



## CONTENTS

APPROVAL PAGE .....	ii
STATEMENT .....	iii
PREFACE .....	iv
NOMENCLATURE AND ABBREVIATION .....	vi
ABSTRACT .....	vii
INTISARI .....	viii
CONTENTS .....	ix
LIST OF FIGURES .....	xiii
LIST OF TABLES .....	xvi
CHAPTER I INTRODUCTION .....	1
1.1 Background .....	1
1.2 Research Problem .....	6
1.3 Research Novelty .....	6
1.4 Research Objective .....	10
1.5 Research Benefits .....	10
1.6 Scope of the Study .....	11
CHAPTER II LITERATURE REVIEW AND THEORETICAL BASIS .....	12
2.1 Literature Review .....	12
2.1.1 Deep Learning-Based Eye Movement Classification .....	14
2.1.2 Hyperparameter Optimization .....	18
2.1.3 Bayesian Optimization in Time Series Classification .....	20
2.1.4 The Recent Study .....	28
2.2 Theoretical Basis .....	29
2.2.1 The Basic Principle of Eye-Tracking .....	29
2.2.2 Feature Extraction of Eye Movement Data .....	30
2.2.2.1 Speed .....	31
2.2.2.2 Direction .....	32
2.2.2.3 Acceleration .....	32
2.2.2.4 Displacement .....	32
2.2.2.5 Standard Deviation .....	33
2.2.3 Deep Learning .....	34
2.2.3.1 Loss Function .....	38
2.2.3.2 Optimizer Algorithm .....	39
2.2.3.3 1 Dimensional-Convolutional Neural Network (1D-CNN) .....	41
2.2.3.4 Long Short-Term Memory (LSTM) .....	43
2.2.3.5 Temporal Convolutional Network (TCN) .....	46
2.2.4 Hyperparameters in Deep Learning .....	48
2.2.4.1 Number of Stacks .....	52
2.2.4.2 Number of Filters .....	53
2.2.4.3 Kernel Size .....	54



2.2.4.4	Dilation Rate .....	55
2.2.4.5	Activation Function.....	56
2.2.4.6	Dropout Rate.....	57
2.2.4.7	Learning Rate .....	58
2.2.4.8	Batch Size .....	59
2.2.4.9	Epoch.....	60
2.2.5	Hyperparameter Optimization.....	60
2.2.5.1	Bayesian Optimization .....	65
2.2.5.2	Hyperband .....	69
2.2.6	Model Evaluation .....	71
2.2.6.1	Evaluation Method.....	71
2.2.6.2	Evaluation Metrics.....	71
2.2.7	Statistical Test .....	74
2.2.7.1	Shapiro-Wilk Test.....	75
2.2.7.2	Paired t-test .....	76
2.2.7.3	Wilcoxon Signed-Rank Test.....	77
2.3	Hypothesis.....	78
<b>CHAPTER III METHODOLOGY .....</b>		<b>79</b>
3.1	Apparatus and Material .....	79
3.1.1	Apparatus.....	79
3.1.2	Material .....	81
3.2	Research Flow.....	83
3.2.1	General Process .....	86
3.2.2	Data Preprocessing for Eye Movement Classification .....	88
3.2.2.1	Data Preprocessing .....	88
3.2.2.2	Feature Engineering .....	89
3.2.2.3	Data Aggregation .....	91
3.2.2.4	Feature Extraction .....	92
3.2.3	Deep Learning Algorithm Comparison .....	93
3.2.4	Optimization of the Best Algorithm.....	95
3.3	System Design .....	96
3.3.1	Deep Learning Algorithm Comparison .....	97
3.3.1.1	1D-CNN.....	101
3.3.1.2	LSTM .....	102
3.3.1.3	BiLSTM.....	103
3.3.1.4	1D-CNN-LSTM .....	105
3.3.1.5	1D-CNN-BiLSTM .....	106
3.3.1.6	TCN .....	107
3.3.2	Optimization of the Best Algorithm.....	108
3.3.2.1	Hyperparameter Search Space .....	111
3.3.2.2	Bayesian Optimization .....	114
3.3.2.3	Hyperband .....	118
3.4	System Evaluation .....	119
3.4.1	Performance Evaluation .....	119



3.4.2	Performance Metric .....	119
3.4.3	Eye Movement Classification Evaluation .....	124
CHAPTER IV	RESULTS AND DISCUSSION .....	125
4.1	Results .....	125
4.1.1	Summary and Overview .....	125
4.1.2	Comparative Analysis of Deep Learning Algorithms for Eye Movement Classification .....	127
4.1.2.1	Results Overview .....	128
4.1.2.2	Confusion Matrix .....	129
4.1.2.3	Overall F1 Score .....	131
4.1.2.4	Smooth Pursuit.....	133
4.1.2.5	Fixation.....	135
4.1.2.6	Saccade.....	137
4.1.2.7	Noise .....	139
4.1.2.8	Macro F1 Score .....	141
4.1.2.9	AUC-ROC.....	143
4.1.3	Hyperparameter Optimization of Deep Learning Model for Eye Movement Classification .....	144
4.1.3.1	Results Overview .....	145
4.1.3.2	Bayesian Optimization .....	146
4.1.3.3	Hyperparameters and Model Complexity .....	150
4.1.3.4	Overall F1 Score .....	152
4.1.3.5	Confusion Matrix .....	153
4.1.3.6	Smooth Pursuit.....	154
4.1.3.7	Fixation.....	156
4.1.3.8	Saccade.....	159
4.1.3.9	Noise .....	161
4.1.3.10	Macro F1 Score .....	163
4.1.3.11	AUC-ROC.....	166
4.2	Discussion .....	167
4.2.1	Effectiveness of Bayesian Optimization for TCN Enhancement.....	168
4.2.2	Comparative Analysis of Deep Learning Algorithms .....	169
4.2.3	Significance of Hyperparameter Optimization .....	170
4.2.4	Enhancing Differentiation Between Fixation and Smooth Pursuit: Leveraging Temporal Features and Deep Learning Models .....	171
4.2.5	Impact of Padding Choices on Smooth Pursuit Classification	171
4.2.6	Importance of Temporal Features and the Role of Non-Causal TCN in Eye Movement Classification .....	173
4.2.7	Preference for ReLU Activation: Enhancing Performance and Efficiency in Eye Movement Classification .....	175
4.2.8	Limitations .....	176
4.2.8.1	Saccade Classification Discrepancy .....	176



4.2.8.2	Generalizability .....	177
4.2.8.3	Limited Hyperparameter Search Space .....	177
4.2.8.4	False Positive Management .....	177
4.2.9	Limitations of TCNs in Real-Time Classification .....	177
4.2.10	Feasibility Evaluation and Challenges of Applying Bayesian Optimization in Real-Time Eye Movement Classification ....	179
4.2.11	Practical Implication .....	180
CHAPTER V	CONCLUSIONS AND FUTURE WORKS .....	182
5.1	Conclusions .....	182
5.2	Future Works .....	184
REFERENCES .....		185
APPENDIX .....		L-1
L.1	F1 Score Metrics Summary for Algorithm Evaluation .....	L-1
L.1.1	1D-CNN Algorithm F1 Score Metrics Summary.....	L-1
L.1.2	LSTM Algorithm F1 Score Metrics Summary .....	L-2
L.1.3	BiLSTM Algorithm F1 Score Metrics Summary .....	L-3
L.1.4	1D-CNN-LSTM Algorithm F1 Score Metrics Summary ....	L-4
L.1.5	1D-CNN-BiLSTM Algorithm F1 Score Metrics Summary (padding='same') .....	L-5
L.1.6	1D-CNN-BiLSTM Algorithm F1 Score Metrics Summary (padding='valid').....	L-6
L.1.7	TCN Algorithm F1 Score Metrics Summary .....	L-7
L.1.8	Optimized TCN with Hyperband Algorithm F1 Score Metrics Summary.....	L-8
L.1.9	Optimized TCN with Bayesian Optimization Algorithm F1 Score Metrics Summary .....	L-9



## LIST OF FIGURES

Figure 1.1	Graphical representation of eye movements in a time series...	2
Figure 1.2	An illustration of gaze gesture interaction. The arrows illustrate trajectories of moving objects. ....	3
Figure 2.1	An illustration of remote eye tracker using Active Display Coordinate System .....	30
Figure 2.2	Layer of deep learning .....	35
Figure 2.3	Caption without citation .....	36
Figure 2.4	Caption without citation .....	37
Figure 2.5	An illustration of backpropagation .....	38
Figure 2.6	Pseudocode of the Adam optimizer algorithm. ....	40
Figure 2.7	The general structure of CNN .....	41
Figure 2.8	The structure of 1D-CNN.....	42
Figure 2.9	Illustration of Long Short-Term Memory (LSTM) Architecture	45
Figure 2.10	Differences in the basic structure of algorithms (a) LSTM and (b) BiLSTM.....	45
Figure 2.11	A dilated causal convolution with dilation factors $d = 1, 2, 4$ and a filter size ks = 3. ....	47
Figure 2.12	A dilated non-causal convolution with dilation factors $d = 1, 2, 4$ and a filter size ks = 3. ....	48
Figure 2.13	Frequencies of architectural hyperparameters. ....	49
Figure 2.14	Frequencies of algorithmic hyperparameter.....	49
Figure 2.15	Residual block of TCN .....	53
Figure 2.16	Illustrative example demonstrating the application of a 50% dropout rate in a neural network. ....	58
Figure 2.17	Steps of hyperparameters optimization (HPO) in a deep learning model .....	61
Figure 2.18	HPO Methods Selection .....	64
Figure 2.19	HPO trend in deep learning for time series classification tasks	65
Figure 2.20	Pseudocode of the Bayesian Optimization algorithm.....	68
Figure 2.21	Pseudocode of the Hyperband optimization algorithm. ....	70
Figure 2.22	Confusion matrix .....	72
Figure 3.1	Exemplary snippet from the GazeCom dataset in one of the files. ....	81
Figure 3.2	Distribution of Eye Movement Types in the GazeCom Dataset, Illustrating Imbalance and Variation Across Videos. ....	82
Figure 3.3	General proposed approach. ....	85
Figure 3.4	General Research Flow Process. ....	87
Figure 3.5	Data processing flowchart highlighting key stages - preprocessing, feature engineering, aggregation, and extraction, preparing features for deep learning integration. ....	88



Figure 3.6 An example of a dataset resulting from the extraction of new features.....	89
Figure 3.7 Pseudocode for the calculation of Pixel per Degree (PPD).....	92
Figure 3.8 Feature extraction procedure from the GazeCom dataset .....	93
Figure 3.9 Flowchart illustrating algorithm comparison process.....	94
Figure 3.10 Flowchart illustrating the optimization process of the selected algorithm .....	96
Figure 3.11 Flowchart illustrating the algorithm comparison and validation	100
Figure 3.12 Overall schematics of the 1D-CNN. ....	102
Figure 3.13 Overall schematics of the LSTM .....	103
Figure 3.14 Overall schematics of the BiLSTM .....	104
Figure 3.15 Overall schematics of the 1D-CNN-LSTM. ....	106
Figure 3.16 Overall schematics of the 1D-CNN-BiLSTM.....	107
Figure 3.17 Overall schematics of the TCN. ....	108
Figure 3.18 Flowchart illustrating the optimization of the best algorithm and validation .....	109
Figure 3.19 The architecture of the proposed TCN model with hyperparameters.....	112
Figure 3.20 Algorithm of Bayesian Optimization with arithmetic mean of F1 scores as objective function .....	116
Figure 3.21 HPO using Bayesian Optimization with LOVO evaluation. ...	117
Figure 3.22 Leave-One-Video-Out (LOVO) Process on GazeCom Dataset	119
Figure 4.1 Confusion matrix plots for eye movement classification algorithms on GazeCom dataset using LOVO evaluation. ....	130
Figure 4.2 Comparison of ROC curves and AUC values for six deep learning algorithms across different eye movement classes. ....	144
Figure 4.3 Illustration of the trade-off between validation loss and average validation F1 score across iterations .....	147
Figure 4.4 Confusion matrix plots for eye movement classification using TCN on GazeCom dataset using LOVO evaluation. ....	154
Figure 4.5 Pairwise comparison of overall F1 scores for smooth pursuit classification between Bayesian-optimized TCN and benchmark models. ....	156
Figure 4.6 Pairwise comparison of overall F1 scores for fixation classification between Bayesian-optimized TCN and benchmark models. ....	158
Figure 4.7 Pairwise comparison of overall F1 scores for saccade classification between Bayesian-optimized TCN and benchmark models. ....	161
Figure 4.8 Pairwise comparison of overall F1 scores for noise classification between Bayesian-optimized TCN and benchmark models. ....	163



Figure 4.9 Pairwise comparison of overall macro F1 scores for eye movement classification between Bayesian-optimized TCN and benchmark models. ....	165
Figure 4.10 Comparison of ROC curves and AUC values for three TCN models across different eye movement classes.....	167
Figure 4.11 Pairwise comparison of overall F1 scores for eye movement classification using 1D-CNN-BiLSTM between 'valid' and 'same' padding. ....	172
Figure 4.12 Pairwise comparison of overall F1 scores for smooth pursuit classification between single deep learning algorithm.....	174



## LIST OF TABLES

Table 1.1	Recent studies of eye movement classification with deep learning .....	7
Table 2.1	Bayesian Optimization: Summary of hyperparameters search space for time series classification.....	21
Table 2.2	Frequency Distribution of Optimized Hyperparameters Based on Model .....	51
Table 2.3	Surrogate model and acquisition function of Bayesian Optimization for time series classification .....	66
Table 2.4	Description of the symbol used in the pseudocode of the Bayesian Optimization process. ....	67
Table 2.5	Description of the symbol used in the pseudocode of the optimization process using Hyperband. ....	70
Table 3.1	Description of features in the GazeCom dataset. ....	82
Table 3.2	Eye Movement Class Distribution per Video .....	84
Table 3.3	Description of Features from the Feature Engineering Process on the GazeCom Dataset. ....	90
Table 3.4	Hyperparameters' Search Space .....	111
Table 3.5	F1 Score Metrics Summary for Algorithm Evaluation .....	121
Table 4.1	Performance Evaluation of Deep Learning Algorithms for Eye Movement Classification: Overall F1 Scores for Each Eye Movement and Overall Macro F1 Scores .....	131
Table 4.2	F1 Score Comparison for Smooth Pursuit Eye Movements Across Six Deep Learning Algorithms in LOVO Evaluation ...	134
Table 4.3	F1 Score Comparison for Fixation Eye Movements Across Six Deep Learning Algorithms in LOVO Evaluation.....	136
Table 4.4	F1 Score Comparison for Saccade Eye Movements Across Six Deep Learning Algorithms in LOVO Evaluation.....	138
Table 4.5	F1 Score Comparison for Noise across Six Deep Learning Algorithms in LOVO Evaluation .....	140
Table 4.6	Macro F1 Score Comparison across Six Deep Learning Algorithms in LOVO Evaluation .....	142
Table 4.7	Performance Evaluation of Deep Learning Algorithms for Eye Movement Classification: AUC-ROC for Each Eye Movement	143
Table 4.8	Hyperparameter Configuration and Performance Metrics at Each Iteration of Bayesian Optimization.....	148
Table 4.9	Hyperparameter Values Comparison among Bayesian-Optimized TCN, Baseline TCN, and Hyperband-Optimized TCN Models. .	150



Table 4.10 Comparison of Model Characteristics and Performance Metrics among Bayesian-Optimized TCN, Baseline TCN, and Hyperband-Optimized TCN Models.....	151
Table 4.11 Comparison of Overall F1 Scores for Fixation, Saccade, Smooth Pursuit, Noise, and Macro F1 Score among Different TCN Models .....	153
Table 4.12 F1 Score Comparison for Smooth Pursuit Eye Movements Across Three TCN Models in LOVO Evaluation .....	155
Table 4.13 F1 Score Comparison for Fixation Eye Movements Across Three TCN Models in LOVO Evaluation .....	157
Table 4.14 F1 Score Comparison for Saccade Eye Movements Across Three TCN Models in LOVO Evaluation .....	159
Table 4.15 F1 Score Comparison for Noise Across Three TCN Models in LOVO Evaluation.....	162
Table 4.16 F1 Score Comparison for Noise Across Three TCN Models in LOVO Evaluation.....	164
Table 4.17 Comparison of AUC-ROC values for Fixation, Saccade, Smooth Pursuit, and Noise among Different TCN Models .....	166