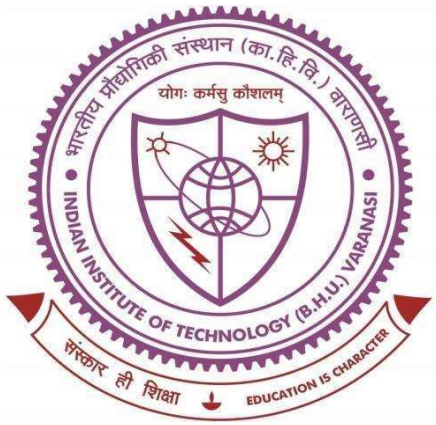
Computational Analysis of alteration of Visual Perception under specific external and internal factors



Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

by

Pratik Purohit

SCHOOL OF BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI – 221005
INDIA

ROLL NO: 17021501

2023

SCHOOL OF BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
B.H.U., Varanasi – 221005
India

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Prasun Roy

(Prof. Prasun Kumar Roy)
Supervisor

(Dr. Shiru Sharma)
Co-supervisor

Date: 27/7/23
Place: Varanasi, India.

SCHOOL OF BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
B.H.U., Varanasi – 221005
India

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I, Pratik Purohit, certify that the work embodied in this Ph.D. thesis is my bonafide work and was carried out by me under the supervision of Prof. Prasun Kumar Roy and Dr. Shiru Sharma from **27th December 2017 to 27th July 2023** at the School of Biomedical Engineering, Indian Institute of Technology (BHU), Varanasi, India. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma.

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Date: 27/07/2023

Place: Varanasi, India

Signature of the Student
(Pratik Purohit)

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of our knowledge.

Prasun Roy 27/7/23

(Prof. Prasun Kumar Roy)
Supervisor

S. Sharma

(Dr. Shiru Sharma)
Co-supervisor

S.K. Mandal 27/07/23

Coordinator
School of Biomedical Engineering
Indian Institute of Technology (BHU)
Varanasi – 221005, India.

समन्वयक/CO-ORDINATOR
जैव चिकित्सा अभियांत्रिकी स्कूल
SCHOOL OF BIOMEDICAL ENGG.
भारतीय प्रौद्योगिकी संस्थान (का.हि.वि.)
INDIAN INSTITUTE OF TECHNOLOGY (B.H.U.)
वाराणसी 221005/VARANASI-221005

SCHOOL OF BIOMEDICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
B.H.U., Varanasi – 221005
India

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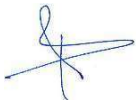

(Pratik Purohit)

Dedicated to My Beloved Family

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

LSD	Lysergic acid diethylamide
MRI	Magnetic Resonance Imaging
M	Modulation Index
n	Hill Coefficient
TS	Tortuisity
α	Volume fraction
k_{pi}	Transfer coefficient for the drug molecules from the blood to the brain tissue
k_{po}	Transfer coefficient for the drug molecules from brain tissue to the blood
C	Drug concentration in the extracellular space
C_a	Drug concentration in plasma
3D	Three dimensional
N	Total number of nodes
λ	Stabilization strength
W_{ij}	Connection weight between node P_i and P_j
T	Ratio of the excitatory and inhibitory connections
I	Interaction strength
GABA	Gamma-aminobutyric acid
ECS	Extra Cellular Space
D	Diffusivity
OASIS	Open Access Series of Imaging Studies
AC-PC	Anterior Commissure - Posterior Commissure
DWI	Diffusion Weighted Imaging
EPI	Echo Planar Imaging
TR	Repetition Time
TE	Time to Echo
FSL	FMRIB Software Library
β	Minimum prism power

AI	Activation Index
EEG	Electroencephalography
V1	Primary Visual Cortex
fMRI	Functional Magnetic Resonance Imaging
Z	Transformation matrix
P	Speed of moving object in the retinotopic space
γ	Cortical magnification factor
χ^2	chi-square
MT/V5	Middle temporal visual area
HARDI	High Angular Resolution Diffusion Imaging
3T	Three Tesla
7T	Seven Tesla
m	Interaction parameter

PREFACE

Visual perception is the process by which our brains interpret and make sense of the information received through eyes. Visual perception is a fundamental aspect of human experience, allowing us to perceive, recognize, and understand the world. The process begins with the capture of light by the eye's retina, where specialized cells, namely photoreceptors, convert the light into electrical signals. Electrical signals are then transmitted to the brain via the optic nerve, where they are further processed and interpreted to create a visual experience. Visual perception gives the ability to perceive colors, shapes, sizes, depth, and motion, enabling us to navigate the complex environment, recognize objects, and interact meaningfully with the world.

Visual perception is a complex and subjective experience. Sensory illusions provide compelling evidence that visual perception is not a fixed representation of objective reality, but exhibits variations and inconsistencies. Due to sensory illusions, perception diverges from the physical properties of a stimulus, showcasing the influence on visual perception. Sensory illusions underscore the dynamic nature of perception by modifying the relationship between the physical world and the perceived world. To underscore, visual perception can be shaped by a multitude of factors.

Various external factors, including the presence of other stimuli, lighting conditions, motion, and contextual cues, influence visual perception. These external factors of the surrounding modify and shape the perception of visual information, affecting contrast detection, brightness perception, object recognition, perceived size, and depth evaluation. Similarly, visual perception is also influenced by a range of internal factors of the personal subject, including sensory adaptation, expectations and beliefs, emotions, cognitive biases,

individual differences, and the effects of biochemical or neuro-pharmaceutical agents. The effects of such biochemical agents on visual perception can be diverse, with neuroactive substances causing distortions and heightened sensitivity, stimulant agents intensifying visual acuity, and depressant agents impairing perception. For instance, ketamine (or pharmaceutical) can lead to variable effects on visual perception depending on the individual susceptibility, dose concentration, and bioavailability. These internal factors play a significant role in shaping visual perception and highlight the complex nature of human cognition.

A quantitative understanding of the effect of modulatory factors can provide valuable insights into the mechanisms of perception and have implications in psychology, neuroscience, cognitive technology, neuropsychiatry, and human-computer interaction. In our thesis, we focused on two factors: how visual perception is affected by the activation of the sympathetic or parasympathetic nervous system (internal factor) and by the object's movement (external factor) affect visual perception.

In the chapter 1 of the thesis, we have provided a broad introduction and prospects of the research problem and provide a delineation of the approach that we take.

Thereafter in chapter 2, we presented a quantitative framework to formulate the variations in visual-spatial perception due to the sympathetic or parasympathetic nervous system activation. By considering the dose amount of the biochemical agent or drug which can induce autonomic nervous system activation, we quantified the activation levels. Using the metric tensor to quantify visual space, we established a relationship between (i) the concentration of the neuromodulator/drug concentration and (ii) the visual-spatial alterations, by utilizing the Hill equation of the chemical reaction kinetics. We then analyzed independent experimental studies using our model and found a close validation ($p>0.99$) between our

theoretical mathematical predictions and the observed experimental findings, characterized by the values of Hill coefficient (n) = 14.8 and k = 1.39 for psilocybin. We successfully predicted and verified the outcome of another experiment with psilocybin using the same values of the system parameters (n = 14.8 and k = 1.39). Additionally, we found that visual-spatial perception modulation closely matched our model under hypoactivation state induced by chlorpromazine, a relaxant pharmaceutical ($\chi 2$; $p>0.99$).

To explain the aforesaid altered visual-spatial perception, we computationally formulated a grid cell-based theoretical framework. Validating our framework, we simulated the effect of a neuromodulating pharmaceutical agent on the computational model of the grid-cell network and observed activity changes that verified the functionality of our model. Furthermore, diffusion MRI-based tractography on human brain scans were performed which revealed the neural tracts connecting the nodal cortical areas for visual-spatial perception in our framework: V2 and the entorhinal cortex. Our quantitative approach holds considerable potential for behavioral screening and for treatment-monitoring tools in neuropsychological cognitive disorders.

Next, we focused on the external factor (motion) in Chapter 3. Our quantitative model established a mathematical relationship between the spatiotemporal coordinates of the external object and of the perceived object; this we undertook by transforming the perception of the moving object from retinotopic space to perceptual space. Through coupled linear equations, our model demonstrated the interaction between visual-spatial and temporal perception. Analyzing the constancy of temporal causality, our model showed that the speed of a moving object influences both visual-spatial and temporal perception. Validated through two experiments, our model accurately predicted their behavioral findings ($\chi 2$; $p>0.99$).

Furthermore, we performed another MRI tractography experiment which showed that the cerebral area V5 may be the anatomical site for the interaction between visual-spatial and temporal perception. Additionally, we formulated a Lotka-Volterra system-type model to analyze the interplay between acetylcholine and dopamine neurotransmitters, exhibiting periodic oscillations. These oscillations may modulate visual perception by influencing the tuning properties of complex cells in cerebral area V5. Our study represented an innovative significant, and validated endeavor to connect motion perception with causality invariance mathematically.

In Chapter 4, we presented the main conclusions and outlined potential future prospects for our studies.