From neural circuits to behavior: Cross-scale integration and computational neuroscience

Xiao Han,[1,2,*] Han Xu,[3,4] Qiufang Fu,[5] Chong Liu,[6] Haiteng Jiang,[4,7,8,9,10] Yong Gu,[11,12] Peng Cao,[13] Wanying Zhao,[5] Wei Wang,[11,12] Neng Gong,[11,12] and Shuang Qiu[14]

[1]Department of Molecular and Cellular Physiology, Stanford University, California 94305-5345, USA
[2]Howard Hughes Medical Institute, Stanford University, California 94305-5345, USA
[3]Department of Psychiatry, The Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou 310009, China
[4]The School of Brain Science and Brain Medicine, Zhejiang University School of Medicine, Hangzhou 310058, China
[5]State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China
[6]Department of Neurosurgery of the Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou 310058, China
[7]Liangzhu Laboratory, State Key Lab of Brain-Machine Intelligence, Zhejiang University, Hangzhou 311121, China
[8]MOE Frontier Science Center for Brain Science and Brain-Machine Integration, Zhejiang University, Hangzhou 310058, China
[9]Affiliated Mental Health Center & Hangzhou Seventh People's Hospital, Zhejiang University School of Medicine, Hangzhou 310013, China
[10]NHC and CAMS Key Laboratory of Medical Neurobiology, Zhejiang University, Hangzhou 310058, China
[11]Institute of Neuroscience, Key Laboratory of Brain Cognition and Brain-inspired Intelligence Technology, Chinese Academy of Sciences, Shanghai 200031, China
[12]CAS Center for Excellence in Brain Science and Intelligence Technology, International Center for Primate Brain Research, Shanghai 200031, China
[13]National Institute of Biological Sciences, Beijing 102206, China
[14]Department of Anesthesiology, The Second Affiliated Hospital, Zhejiang University School of Medicine, Hangzhou 310009, China
*Correspondence: hanxiao3@stanford.edu; hanxiao3579@gmail.com (X.H.)

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INTRODUCTION

Neuroscience is converging on a central question: how to achieve cross-scale integration from molecules and cells, through neural circuits, to cognition, consciousness, and behavior. Understanding brain function now requires connecting information across levels, systems, and timescales, while the rise of artificial intelligence is prompting the field to revisit classic questions about perception, consciousness, and the nature of intelligence with new computational tools. Held as part of the Innovation Conference on Life 2026 in Zhuhai, this session, "From Neural Circuits to Behavior: Cross-Scale Integration and Computational Neuroscience," brought together researchers exploring how multi-scale, multi-modal data can reveal principles of brain organization in development, cognition, and disease.

NEURAL MECHANISMS OF HIGHER COGNITION AND PERCEPTION

Qiufang Fu (State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences):

Dynamic neural representations of natural scenes. How the brain builds scene representations from edge and surface features remains unclear. In three EEG decoding studies, Qiufang's team found that surface information facilitated decoding of individual scenes and basic-level categories, whereas line drawings were decoded earlier and more accurately at the superordinate level (natural vs. man-made), even after controlling for spatial frequency. Under backward masking, edges conferred a behavioral advantage. In object-embedded scenes, surface features enhanced scene but not object decoding, and scene representations preceded object representations. These findings reveal a feature-dependent hierarchy: surface features support detailed representations, whereas edges dominate as representations become more abstract or processing time is limited.

Yong Gu (Center for Excellence in Brain Science and Intelligence Technology, Chinese Academy of Sciences):

Multisensory coding of self-motion perception. Primate self-motion perception integrates vestibular and optic flow signals, with congruent cues improving heading judgments. In MST and VIP, congruent visual-vestibular neurons plausibly explain this multisensory enhancement. VPS, however, is dominated by conflict neurons, which by encoding logic should impair discrimination. Moreover, microstimulating VPS biases vestibular heading perception ipsilaterally regardless of the neurons' heading preference, a hemispheric decoding rule unlike the labeled-line readout of MST and VIP. Thus, a region's function cannot be inferred from encoding properties alone; encoding and decoding may follow distinct principles. Vestibular signals encode acceleration for rapid decisions, whereas optic flow provides sustained velocity. How they support path integration remains open.

Two other talks in the session broadened the scope further: Neng Gong (Center for Excellence in Brain Science and Intelligence Technology, Chinese Academy of Sciences), examined self-recognition in monkeys, infants, and robots. Wei Wang (Center for Excellence in Brain Science and Intelligence Technology, Chinese Academy of Sciences) presented on "Seeing the world in a grain of sand: Fine global and local representations in foveal and parafoveal vision".

NEURAL CIRCUITS UNDERLYING EMOTION AND DISEASE

Han Xu (Zhejiang University School of Brain Science and Brain Medicine):

Neural mechanisms and interventions for social anxiety. Excessive social fear can drive maladaptive avoidance and contribute to social anxiety disorder, yet how adverse social experiences become lasting avoidance remains unclear. Using a social fear conditioning paradigm in mice, researchers found social fear expression was driven by dorsomedial prefrontal cortex (dmPFC) hyperactivity, arising from a disinhibitory microcircuit in which SST interneurons suppressed PV interneurons, releasing pyramidal neurons from inhibition. The dmPFC acted through a glutamatergic projection to the lateral habenula; inhibiting this projection restored social approach without affecting locomotion or baseline anxiety. In humans, prefrontal–habenular resting-state connectivity correlated with social anxiety, identifying this circuit as a potential cross-species biomarker and therapeutic target.

Peng Cao (National Institute of Biological Sciences, Beijing):

Neural mechanisms of brain-body interaction. The brain senses organ pathology through neural circuits, but these remain poorly defined for most organs. Peng's work maps such circuits across brain–body axes. In the gut–brain axis, mice display retching-like behavior, challenging the assumption that rodents cannot vomit: intestinal damage triggers IL-33 release and enterochromaffin serotonin secretion, activating vagal afferents that relay to $TAC1^+$ NTS neurons driving nausea and retching. In the lung–brain axis, $PDYN^+$ NTS neurons were identified as the cough reflex hub, with dynorphin–kappa receptor signaling acting as a brake. These findings show that the brain senses organ-specific pathology via dedicated afferent circuits, informing therapies for chemotherapy-induced emesis, chronic cough, and cardiac arrest resuscitation.



Figure 1. Speakers at the session "From neural circuits to behavior: Cross-scale integration and computational neuroscience," part of the Innovation Conference on Life 2026, held in Zhuhai, China, July 2026.

Chong Liu (Department of Neurosurgery of the Second Affiliated Hospital, Zhejiang University School of Medicine):

Decoding the spatiotemporal dynamics of cellular pliancy in stem cell carcinogenesis: From mechanism to intervention. Chong presented his team's work on how somatic stem cells acquire malignant potential, framed around cellular pliancy, the intrinsic susceptibility of stem cells to oncogene-driven remodeling. Using genetically engineered mouse models, he showed that neural stem cells give rise to OPCs that become glioma stem cells, and that blocking this trajectory via IGF1R suppresses gliomagenesis in vivo. Organismal inputs shape this process directly: olfactory experience promotes glioma initiation through neuron-derived IGF1, while sleep deprivation and chronic stress enhance tumor stemness. His consortium developed tools for clonal tracking, multi-mutation modeling, and spatial multi-omics. The goal is identifying "pliancy checkpoints" as targets for cancer prediction and prevention.

The session also featured a talk by Shuang Qiu (Zhejiang University School of Medicine) on neuronal network mechanisms underlying vmPFC-mediated fear termination.

COMPUTATIONAL MODELING AND MEDICAL AI

Haiteng Jiang (MOE Frontier Science Center for Brain Science and Brain-machine Integration, Zhejiang University):

Exploring the universality, generalizability, and interpretability of intelligent sleep staging. Deep learning approaches to sleep staging remain limited by scarce labels, device variability, and poor cross-center generalization. This study built LPSGM, a large sleep EEG model trained on roughly 24,000 public cases from 16 sites plus 231 private cases (225,000 hours of PSG), using a unified CNN-Transformer architecture adaptable to varying channel configurations. On external testing, it achieved 85.68% and 84.13% accuracy on the HQ and SYSU datasets, outperforming baselines. Grad-CAM confirmed the model attends to AASM-relevant features such as spindles and slow waves. Clinically, it matched three technicians while cutting reporting time to minutes, though performance dropped in depression and narcolepsy.

Wanying Zhao (Institute of Psychology, Chinese Academy of Sciences):

An information-theoretic account of the neural computational mechanisms underlying multimodal semantic integration. Human communication is multimodal, yet quantifying semantic information across heterogeneous modalities within a unified framework remains challenging, since modality-specific representations occupy heterogeneous spaces.[1,2,3] This work introduces an information-theoretic framework built on a cross-modal semantic probability alignment method, which maps representations such as speech and gesture into a shared probabilistic semantic space and uses reliability weighting to quantify each modality's contribution. From this space, a continuous measure of semantic integration was derived by modeling unimodal and multimodal probability distributions. EEG data from 60 participants showed this measure predicts gesture-speech integration during the N400 and P600 windows, demonstrating that information-theoretic measures can track dynamic multimodal semantic processing.

DISCUSSION AND FUTURE PERSPECTIVES

Across topics spanning visual neuroscience, multisensory integration, language cognition, neuromodulation, tumor biology, and artificial intelligence, the symposium converged on a shared question: how does the brain integrate information across regions, timescales, and systems to generate coherent perception and behavior? Studies of visual and cross-modal processing suggested that diverse information is encoded in parallel and integrated at later stages, and that fast and slow pathways reflect a trade-off supporting distinct sensory and cognitive functions. These findings point toward a dynamic view of brain function, with translational relevance ranging from AI to education, neuromodulation, and clinical intervention.

Central to this view is the mesoscopic level of brain organization, including neural circuits, cell-type-specific populations, and neuronal ensembles. This level bridges molecular and cellular mechanisms with cognitive function. Parallel encoding, pathway divergence, and progressive integration are properties of circuits rather than of individual molecules or cells, and macroscopic measurements alone cannot fully resolve them. The mesoscopic level is therefore where computational principles emerge from cellular components and where they can be causally tested. Cell-type-specific recording and manipulation can link circuit mechanisms down to their molecular substrates and up to perception and behavior. Translational strategies such as neuromodulation and brain-inspired AI likewise act on, or draw from, circuit-level organization. This makes the mesoscopic level the most direct route toward a mechanistic, cross-scale account of brain function.

Advancing this understanding will require integrating methodological, conceptual, and translational approaches. Large-scale models, whole-brain recording, multimodal data integration, and causal intervention tools will be essential for moving from correlation to causation. AI models, in turn, must become more interpretable and clinically trustworthy. These advances could enable objective diagnosis and precise intervention for neurological and psychiatric disorders, and could inform embodied AI capable of predictive, multi-scale integration. Together, they reflect a growing convergence of neuroscience, medicine, and AI around one question: how biological systems transform information across scales into cognition and behavior.

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AUTHOR CONTRIBUTIONS

Conceptualization and coordination: Xiao Han. Writing—original draft: Xiao Han, Han Xu, Qiufang Fu, Chong Liu, Haiteng Jiang, Yong Gu, Peng Cao, Wanying Zhao, and Wei Wang. Writing—review and editing: all authors. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.