BIOGRAPHICAL SKETCH

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NAME: Krishna Vaughn Shenoy, PhD

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POSITION TITLE: Hong Seh and Vivian W. M. Lim Professor, Stanford University & Investigator, HHMI

EDUCATION/TRAINING

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/YYYY	FIELD OF STUDY
UC San Diego	---	9/1986 – 6/1987	Electrical Engineering and Computer Science (EECS)
UC Irvine	B.S.	6/1987 – 6/1990	EECS, Prof. G.L. Shaw
MIT	S.M.	8/1990 – 6/1992	EECS, Prof. C.G. Fonstad
MIT	Ph.D.	6/1992 – 6/1995	EECS, Prof. C.G. Fonstad
Caltech	Postdoc Senior PD	7/1995 – 6/1998 7/1998 – 7/2001	Systems Neuroscience, Prof. R.A. Andersen

A. Personal Statement

I have trained in both electrical engineering (MIT PhD) and systems neuroscience (Caltech postdoc). Since joining the Stanford faculty 20 years ago I have directed (**NPSL**) and co-directed (**NPTL**) two research groups, and I have taught numerous undergraduate and graduate courses centered on systems neuroengineering.

Since 2001 I have directed the “Neural Prosthetic Systems Lab” (**NPSL**). We focus on systems and computational neuroscience questions regarding how populations of individual premotor and motor cortical neurons prepare and generate movements and participate in decision making. Approaches include linear and non-linear dynamical systems data analysis and modeling (e.g., single-trial methods, dimensionality reduction, real-time interventions, LDSs and RNNs; in collaboration with Profs. David Sussillo and Maneesh Sahani), rhesus and squirrel monkey neurophysiology (e.g., NeuroPixels, Utah arrays, head-mounted wireless systems) and optogenetics and 2-photon GCaMP optical imaging (in collaboration with Prof. Karl Deisseroth), and closed-loop brain-machine interface (BMI) design and demonstrations (e.g., decode / control algorithms).

Since 2009 I have co-directed, along with Prof. Jaimie Henderson MD (Neurosurgeon, Dept. of Neurosurgery, Stanford) a human clinical-trial based research group named the “Neural Prosthetics Translational Lab” (**NPTL**). We work closely with Profs. Leigh Hochberg and John Donoghue and their groups at Brown/MGH as part of the BrainGate clinical trial consortium (we are the 2nd site). Here we focus on basic and applied systems and computational neuroscience questions regarding how populations of individual human premotor and motor cortical neurons prepare and generate movements (e.g., arm/hand movements, decision making, speech, handwriting). This is enabled by the chronic implantation of Utah arrays, which record from populations of individual neurons, in people with tetraplegia. Approaches include dynamical systems data analyses and modeling, neurophysiology from people with tetraplegia (e.g., spinal cord injury, ALS, brainstem stroke), power-constrained fully-implantable wireless system design and BMI design for high-performance and high-robustness real world operation with commercial off-the-shelf interfaces (e.g., tablets). All of these activities are either directly or indirectly relevant to the current research proposal.

Several of my former trainees are now in tenure-track academic positions: (1) **Aaron Batista PhD**, Professor of BioE & Neurosci., U. Pittsburgh; (2) **Chand Chandrasekaran PhD**, Assist. Prof. of BioE, Psych. & BioE, Boston U.; (3) **Cynthia Chestek PhD**, Assoc. Prof. of BioE & EE, U. Michigan; (4) **John Cunningham PhD**, Prof. of Statistics & Neurosci., Columbia U.; (5) **Mark Churchland PhD**, Assoc. Prof. of Neurosci., Columbia U.; (6) **Ilka Diester PhD**, Prof. of Neurosci., U. Freiburg; (7) **Vikash Gilja PhD**, Assoc. Prof. of ECE & Neurosc., UCSD; (8) **Jonathan Kao PhD**, Assist. Prof. of EE & Neurosci., UCLA; (9) **Matthew Kaufman PhD**, Assist. Prof. of Neurosci., U. Chicago; (10) **Paul Nuyujukian MD PhD**, Assist. Prof. of BioE, Neurosurgery & EE, Stanford U.; (11) **Chethan Pandarinath PhD**, Assist. Prof. of BioE & Neurosci., Emory U. and Georgia Tech; (12) **Stephen Ryu MD**, Adjunct Prof. of EE, Stanford U.; (13) **David Sussilo PhD**, Adjunct Professor of EE, Stanford U.; (14) **Byron Yu PhD**, Prof. of BioE & EE, CMU. Many others graduated (PhDs and are now postdocs (xx).

I also co-chair the Neurosciences PhD Program's Diversity, Equitability and Inclusion (DEI) committee, and help lead EE's DEI efforts, to: (1) advance the recruitment, retention, and delivery of an extremely high-quality experience for URM, BIPOC and FLI students, postdocs and staff as well as everyone.

B. Positions and Honors

Positions and Employment

1988-1990	NSF REU, Research Assistant, Neurobiology Center, UC Irvine (Prof. Gordon L. Shaw)
1989	Summer Intern, Rockwell Semiconductor Products Division, Newport Beach, CA
1990-1992	M.S. student Research Assistant, EECS Department, MIT (Prof. Clifton G. Fonstad, Jr.)
1992-1995	Ph.D. student Research Assistant, EECS Department, MIT (Prof. Clifton G. Fonstad, Jr.)
1995-1998	Postdoc, Division of Biology (systems neuroscience), Caltech (Prof. R. A. Andersen)
1998-2001	Senior postdoc, Division of Biology (systems neuroscience), Caltech (Prof. R. A. Andersen)
2001-2008	Assistant Professor, Stanford University
2008-2012	Associate Professor, Stanford University
2012-2017	Professor, Stanford University
2015-	Investigator, Howard Hughes Medical Institute
2017-	Hong Seh and Vivian W. M. Lim Professor of Engineering (endowed chair), Stanford University Investigator, Howard Hughes Medical Institute Departments of Electrical Engineering and, by courtesy, of Bioengineering and Neurobiology Wu Tsai Neurosciences Institute, Bio-X Institute, Neurosciences PhD Program Stanford University

Other Experiences and Professional Memberships

1988-	Member, Institute of Electrical and Electronics Engineers (IEEE)
1988-	Elected Member, Eta Kappa Nu (HKN), national electrical engineering honor society
1988	Elected Member, Tau Beta Pi (TBΠ), national engineering honor society
1989-1990	Elected President, Tau Beta Pi (TBΠ), UC Irvine chapter
1995-	Member, Society for Neuroscience
2000-	Member, Neural Control of Movement
2003-2005	Elected Fellow, Defense Science Research Council, DARPA
2005-2009	Elected Member, Defense Science Research Council, DARPA
2006-	Member, American Physiological Society
2008-2013	Editorial Board, Journal of Neurophysiology
2016-	Scientific Advisory Board, CTRL-Las Inc. (now part of Facebook), NYC, NY (ctrl-labs.com)
2016-	Scientific Advisory Board, Heal Inc., Los Angeles, CA (heal.com)
2016-	Scientific Advisory Board, NSF ERC CNSE, U. Washington, Seattle, WA (csne-erc.org)
2017-	Consultant, Neuralink Inc., Fremont, CA (neuralink.com)
2018-	Scientific Advisory Board, MIND-X Inc., Bethesda, MD (mind-x.io)
2018-	Scientific Advisory Board, Inscopix Inc., Palo Alto, CA (inscopix.com)

Honors

1989-1990	Presidential Undergraduate Fellowship, UC Irvine
1989-1990	Hembd Memorial Scholarship, UC Irvine
1990-1995	Graduate Research Fellowship, National Science Foundation
1992-1995	Graduate Fellowship, Fannie and John Hertz Foundation
1995-1996	Alcott Postdoctoral Fellow, Division of Biology, Caltech
1996	Doctoral Thesis Prize, Fannie and John Hertz Foundation
1996-1999	F32 Postdoctoral Fellowship, National Eye Institute, National Institutes of Health
1999-2004	Burroughs Wellcome Fund Career Award in Biomedical Sciences
2006-	Elected Senior Member, Institute of Electrical and Electronics Engineers
2001-2008	Robert N. Noyce Faculty Scholar, School of Engineering, Stanford University
2001-2008	William George Hoover Faculty Scholar, School of Engineering, Stanford University
2002-2004	Alfred P. Sloan Research Fellow
2007-2009	McKnight Technological Innovations in Neurosciences Award
2008-2011	Charles Lee Powell Faculty Scholar, School of Engineering, Stanford University
2009-2012	NIH EUREKA Award

2009-2016	NIH Director's Pioneer Award
2010	Stanford University Postdoctoral Mentoring Award
2012	North American Konkani Association Sammelan, Award of Excellence in Research
2013	UC Irvine Distinguished Alumnus Award, Henry Samueli School of Engineering
2015	Elected Member, Hall of Fame, Henry Samueli School of Engineering, UC Irvine
2015-	Elected Fellow, American Institute for Medical and Biological Engineering (AIMBE)
2018	Carnegie Prize in Mind and Brain Sciences, Carnegie Mellon University & Carnegie Corp.

C. Contributions to Science (>140 journal papers)

1) **The role of primary motor (M1) and premotor (PMd) cortex is still poorly understood and quite debated.** Reasons for this center on the large variety of single-neuron responses making it possible for individual cells to be interpreted as relating to numerous different movement parameters. Motor cortex has been studied in this way for decades due to the paradigm setting way in which primary visual cortex represents parameters of the outside world. But motor cortex need not represent anything in particular; rather, it must generate movement to allow the organism to survive and thrive. Creating new theories, experiments and computational methods for understanding large (electrode array) datasets is a core focus of our basic neuroscience research. It leads to a so-called "dynamical systems perspective" with fundamental implications beyond the motor system. We have reported evidence of a simple, yet powerful, dynamical system in motor cortex which also involves other cortical and subcortical areas. Four papers include:

1. Pandarinath C, O'Shea DJ, Collins J, Jozefowicz R, Stavisky SD, Kao JC, Trautmann EM, Kaufman MT, Ryu SI, Hochberg LR, Henderson JM, **Shenoy KV**, Abbott LF, Sussillo D (2018) Inferring single-trial neural population dynamics using sequential auto-encoders. **Nature Methods.** 15:805-815.
2. Sussillo D, Churchland MM, Kaufman MT, **Shenoy KV** (2015) A neural network that finds a naturalistic solution for the production of muscle activity. **Nature Neuroscience.** 18:1025-1033.
3. Churchland MM*, Cunningham JP*, Kaufman MT, Foster JD, Nuyujukian P, Ryu SI, **Shenoy KV** (2012) Neural population dynamics during reaching. **Nature.** 487:51-56.
4. Churchland MM*, Yu BM*, Cunningham JP, Sugrue LP, Cohen MR, Corrado GS, Newsome WT, Clark AM, Hosseini P, Scott BB, Bradley DC, Smith MA, Kohn A, Movshon JA, Armstrong KM, Moore T, Chang SW, Snyder LH, Lisberger SG, Priebe NJ, Finn IM, Ferster D, Ryu SI, Santhanam G, Sahani M, **Shenoy KV** (2010) Stimulus onset quenches neural variability: a widespread cortical phenomenon. **Nature Neuroscience.** 13:369-378.

2) **We also ask how it is possible for a population of neurons, many of which project directly to the spinal cord and on to muscles, can be highly active without causing movement and, more generally, how one brain area can selectively and dynamically communicate with another area.** This question arises naturally since preparatory activity (preceding movement) in premotor and motor cortex exists without generating movement. Having not found the prevailing postulate that cortical interneurons gate these signals such that they do not reach the muscles, we hypothesized that population preparatory activity may have certain patterns thereby preventing movement initiation. In linear algebra terminology, the neural activity resides in certain **"null space"** dimensions while preparing a movement, and then evolves into other activity patterns in a precise manner thereby entering dimensions **"potent space"** dimensions for generating movement. We found evidence that this mechanism is in operation, and that it can also account for flexible communication between cortical areas. The same mechanism appears to also be in operation during feedback control. Four papers include:

1. Vyas S, Golub MD, Sussillo D, **Shenoy KV** (2020) Computation through neural population dynamics. **Annual Review of Neuroscience.** 43:249–275.
2. Williams AH, Kim TH, Wang F, Vyas S, Ryu SI, **Shenoy KV**, Schnitzer M, Kolda TG, Ganguli S (2018) Unsupervised discovery of demixed, low-dimensional neural dynamics across multiple timescales through tensor components analysis. **Neuron.** 98:1-17
3. Stavisky SD, Kao JC, Ryu SI, **Shenoy KV** (2017) Motor cortical visuomotor feedback activity is initially isolated from downstream targets in output-null neural state space dimensions. **Neuron.** 95:195-208.
4. Kaufman MT, Churchland MM, Ryu SI, **Shenoy KV** (2014) Cortical activity in the null space: permitting preparation without movement. **Nature Neuroscience.** 17:440-448.

3) In order to understand the role of arm-movement preparatory activity in relation to arm-movement generation activity we have necessarily focused on the so-called "instructed delayed-reach behavioral paradigm". **This has led to insights regarding the interpretation of preparatory population neural activity as reflecting the initial state of a dynamical system, and the resulting evolution of this dynamical system (instantiated in neural circuits) resulting in movement population neural activity**. We have also reported moving beyond this task to other behavioral paradigms – including movements without a delay period, movements redirected to new (hopped) reach targets mid-reach, and during visual-motor learning – thereby putting our theories and

predictions to direct experimental test in more generalized behaviors. We found that our theories held up end we discovered entirely new neural population features that further advanced the theory. Four papers include:

1. Vyas S, O'Shea DJ, Ryu SI, **Shenoy KV** (2020) Causal role of motor preparation during error-driven learning. **Neuron.** 106:329-339.
2. Ames KC, Ryu SI, **Shenoy KV** (2019) Simultaneous movement preparation and execution in a last-moment reach correction task. **Nature Communications.** 10:2718.
3. Vyas S, Even-Chen N, Stavisky SD, Ryu SI, Nuyujukian P, **Shenoy KV** (2018) Neural population dynamics underlying motor learning transfer. **Neuron.** 97: 1-10.
4. Ames KC, Ryu SI, **Shenoy KV** (2014) Neural dynamics of reaching following incorrect or absent motor preparation. **Neuron.** 81:438-451.

4) In collaboration with Prof. Bill Newsome, we have been investigating the dynamical systems perspective (that we designed and developed with the motor system), to help reveal lawful neural population behavior from prefrontal and premotor cortical activity during sensory-integration decision tasks. We saw a wonderful intellectual intersection where Bill's group was seeing the same sort of highly heterogeneous, complex single-neuron responses in prefrontal cortex that we see in motor cortex. Our approach to this problem has been to understand the dynamical structure of the neural population activity, through specific dimensionality-reduction and state-space approaches combined with recurrent neural network (RNN) modeling so that we can analytically understand the brain's solution. We discovered a new mechanism for how prefrontal cortex may select and integrate sensory information, which opens up new avenues of investigation in this area of neuroscience and in decision making, including in motor cortex. Four example papers include:

1. Peixoto D*, Verhein JR*, Kiani R, Kao JC, Nuyujukian P, Chandrasekaran C, Brown J, Fong S, Ryu SI, **Shenoy KV**, Newsome WT (2021) Decoding and perturbing decision states in real time. **Nature.** 589:1-7.
2. Chandrasekaran C, Peixoto D, Newsome WT, **Shenoy KV** (2017) Laminar differences in decision-related neural activity in dorsal premotor cortex. **Nature Communications.** 8:614.
3. Mante V*, Sussillo D*, **Shenoy KV**, Newsome WT (2013) Selective integration of sensory evidence by recurrent dynamics in prefrontal cortex. **Nature.** 503:78-84.
4. **Shenoy KV**, Sahani M, Churchland MM (2013) Cortical control of arm movements: A dynamical systems perspective. **Annual Review of Neuroscience.** 36:337-359.

5) **The final focus area is applied neuroscience and neurotechnology.** Regarding optogenetics and optical imaging, in this collaborative research with Karl Deisseroth's group, we were among the first to design and demonstrate a set of optogenetic constructs that work in rhesus and squirrel monkeys thereby opening up many new scientific lines of investigation. More recently, we have been developing 2-photon GCaMP-based optical imaging of single-cell resolution neural activity, and later recovering neuroanatomy via CLARITY, in rhesus making arm movements which is quite challenging (but achievable) to maintaining stable.

In our BMI research, in both monkeys and in clinical trials with people with tetraplegia, we have focused on high-performance and high-robustness control of computer cursors to restore lost communication channels (#1 below). Most recently we discovered speech-related single-neuron resolution signals in human motor cortex (#2 below), discovered a new 'compositional' organization in human premotor and motor cortex (#3 below) and designed a very high performance handwriting-based BCI (#4 below). We were also the first to use NeuroPixel linear-electrode-array technology in rhesus monkeys, and we are a part of the team that has designed, fabricated and now validating a monkey optimized version of NeuroPixels (Shenoy-Moore-Shadlen-Tsao-HHMI-IMEC effort). Four papers include:

1. Pandarinath C*, Nuyujukian P*, Blabe CH, Sorice B, Saab J, Willett F, Hochberg LR, **Shenoy KV****, Henderson JM** (2017) High performance communication by people with paralysis using an intracortical brain-computer interface. **eLife.** 6:e18554
2. Stavisky SD, Willett FR, Wilson GH, Murphy BA, Rezaii P, Avansino D, Memberg WD, Miller JP, Kirsch RF, Hochberg LR, Ajiboye AB, Druckmann S, **Shenoy KV****, Henderson JM** (2019) Neural ensemble dynamics in dorsal motor cortex during speech in people with paralysis. **eLife.** 8:e46015
3. Willett FR*, Deo DR*, Avansino DT, Rezaii P, Hochberg LR, Henderson JM**, **Shenoy KV**** (2020) Hand knob area of premotor cortex represents the whole body in a compositional way. **Cell.** 181:396–409.
4. Willett FR, Avansino DT, Hochberg LR, Henderson JM**, **Shenoy KV**** (2021) High-performance brain-to-text communication via imagined handwriting. **Nature.** In press.

D. Additional Information: Research Support

Ongoing Research Support

1. NIH-NIDCD R01-DC014034 Henderson & Shenoy (Multi-PDs/PIs) 09/30/20-09/29/25

“Advanced neural decoders for communication interfaces in humans.” Design and demonstrate advanced neural decoding methods for intra-cortical brain-computer interfaces (iBCIs) for people with severe speech and motor impairment (SSMI). **Role: Multi-PD/PI (RO1 renewal for Years 6-10)**

2. NIH-NIDCD U01DC019430. Henderson & Shenoy (Multi-PDs/PIs) 04/01/21-3/31/26 3.0 cal. mo.
   “Single-neuron population dynamics in human speech motor cortex for a speech prosthesis.” Develop an intracortical brain-computer interface (iBCI) to restore communication at conversational speeds to people. **Role: Multi-PD/PI**
3. NIH-NINDS UH2-UH3 NS095548 Hochberg & Nurmikko (Multi PDs/PIs) 09/01/15-08/31/23
   “High bandwidth wireless interfaces for continuous human intracortical recording.” Design and demonstrate electrode-array recording and iBCI operation with a custom, fully-implantable wireless transmission system each other will enable rapid testing and comparison. **Role: Co-investigator**
4. NIH-NIDCD U01-DC017844 Hochberg (PI) 04/01/19-03/31/24
   “Intuitive, complete neural control of tablet computers for communication.” Translate knowledge about decoding motor cortical activity to design and demonstrate rapid and intuitive tablet-oriented iBCIs for people with SSMI. **Role: Site PI, along with Henderson**
5. NIH-NINDS R01 Kao (PI) 04/01/21-3/31/26 0.25 cal. mo.
   “An open source simulator for multi degree-of-freedom brain-machine interfaces”
   Design and validate an accurate software-only simulator for BMIs. The ability to benchmark algorithms to for people with SSMI. **Role: Site PI, along with Henderson (in NCE of Year 2 of UH2)**
6. NIH-NINDS BRAIN R01NS116623 Moore, Shenoy, Wallis (Multi-PDs/PIs) 9/30/20-09/29/25
   “Large-scale recordings in Primate Prefrontal Cortex: Mechanisms of Value and Attention.” The goal of this project is to advance neural decoding methods such that attention and/or value can be read-out in real time, and used as a contingent signal for altering a visual stimulus, in order to probe the relationship between internal cognitive neural states and behavior. **Role: Multi-PI**
7. NIH-NIMH R01MH086373 *Renewal* Deisseroth (PI) 12/01/20-11/31/25 0.25 cal. mo.
   “Brain-spanning and scale-crossing circuitry mediating motivational drives.” To advance optical and electrical data recording experimental and computational methods in rodents, in order to advance understanding of thirst/reward circuits. **Role: Co-investigator**
8. ONR W911NF-14-2-0013 Shenoy (PI) 12/1/2017-5/31/21
   “Dissecting the causal role of neural dynamics in supporting computation and behavior.” Computational modeling and analysis of decision-related activity from motor cortex. **Role: PI, along with Sussillo (Co-PI)**
9. Simons Foundation, Collaboration on the Global Brain, 543045 Shenoy (PI) 07/01/17-8/31/23
   “Computation through dynamics.” Measure and model cortical population activity to advance a “Computation Through Dynamics” (CTD) understanding of how computations are performed via dynamics. **Role: PI**
10. Howard Hughes Medical Institute (HHMI), Investigator Shenoy (PI), renewable 09/01/15-08/31/21
    Cortical neural population measurement and computational modeling, including for use in iBCIs for people with SSMI. **Role: PI**

Completed Research Support (from last 3 years)

1. NIH-NIDCD R01-DC014034 (competitively renewed) Henderson (PI) 04/01/15-08/31/20
   “Advanced Neural Decoders for Communication Interfaces.” Design advanced neural decoding methods and interfaces for a high-performance communication system for people with locked-in syndrome. **Role: Co-I**
2. NIH-NINDS UO1-NS098968 Cash (PI) 9/1/16-08/31/20
   “Understanding the neural basis of volitional state through continuous recordings in humans.” Design and develop analysis techniques for measuring and tracking neural population states. **Role: Co-I**
3. DARPA BTO “NeuroFAST” W911NF-14-2-0013 Deisseroth (PI) 12/23/13-04/01/20
   “NeuroFAST: Neuroscience: Function, Anatomy, Science, and Technology.” Design and develop optical cortical imaging system for awake, reaching rhesus monkeys. Perform series of basic science and neural prosthetics experiments and analyses. **Role: Co-PI**
4. Simons Foundation 325380 Ganguli & Shenoy (Multi-PIs) 09/01/14-08/31/18
   “Towards a theory of multi-neuronal dimensionality, dynamics and measurement.” Measure cortical population activity while monkeys perform various arm movements in order to advance theoretical understanding of the dimensionality of this neural activity. **Role: PI**