

Contents

1	Approach and scope	1
1.1	The approach	1
1.1.1	Data, models, and theory	1
1.1.2	From physiology to behavior and back via theory and models	3
1.2	The problem of vision	4
1.2.1	Visual tasks and subtasks	5
1.2.2	Vision seen through visual encoding, selection, and decoding	7
1.2.3	Visual encoding in retina and V1	10
1.2.4	Visual selection and V1's role in it	12
1.2.5	Visual decoding and its associated brain areas	14
2	A very brief introduction of what is known about vision experimentally	16
2.1	Neurons, neural circuits, and brain regions	16
2.1.1	Neurons, somas, dendrites, axons, and action potentials	16
2.1.2	A simple neuron model	17
2.1.3	Random processes of action potential generation in neurons	18
2.1.4	Synaptic connections, neural circuits, and brain areas	18
2.1.5	Visual processing areas along the visual pathway	19
2.2	Retina	22
2.2.1	Receptive fields of retinal ganglion cells	22
2.2.2	Sensitivity to sinusoidal gratings, and contrast sensitivity curves	25
2.2.3	Responses to spatiotemporal inputs	30
2.2.4	P and M cells	34
2.2.5	Color processing in the retina	35
2.2.6	Spatial sampling in the retina	37
2.2.7	LGN on the pathway from the retina to V1	38
2.3	V1	39
2.3.1	The retinotopic map	39
2.3.2	The receptive fields in V1—the feature detectors	40
2.3.3	Orientation selectivity, bar and edge detectors	41
2.3.4	Spatial frequency tuning and multiscale coding	42
2.3.5	Temporal and motion direction selectivity	43
2.3.6	Ocular dominance and disparity selectivity	46
2.3.7	Color selectivity of V1 neurons	48
2.3.8	Complex cells	48
2.3.9	The influences on a V1 neuron's response from contextual stimuli outside the receptive field	52

2.4	Higher visual areas	54
2.4.1	Two processing streams	54
2.4.2	V2	55
2.4.3	MT (V5)	57
2.4.4	V4	59
2.4.5	IT and temporal cortical areas for object recognition	60
2.5	Eye movements, their associated brain regions, and links with attention	60
2.5.1	Close link between eye movements and attention	62
2.6	Top-down attention and neural responses	63
2.7	Behavioral studies on vision	65

3 The efficient coding principle 67

3.1	A brief introduction to information theory	68
3.1.1	Measuring information	68
3.1.2	Information transmission, information channels, and mutual information	70
3.1.3	Information redundancy, representation efficiency, and error correction	74
3.2	Formulation of the efficient coding principle	77
3.2.1	An optimization problem	77
3.2.2	Exposition	79
3.3	Efficient neural sampling in the retina	83
3.3.1	Contrast sampling in a fly's compound eye	83
3.3.2	Spatial sampling by receptor distribution on the retina	85
3.3.3	Optimal color sampling by the cones	89
3.4	Efficient coding by visual receptive field transforms	90
3.4.1	The general analytical solution for efficient coding of Gaussian signals	91
3.5	Case study: stereo coding in V1 as an efficient transform of inputs in the dimension of ocularity	96
3.5.1	Principal component analysis K_o	98
3.5.2	Gain control	102
3.5.3	Contrast enhancement, decorrelation, and whitening in the high S/N regime	105
3.5.4	Many equivalent solutions of optimal encoding	106
3.5.5	Smoothing and output correlation in the low S/N region	108
3.5.6	A special, most local, class of optimal coding	110
3.5.7	Adaptation of the optimal code to the statistics of the input environment	110
3.5.8	A psychophysical test of the adaptation of the efficient stereo coding	117
3.5.9	How might one test the predictions physiologically?	120
3.6	The efficient receptive field transforms in space, color, time, and scale in the retina and V1	120
3.6.1	Efficient spatial coding in the retina	123
3.6.2	Efficient coding in time	134
3.6.3	Efficient coding in color	138
3.6.4	Coupling space and color coding in the retina	142
3.6.5	Spatial coding in V1	147

Lecture 1,
3.1-3.4

April 22

Lecture 2,
3.4 - 3.5.9
April 29

Lecture 3,
3.6.1 to 3.6.4

May 6

Lecture 4,
3.6.5 to 3.6.9

May 13

Contents | ix

3.6.6	Coupling the spatial and color coding in V1	154
3.6.7	Coupling spatial coding with stereo coding in V1—coding disparity	161
3.6.8	Coupling space and time coding in the retina and V1	164
3.6.9	V1 neurons tuned simultaneously to multiple feature dimensions	167
3.7	The efficient code, and the related sparse code, in low noise limit by numerical simulations	170
3.7.1	Sparse coding	171
3.8	How to get efficient codes by developmental rules and unsupervised learning	173
3.8.1	Learning for a single encoding neuron	174
3.8.2	Learning simultaneously for multiple encoding neurons	175
4	V1 and information coding	177
4.1	Pursuit of efficient coding in V1 by reducing higher order redundancy	177
4.1.1	Higher order statistics contain much of the meaningful information about visual objects	178
4.1.2	Characterizing higher order statistics	180
4.1.3	Efforts to understand V1 neural properties from the perspective of reducing higher order redundancy	183
4.1.4	Higher order redundancy in natural images is only a very small fraction of the total redundancy	185
4.2	Problems in understanding V1 solely based on efficient coding	186
4.3	Multiscale and overcomplete representation in V1 is useful for invariant object recognition from responses of selected neural subpopulations	187
4.3.1	Information selection, amount, and meaning	188
5	The V1 hypothesis—creating a bottom-up saliency map for preattentive selection and segmentation	189
5.1	Visual selection and visual saliency	189
5.1.1	Visual selection—top-down and bottom-up selections	189
5.1.2	A brief overview of visual search and segmentation—behavioral studies of saliency	195
5.1.3	Saliency regardless of visual input features	197
5.1.4	A quick review of what we should expect about saliencies and a saliency map	200
5.2	The V1 saliency hypothesis	201
5.2.1	Detailed formulation of the V1 saliency hypothesis	202
5.2.2	Intracortical interactions in V1 as mechanisms to compute saliency	204
5.2.3	Reading out the saliency map	206
5.2.4	Statistical and operational definitions of saliency	207
5.2.5	Overcomplete representation in V1 for the role of saliency	208
5.3	A hallmark of the saliency map in V1—attention capture by an ocular singleton which is barely distinctive to perception	209
5.3.1	Food for thought: looking (acting) before or without seeing	215
5.4	Testing and understanding the V1 saliency map in a V1 model	215
5.4.1	The V1 model: its neural elements, connections, and desired behavior	216
5.4.2	Calibration of the V1 model to biological reality	222

Lecture 5,
3.7 - 4.3

May 20

Lecture 6:
5.1 to 5.3.1

May 27

Lecture 7/8,
5.4.1-5.4.7

June 3/17th

x | Contents

5.4.3	Computational requirements on the dynamic behavior of the model	225
5.4.4	Applying the V1 model to visual search and visual segmentation	227
5.4.5	Other effects of the saliency mechanisms—figure-ground segmentation and the medial axis effect	247
5.4.6	Input contrast dependence of the contextual influences	250
5.4.7	Reflections from the V1 model	250
5.5	Additional psychophysical tests of the V1 saliency hypothesis	252
5.5.1	The feature-blind “auction”—maximum rather than summation over features	252
5.5.2	The fingerprints of colinear facilitation in V1	257
5.5.3	The fingerprint of V1’s conjunctive cells	260
5.5.4	A zero-parameter quantitative prediction and its experimental test	266
5.5.5	Reflections—from behavior back to physiology via the V1 saliency hypothesis	269
5.6	The roles of V1 and other cortical areas in visual selection	269
5.6.1	Using visual depth feature to probe contributions of extrastriate cortex to attentional control	271
5.6.2	Salient but indistinguishable inputs activate early visual cortical areas but not the parietal and frontal areas	275
5.7	V1’s role beyond saliency—selection versus decoding, periphery versus central vision	279
5.7.1	Implications for the functional roles of visual cortical areas based on their representations of the visual field	281
5.7.2	Saliency, visual segmentation, and visual recognition	282
5.8	Nonlinear V1 neural dynamics for saliency and preattentive segmentation	285
5.8.1	A minimal model of the primary visual cortex for saliency computation	286
5.8.2	Dynamic analysis of the V1 model and constraints on the neural connections	299
5.8.3	Extensions and generalizations	312
5.9	Appendix: parameters in the V1 model	313

Lecture 9,
5.5.1 -5.5.5

June 24

Lecture 10,
5.6 -5.7

July 1

Supplementary?
5.8

6 Visual recognition as decoding 315

6.1	Definition of visual decoding	315
6.2	Some notable observations about visual recognition	317
6.2.1	Recognition is after an initial selection or segmentation	317
6.2.2	Object invariance	318
6.2.3	Is decoding the shape of an object in the attentional spotlight a default routine?	319
6.2.4	Recognition by imagination or input synthesis	321
6.2.5	Visual perception can be ambiguous or unambiguous	323
6.2.6	Neural substrates for visual decoding	325
6.3	Visual decoding from neural responses	326
6.3.1	Example: decoding motion direction from MT neural responses	327
6.3.2	Example: discriminating two inputs based on photoreceptor responses	330
6.3.3	Example: discrimination by decoding the V1 neural responses	332
6.3.4	Example: light wavelength discrimination by decoding from cone responses	334
6.3.5	Perception, including illusion, of a visual feature value by neural population decoding	338

Lecture 11,
6.1 to 6.3.3.

July 8th

Lecture 12
6.3.4 to
6.3.8

July 15th

Lecture 13,
6.4
July 22nd

Lecture 14, →
6.5 and advanced
materials

July 29

6.3.6	Poisson-like neural noise and increasing perceptual performance for stronger visual inputs	345
6.3.7	Low efficiency of sensory information utilization by the central visual system	345
6.3.8	Transduction and central inefficiencies in the framework of encoding, attentional selection, and decoding	346
6.4	Bayesian inference and the influence of prior belief in visual decoding	347
6.4.1	The Bayesian framework	348
6.4.2	Bayesian visual inference is highly complex unless the number and the dimensions of possible percepts are restricted	349
6.4.3	Behavioral evidence for Bayesian visual inference	350
6.5	The initial visual recognition, feedforward mechanisms, and recurrent neural connections	361
6.5.1	The fast speed of coarse initial recognition by the primate visual system	361
6.5.2	Object detection and recognition by models of hierarchical feedforward networks	361
6.5.3	Combining feedforward and feedback intercortical mechanisms, and recurrent intracortical mechanisms, for object inference	363
7	Epilogue	364
7.1	Our ignorance of vision viewed from the perspective of vision as encoding, selection, and decoding	364
7.2	Computational vision	365
	References	367
	Index	380