern, with a rise in input from (0-45)ms and a steady state from (190-315)ms. On the other hand, the mean feedforward input for the auditory stimulus at $x = 150\ cm$ and $y = 30\ cm$ was zero for the entire duration of the simulation. This suggests that the feedforward connection for auditory stimuli may not be as dependent on the location of the stimulus as the feedforward connection for tactile stimuli.An empirical hypothesis suggests that the multisensory area integrates information based on the proximity of the stimuli from different modalities. Simulation results confirm that multisensory neural activity depends on both the auditory and tactile stimuli location. Multisensory activity is higher when the auditory stimulus is closer to the tactile stimulus location, possibly due to stronger and temporally aligned feedforward connections. These simulation results are consistent with the findings of (Serino et al. ,2015) who showed that the multisensory evoked potential amplitude is larger for stimuli presented in close spatial proximity. The MEP amplitude decreases as the distance between the stimuli increases, supporting the hypothesis that multisensory integration depends on the proximity of the stimuli. The results highlight the complex interplay between different sensory modalities in the brain and suggest that the multisensory area integrates information based on factors such as stimulus location and proximity.

*4) **Influence on Multisensory Area by Isolated Weights of Feedback Connections** :* Observing the mapping of the feedback inputs from the Multisensory area to each isolated unisensory area over the



(a) Start of Simulation (b) End of Simulation

Fig. 12: Feedback Inputs to Tactile Area

The feedback inputs to the multisensory area in response to the tactile stimulus as shown in Fig. 12 are uniform and relatively low (0.0019 Hz at t=100ms and 2.2 Hz at t=300ms), suggesting that the multisensory area is not receiving much information from the tactile area through feedback connections. This is in contrast to the relatively high feedforward inputs from the tactile area to the multisensory area, which suggests that most of the information flow between these areas is through feedforward connections.

(a) Start of Simulation (b) End of Simulation

Fig. 13: Feedback Inputs to Auditory Area

For the auditory area as shown in Fig. 13, the feedback inputs are more complex, with a range of values from 0.0005 to 0.0015 Hz at t=100ms. The highest values are found in the enclosed space of x=0-7 and y=0-10, suggesting that the feedback connections from the multisensory area are strongest in this region. At t=300ms, the feedback inputs are higher and more uniform (1-2 Hz) across x for all y values, indicating that the multisensory area is receiving more information from the auditory area through feedback connections at this time.
These results suggest that the feedback connections from the multisensory area to the unisensory areas are not uniform and can vary depending on the location of the stimulus. This is consistent with the findings of (Serino et al. ,2015), which showed that feedback from the multisensory area to the unisensory areas is strongest for stimuli located in the peripersonal space. Overall, the results suggest that the feedback connections play a role in modulating the inputs to the multisensory area, with stronger feedback inputs in regions where stimuli are located in the peripersonal space. This is consistent with the idea that the multisensory area is involved in integrating information from the different sensory modalities to provide a coherent representation of the external world within the peripersonal space.

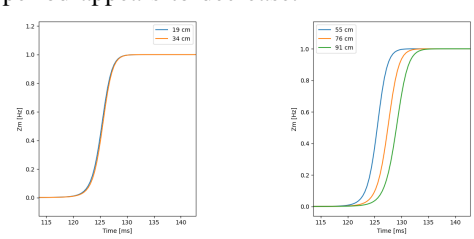
B. Audio-Tactile Simulations

The reaction rate is defined as $RT^{90\%}$ 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 ms, we further use:

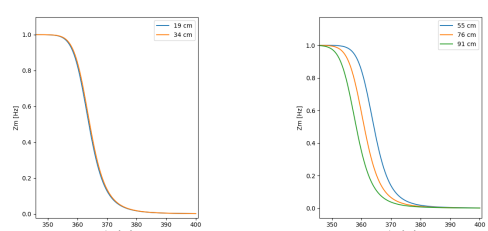
$$RT = 3RT^{90\%} + 60 \tag{20}$$

Being said we studied the isolated affects of each unisensory area we now divulge into the whole model interaction as illustrated in Fig. 2.

*1) **Influence of Auditory Stimulus Location on Multisensory Activity**:* The distance of the auditory stimulus location appears to have an effect on the multisensory area activity. As the distance increases, the time at which the response reaches its peak (steady-state) increases, and the duration of the steady-state period appears to decrease.



(a) Rising Slope



(b) Falling Slope

Fig. 14: Effect of Auditory Stimuli Location

Looking at the rising and falling slopes in Fig. 14, it seems that they are relatively consistent across the different

distances, with a rise time of around $7-9ms$ and a fall time of around $26-28ms$. However, the duration of the steady-state period appears to decrease with increasing distance, with the response staying at 1 Hz for approximately 226-223 ms for $xa = 19-55cm$, but only $208-219ms$for $xa = 76-91cm$. Comparing these results to (Serino et al. ,2015), it appears that the rising and falling slopes of the multisensory area activity are consistent with the findings reported in that study. However, the duration of the steady-state period in the current results is somewhat shorter than that reported by (Serino et al. ,2015), who found that the multisensory response remained elevated for approximately 300-400 ms. This difference is due to differences in the experimental setup or model parameters used in the two studies. Furthermore, notice that there are some delay's in raising multisensory activity for different distances, this could be due to the time it takes for the auditory stimulus to reach the hand at different distances. As the distance between the hand and the auditory stimulus increases, the sound wave has to travel a greater distance and therefore takes longer to reach the hand. This delay in the arrival of the auditory input to the multisensory area could explain the delayed rise in multisensory activity observed in the experiment for greater distances.

*2) **Influence of Auditory Stimulus Location on Reaction Times**:* One possible explanation for this is that it relates to the processing of multisensory information in the brain. As the distance of the auditory stimulus increases, there may be a delay in the integration of the auditory and tactile signals, resulting in slower reaction times. On the other hand, if the auditory stimulus is too close to the hand, there may be interference between the two stimuli, resulting in slower reaction times.There is an optimal window for multisensory integration, where the auditory and tactile signals are integrated most efficiently to produce the fastest reaction times. This window may be influenced by factors such as the distance between the stimuli and the timing of their presentation. This is consistent with the findings of (Serino et al. ,2015), who found that there is an optimal temporal window for multisensory integration that varies with the distance between the stimuli.

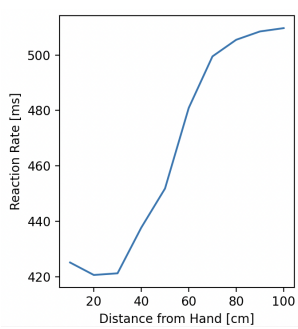


Fig. 15: Effects of Auditory Stimuli on Reaction Rates

The s-curve shape of the plot as given above in Fig. 15, suggests that there is an optimal distance for the auditory stimulus to maximize the reaction time, with both shorter and longer distances resulting in slower reaction times. The fastest reaction time was at a distance of about 30cm, and the slowest was at a distance of about 100cm.

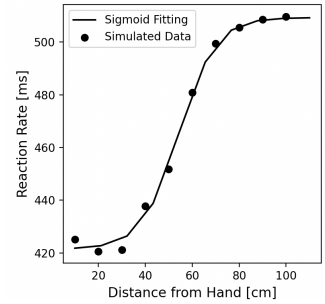


Fig. 16: Sigmoidal Fitting to Reaction Rates

In this study, we investigated the relationship between the perception of the (PPS) and multisensory integration. We found that the PPS boundary was located at a distance of 54.32 cm from the hand, with a slope of 7.82 ms/cm. To obtain these values, we fitted a sigmoidal function given by:

$$\frac{a}{1+e^{\frac{-(x-b)}{c}}}+d \tag{21}$$

where a and d are the minimum and maximum values of the reaction rate, x is the distance, b and c are the central point e.g."PPS Boundary" and slope, respectively. To fit the reaction times as a function of auditory stimulus distance, using the initial guesses of [1000, 50, 10, 450] and a bound of search from zero to infinity for all parameters. The resulting function had a sigmoidal shape, with an inflection point at the PPS boundary and a steep slope that represents the sensitivity to changes in auditory distance. We hypothesize that this behavior is due to the integration of auditory and tactile information in the multisensory area of the brain, leading to the perception of the PPS. Our findings are consistent with previous studies that have shown the importance of multisensory integration in the perception of the PPS, including the work of (Serino et al. ,2015)

VI. Results

A. Study of Schizophrenia

The pruning mechanism implemented in the auditory unisensory area affected the weights between neurons and the multisensory area in interesting ways. The weights between neurons in the auditory unisensory area were affected such that the weakest connections were systematically destroyed, resulting in an exponential decrease in the weights. The weight pruning affected information sending and retrieval between neurons in the auditory unisensory area and the multisensory area. The pruning caused a reduction in the number of inputs received by the multisensory neuron, which in turn affected the firing rate of the multisensory neuron. A possible hypothesis for this behavior is that the pruning mechanism allowed the multisensory neuron to selectively receive the most salient inputs from the auditory unisensory area, leading to enhanced multisensory processing.

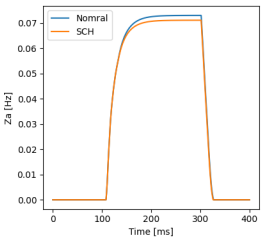


Fig. 17: Pruning Affect on Response of Auditory Area

The findings as shown in Fig. 17, suggest that the pruning mechanism implemented in the auditory unisensory area may have affected the neural response of the auditory neurons in the multisensory area. The decrease in steady-state level of the response in the schizophrenia patients compared to normal patients could be attributed to the pruning of the weakest feed-forward and feedback connections in the auditory unisensory area. This pruning may have resulted in a reduction of the information that is being sent and retrieved between neurons in the auditory unisensory area and the multisensory area. This reduction in information could have led to a decrease in the neural response of the auditory neurons in the multisensory area.

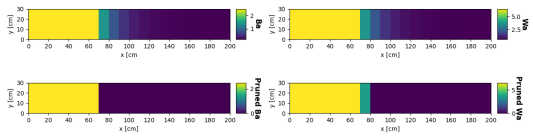


Fig. 18: Pruning Affect on Synaptic Weights of Auditory Area

Pruning of the feedback and feedforward weights in the area has a significant impact on the transmission of information between neurons and the multisensory area. In the implementation, the weights were pruned systematically, and the highest weights were found to be concentrated in a specific region of the auditory unisensory area. The exponential decrease of the weights beyond this region suggests that the neurons in this area might have a higher degree of connectivity, which could result in a more effective transmission of information. Pruning the weaker connections results in a reduced flow of information from the unisensory area to the multisensory area, which might affect the multisensory integration process. A possible hypothesis is that pruning the weaker connections could result in a more efficient information transfer between the unisensory and multisensory areas, leading to an improvement in the multisensory integration process. In which we should assess the PPS Boundary and Slope Representation.

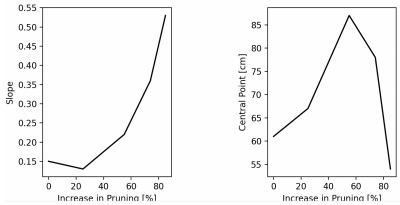


Fig. 19: Pruning Affect on PPS Boundary

The observed increase in PPS boundary with a moderate level of pruning and its subsequent decrease with further pruning could be explained by the idea that pruning weaker connections in the sensory areas could help sharpen the spatial resolution of PPS representation in which we can confirm our previous hypothesis. However, excessive pruning may lead to a loss of sensory information and a reduction in PPS sensitivity. This could explain the observed decrease in the PPS boundary with higher levels of pruning. The increase in slope with moderate pruning could be explained by the hypothesis that moderate pruning could help to sharpen the slope of the sigmoidal function by selectively retaining stronger connections. The mountain shape of the slope curve could suggest that there is an optimal level of pruning beyond which further pruning is detrimental to the slope of the function. These results are consistent with (Di Cosmo et al. ,2018), who reported that patients with schizophrenia had a reduced PPS boundary compared to healthy controls. These findings suggest that pruning weaker connections could be a mechanism underlying the PPS boundary deficits observed in schizophrenia patients. However, further studies are needed to investigate the specific effects of pruning on multisensory integration and PPS representation in schizophrenia.

VII. Conclusion

It appears that the brain integrates information from different sensory modalities through a complex interplay between unisensory and multisensory areas. The unisensory areas contain neurons that are recurrently connected and arranged in a ”Mexican hat” pattern, which promotes excitation of nearby neurons and inhibition of those further away. External stimuli activate a limited number of unisensory neurons, which prevents excitation from spreading across the unisensory area.The multisensory area integrates information from different sensory modalities based on the proximity of the stimuli, and the closer the auditory and tactile stimuli are to each other, the more likely they are to be integrated by the multisensory area. The feedback connections from the multisensory area to the unisensory areas also play a crucial role in this process, allowing for reciprocal activation of the unisensory areas and enhancing the perception of unimodal stimuli.

Overall, the findings suggest that pruning mechanisms may have a significant impact on the response of neurons in individuals with schizophrenia, particularly in the auditory unisensory area. However, further studies are needed to fully understand the implications of pruning mechanisms on multisensory integration and the PPS boundary in individuals with schizophrenia. The comparison to the study by (Di Cosmo et al. ,2018) highlights the importance of understanding the neural mechanisms underlying multisensory integration and the impact of schizophrenia on these mechanisms.

References

[1] Di Cosmo, G., Costantini, M., Salone, A., Martinotti, G., Di Iorio, G., Di Giannantonio, M., Ferri, F. (2018). Peripersonal space boundary in schizotypy and schizophrenia. Schizophrenia research, 197, 589-590.

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

[3] Makin, T. R., Holmes, N. P., Ehrsson, H. H. (2008). On the other hand: Dummy hands and peripersonal space. Behavioural brain research, 191(1), 1-10.

[4] Murray, J. D., Anticevic, A., Gancsos, M., Ichinose, M., Corlett, P. R., Krystal, J. H. (2016). Linking microcircuit dysfunction to cognitive impairment: effects of disinhibition associated with schizophrenia in a cortical working memory model. Cerebral cortex, 26(2), 796-807.

[5] Rabinovich, M. I., Huerta, R., Laurent, G. (2008). Neuroscience: transcranial magnetic stimulation and synaptic plasticity. Nature, 453(7198), 1178-1180.

[6] Schizophrenia.com. (2021). What is Schizophrenia?. Retrieved September 3, 2021, from https://www.schizophrenia.com/prev1.htm Shams, L., Seitz, A. R. (2008). Benefits of multisensory learning. Trends in cognitive sciences, 12(11), 411-417.

[7] Farnè, A., Làdavas, E. (2002). Auditory peripersonal space in humans. Journal of Cognitive Neuroscience, 14(8), 1030-1043.

[8] Murray, J. D., Anticevic, A., Gancsos, M. (2014). Linking microcircuit dysfunction to cognitive impairment: effects of disinhibition associated with schizophrenia in a cortical working memory model. Cerebral Cortex, 24(4), 1014-1023.

[9] Nelson, B., Sass, L. A., Kirschner, K., Parnas, J. (2013). The structure of the psychotic experience: latent class analysis of the SAPS and SANS in six independent samples. Schizophrenia research, 143(2-3), 210-215.

[10] Kuehn, E., Dinse, H. R., Tegenthoff, M. (2017). Plasticity of multisensory body representation: evidence from the crossmodal congruency task. Progress in brain research, 236, 95-121.

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

[12] Rubenstein, J. L., Merzenich, M. M. (2003). Model of autism: increased ratio of excitation/inhibition in key neural systems. Genes, brain and behavior, 2(5), 255-267.

[13] Tsakiris, M., Hesse, M. D., Boy, C., Haggard, P., Fink, G. R. (2007). Neural signatures of body ownership: a sensory network for bodily self-consciousness. Cerebral Cortex, 17(10), 2235-2244.

[14] Martín-Rodríguez, J. F., Barrios, F. A., Pérez, D. L. (2017). Neurobiology of body distortions. In Body Image and Identity in Contemporary Societies (pp. 105-128). Palgrave Macmillan, Cham.

[15] Häfner, H., Maurer, K., Löffler, W., an der Heiden, W. (2005). Depression, negative symptoms, social stagnation and social decline in the early course of schizophrenia. Acta Psychiatrica Scandinavica, 104(1), 45-52.

[16] Oorschot, M., Lataster, T., Thewissen, V., Lardinois, M., van Os, J., Delespaul, P. (2020). Symptom dimensions are associated with the course of social functioning in patients with psychotic disorders. Schizophrenia research, 220, 212-218.

[17] Vogeley, K., Kupke, C. (2007). Disturbances of Embodiment and Identity in Schizophrenia: An Autopoietic Theory. In The Self in Neuroscience and Psychiatry (pp. 243-254). Cambridge University Press.