CHAPTER 4

Conclusion and Future Scope

The ability to detect and interpret visual stimuli enables organisms to gather valuable survival information about their environment. However, visual perception is a complex and subjective experience that is influenced by various factors associated with the surrounding environment and the individual observer. These influential factors can be categorized as external and internal, and they play a crucial role in shaping how external events are visually perceived.

Indeed, visual perception is significantly affected by external factors related to the characteristics and dynamics of the surrounding environment. The stimuli present in the environment, such as high-contrast elements and surrounding textures, have the power to shape the perception of contrast, brightness, and object recognition. Furthermore, the relationship between the observer's body size and the size of objects in the environment can modify the perception of object size and spatial relationships. Motion is another critical factor that exerts a substantial influence on visual perception. The presence of motion in the visual field provides dynamic information that shapes the understanding of objects, depth perception, attentional focus, and visual stability. An intriguing phenomenon known as motion-induced compression demonstrates how motion cues can distort the perception of an object's length. Additionally, contextual cues have a profound impact on the perception of velocity and can alter the perception of the speed of moving objects.

Similarly, visual perception can be influenced by internal factors. For example, sensory adaptation showcases the brain's remarkable ability to adjust sensitivity and efficiently process new sensory information. Expectations, beliefs, and cultural milieu shape the interpretation of visual sensory input, highlighting the power of past experiences and cognitive biases. Emotions have a profound impact on visual perception by biasing the interpretation of visual information. Cognitive biases, which are rooted in mental shortcuts, can introduce distortions in visual perception and potentially warp one's understanding of reality. Individual differences, such as cognitive abilities, attentional capacity, age, and expertise, contribute to diverse interpretations of the same visual information. Age-related changes and expertise in specific domains can significantly affect visual perception.

Furthermore, biochemical, neuromodulating agents or related pharmaceuticals have a significant impact on visual perception by directly altering neural processes. Such substances may alter disrupt normal neural processing, resulting in visual distortions, while stimulant drugs can enhance visual acuity and sensitivity to visual stimuli. Likewise, depressant drugs can suppress visual perception, leading to impaired cognitive processing and reduced visual clarity. The effects of ketamine on visual perception vary among individuals, with some reporting enhanced experiences and others experiencing perceptual distortions. It is essential to consider factors such as dosage, individual tolerance, and the coexistence of other substances when understanding the effects of biochemicals on visual perception. Moreover, it's worth noting that long term administration of neuropharmaceuticals can have both immediate and long-lasting effects on visual perception and overall cognitive functioning.

The study and analysis of visual perception under the modulatory factors has potential to unlock valuable insights into the intricate mechanisms of visual perception in the brain. Such

insights have significant implications for various disciplines, including psychology, ergonomics, neuroscience, neuropsychiatry, and human-computer interaction, as well as the occupational safety of driving and flying by individuals under altered physiological status. Therefore, our investigations have been driven by the central objective of developing a quantitative and computational model that could captures the changes in visual perception. We have focused on two crucial elements: the activation of the sympathetic or parasympathetic nervous system (an internal factor) and the movement of objects (an external factor), as elucidated one by one below.

4.1 Internal Factor

The ecological approach to psychological dynamics posits the central nervous system as a perception-action system, with the sympathetic and parasympathetic nervous systems controlling the body's response to external situations, leading to changes in sensory information processing. While our study focused on visual perception, it is worth noting that methodology holds potential for extension to other sensory modalities.

To investigate how neuropharmacological action affects perception, we introduced the modulation index (M), a mathematical coefficient that captures the perceptual alterations induced by biochemical or drugs. By employing the Hill equation from reaction dynamics, we established a clear relationship between the activation level (dose amount) and the modulation index. The relationship provided mathematical representation of the underlying biochemical interactions between drug molecules and neural receptors, which give rise to perceptual alterations. Additionally, we developed a metric tensor to characterize the geometric properties of the visual space and elucidated how its components vary with the modulation index (M). Notably, hyperactivation and hypoactivation conditions yielded opposing

perceptual deviations, as indicated by the arousal index (μ) being +1 and -1 for hyper- and hypo-activational pharmaceuticals, respectively. Moreover, the intensity of perceptual distortion was found to be contingent upon an individual's tolerance to the drug, as captured by the personalized Weber constant (P).

In order to quantify the levels of hyperactivation and hypoactivation, we formulated a differential equation that describes the spatiotemporal dynamics of drugs within the brain. By analyzing experimental data from subjects who have been administered psilocybin, a hyperactivation-inducing agent, we were able to compute the temporal variation in the metric tensor of the visual space following oral ingestion. Subsequently, we derived the values of the Hill coefficient (n) and half-effective drug concentration. We repeated the process for the chlorpromazine, a hypoactivation inducing pharmaceutical. The parameters used to quantify drug effects, such as the Hill coefficient (n) and half effective drug concentration, can vary for different drugs. Thus, the findings highlighted the importance of considering individual pharmacological characteristics when studying perceptual effects, since bioavailability and biochemical reaction dynamics can influence the values of the parameters like the Hill coefficient and half effective drug concentration.

Our quantitative model contributed toward understanding the intricate relationship between neuropharmacological action, the subjects, perception, and the underlying mechanisms within the central nervous system. Through the integration of mathematical models validated by experimental findings, we shed light on how drugs can influence perception and the potential for personalized variations based on an individual's tolerance.

Next, our study presented a framework centered around grid cells, uncovering a potential fundamental principle in the neuronal basis of visual space geometry under the

influence of drug-induced autonomic nervous system activation. By conducting a thorough analysis, we indicated that grid cells in the visual cortex's *local* spatial map and the entorhinal cortex's global *spatial* map may be vital for representing spatial information at the neuronal level. Moreover, our MRI-tractography experiment showed the anatomical connection between the entorhinal-hippocampal network and the visual cortex, indicating to their collaborative role in integrating sensory information with prior knowledge for encoding positions in the visual space. Importantly, we demonstrated that drug-induced activation of the nervous system alters the interaction among grid cells, ultimately leading to perceptible changes in how individual perceives the physical space.

Thereafter, we simulated a network of drug-altered grid cells, which exhibited modified firing characteristics, indicative of the potential modulation of visual-spatial perception. In addition, we introduced a new parameter called the activity index (AI), which effectively quantifies changes in the activity of the grid cell network. Remarkably, our findings demonstrate that the AI coefficient follows the dynamics of the Hill equation, similar to the modulation index described in Equation (2.14). Our study provided the advancements in comprehending the neural mechanisms involved in visual space perception and offers novel insights into the impact of drug-induced autonomic nervous system activation on the visual-spatial perception during pharmacological effect. Our framework has applicability to multimodal sensory systems, arises from experimental observation of the grid cell-like neural representations in various perceptual modalities, including visual, olfactory, auditory, and sensorimotor domains. Thus, our model highlights the general nature of grid cells in representing cognitive maps across different sensory modalities in different brain regions.

In high-stress professions like aviation, submarine navigation, and space exploration, where split-second decisions can have life-altering consequences, maintaining peak performance is crucial. However, heightened arousal can lead to hyperactivation and errors in judgment, primarily due to changes in visual or auditory perception. By monitoring and quantifying arousal, it may be possible to develop an algorithmic system that delivers real-time feedback to human operators. Through timely alerts and notifications, the algorithm may effectively warn operators when excessive arousal may compromise visual perception, enabling them to take immediate corrective actions. Implementation of our framework in high-stress professions mitigates the risks associated with arousal-induced perceptual distortions. The combination of our quantitative model and the feedback algorithm has potential to formulate creates a comprehensive ergonomic system that not only quantifies and predicts perceptual alterations but may also actively guide and assists human operators in making correct judgments.

Our quantitative approach can used to develop an innovative and cost-effective behavioral-psychometric test using experimental measurements of the metric tensor, specifically handwriting alteration, to assess cerebral arousal and identify depressive disorders, manic disorders, and cyclothymic disorders. Notably, studies have suggested that mood disorders, like bipolar psychosis, lead to spatial changes in handwriting over time, thereby furnishing possibility of our diagnostic analysis. This novel behavioral testing holds promise as an economical biomarker, facilitating the monitoring of therapeutic outcomes for patients with bipolar or mood disorders. Furthermore, leveraging our in-silico models for neuropsychiatric patients and therapeutic interventions may offer the potential to refine

existing neuroinformatics models and create more accurate computational representations of neuropsychological disorders.

4.2 External Factor

Perceiving the movement of objects is vital for visual perception. Perceiving moving objects involves integrating information from both spatial and temporal perception, which can influenced by the motion, an external factor, itself. We aimed to establish a theoretical mathematical framework that enhances our understanding of how we perceive moving objects. We focused on the invariant representation of temporal causality in both retinotopic and perceptual spaces. By representing the change in position of a moving object using spatiotemporal coordinates, we derived the transformation equations that provide insights into the conversion of coordinates from retinotopic space to perceptual space. The transformation equations revealed valuable information and insight about perception. The speed parameter (P) effectively captured the dynamic nature of an object's position, while the fidelity parameter accounted for the potential impact of the brain's anatomical characteristics on perception. Through the analysis of experimental data from the moving arc experiment, we empirically confirmed that the fidelity parameter remains constant. By utilizing the transformation equations and incorporating the fidelity parameter value of 0.74 as obtained from the moving arc experiment, we successfully predicted the perceived time, which was well validated by the experimental outcomes. The empirical analysis and observation provided additional support for the validity of our transformation equations.

Indeed, the transformation equations provided evidence for the interaction between spatial and temporal information during visual-spatial and temporal perception. Although this

interaction remains covert when observing a moving object, the interaction becomes overt in the Pulfrich phenomenon. Notably, the activation of the cerebral visual area V5 is consistent during both the perception of a moving object and the Pulfrich illusion. These findings of our gain further support from our subsequent MRI tractography investigations, revealing neural tracts connecting area V5 with other focal brain regions responsible for visual-spatial and temporal perception. As shown by the centrality analysis of our network formulation, area V5 is identified as the pivotal node which is facilitating the versatile interaction between visual-spatial perception and temporal perception. Our theoretical framework provided an useful basis into the mechanisms governing the amalgamation of spatial information and temporal information in visual perception which not only add knowledge of how the brain processes visual stimuli but also holds appreciable potential for innovative progress in fields like virtual reality, motion perception, augmented reality, visual rehabilitation, and the comprehension and treatment of neurological disorders associated with perception impairments.

Furthermore, we have devised a mathematical model based on the Lotka-Volterra system to quantify the seminal interplay between spatial perception and temporal perception as mediated by the neurotransmitters acetylcholine and dopamine in cerebral area V5. Through our model, we have made intriguing observations regarding the interaction parameter (m), which represents the degree of interaction between neurotransmitters. We found that the interaction parameter (m) can influence the oscillatory behavior of acetylcholine and dopamine concentrations. Our findings have unveiled that the interaction between acetylcholine and dopamine may have impact on the receptive field properties of complex cells in area V5, leading to a change of the tuning speed. Although modulatory effect was less at lower speeds, it became increasingly significant as the speed of the object escalates. As a result, we proposed

that the interaction parameter (m) exhibits a direct proportionality to the speed of the moving object (P), as the parameter (m) directly influences the interaction between acetylcholine and dopamine, thereby altering the perception of object motion.

The ability of blind wounded soldiers to perceive motion despite the loss of primary visual cortex has been a significant finding in the annals of clinical neurology. It highlighted the continued activity and information processing in cerebral area MT/V5, even when the transmission of visual information from the primary visual cortex is impaired. This phenomenon indicated the crucial role of area V5 as a central processing hub for integrating spatiotemporal information across sensory systems. The possibility that area V5 may processes information from multiple sensory modalities further strengthens the scalability and practicality of the mathematical framework and analysis proposed in this study. Additionally, the broader usefulness of area V5's functionality has the possibility to uncover the geometrical principles governing brain functions. The mathematical model that we developed holds promise for practical applications, particularly in environments where individuals encounter fast-moving objects. By detecting and predicting perceptual errors caused by the dynamics of moving stimuli, our methodology can be employed in human warning systems. For instance, this system could issue alerts to human operators, such as fighter jet pilots or speeding drivers, helping them to avoid judgment errors caused by high-speed.

Our study presented a theoretical mathematical formulation that described the interaction between visual-spatial and temporal perception when a subject perceives moving objects. The formulation is validated by experimental observations. Further, we indicated that cerebral area V5 serves as an anatomical correlate that acts as the nodal hub of the aforesaid interaction between visual-spatial perception and temporal perception. The physiological basis

of the interaction is elucidated by a Lotka-Volterra system, which highlighted the interplay between acetylcholine and dopamine neurotransmitters. The neurotransmitter concentrations exhibited periodic variation with an orthogonal phase shift, which occurred at the axodendritic synapse of complex cells in area V5.

4.3 Future Prospects

The studies presented in the thesis primarily revolve around theoretical, mathematical and computational approaches. Nevertheless, these investigations have revealed novel research questions that call for exploration through appropriate experimental design and theoretical modeling.

With the primary objective to investigate the influence of neuropharmacological agents on perception, experiments need to be conducted to record the activity of grid cells under various dosages and types of these neuromodulating chemicals.

Two proposed experiments are:

(i) fMRI experiments on humans engaged in visual tasks while under the influence of drugs that modulate activation levels, this study can uncover the quantitative and qualitative impact of drugs on visual perception and the associated brain activity.

(ii) Valuable insights into the neural mechanisms that underlie visual perception can be obtained by performing experimental physiological recordings in monkeys using cerebral electrodes, while these primates participate in visual tasks under varying levels of pharmacologically induced activation.

Moreover, the state-of-the-art techniques such as ultrahigh density electrophysiological probes as neuropixel technology (Jun et al., 2017; van Daal et al., 2021; Paulk et al., 2022),

has demonstrated promising results in previous studies and could provide valuable information regarding the aforementioned aspects of visual spatial perception. These experiments hold promise for deepening the understanding of the intricate processes governing visual perception and response to pharmacological modulation.

We focused on the normal healthy brain while developing our mathematical framework for the alteration in the visual-spatial perception and temporal perception due to motion. However, the neurochemical basis of the perceptual phenomenon, shown by dopamine-acetylcholine interaction, can signify the possibility of a change in motion perception due to the relative imbalance of the neurotransmitters away from the normal levels occurring in healthy individuals. The disparity or abnormalities of the neurotransmitter levels in the brain can occur due to several factors such as due to underlying neurological or psychiatric disorders. Under these situations, the perception of stimuli moving in the external environment can become different as compared to the normal brain. For instance, patients with dopaminergic hyperactivation (as schizophrenia) (Chen, 2011; Kim et al., 2013b) or with cholinergic hypoactivation (as melancholic depression) experience altered perception of the moving object (Golomb et al., 2009a).

Accordingly, we can take that the underlying impaired pathophysiological status of the brain can be detected and estimated by measuring the perception of the moving stimuli by the patient and comparing it with the mathematical prediction for the normal brain. The perception of moving stimuli in patients may deviate from healthy normal subjects due to relative changes in the level of the neurotransmitters in the patient. Thus, our model, based on perceived movement alteration, can act as a potential biomarker to identify the presence and gauge the intensity of a neurological condition, the method could be developed as an affordable visual

ophthalmological procedure for psychiatric diagnostics in neuroscience clinics with visual optometric computer screens. Furthermore, for precise diagnosis, it may be desirable to have a high precision level of accurate experimentation (for example estimating subjective spatial and temporal segments). For such enhanced accuracy, one can use higher fidelity visual stimulation apparatus and measurement devices, for instance through experimental platforms and paradigm designing facilities such as the E-Prime system (Richard and Charbonneau, 2009) or PsychPhy platforms (Peirce, 2007).

Moreover, our approach may be developed for further understanding motion perception in the clinical neuroscience scenario. For potential applicability in medical settings, a mathematical framework needs to be developed which can model the modulation and alteration of the perception of a moving object as the neurotransmitter levels changes due to a neurological disorder. Next, for validation of the mathematical framework, the experiments which can measure motion perception as well as neurotransmitter levels, need to be devised and performed on normal healthy controls along with patients. Indeed, behavioral experiments can be readily planned to measure the perception of moving stimuli. Furthermore, radiological techniques such as Positron Emission Tomography (Ceccarini et al., 2020) and Magnetic Resonance Spectroscopy (Novotny et al., 2003) can be used for quantitative evaluation of the neurotransmitter levels in individuals, and here the accuracy of the assessment can be much upgraded by neoruimaging analysis modules such as Clinica module (for PET) (Routier et al., 2021) or FSL-MRS system (for spectroscopy) (Clarke et al., 2021). This is an area that we will pursue in a future investigation. To sum up, we note that there may be an appreciable implication of the procedure of our study to the experimental aspects of clinical neuroscience in the healthcare context.

In summary, it is worth noting that the methodology of our investigation holds considerable implications for the experimental aspects of neurology and psychiatry, offering potential avenues for further exploration.