Headset-Integrated Brain-Machine Interface for Mind Imagery and Control in VR/MR Applications

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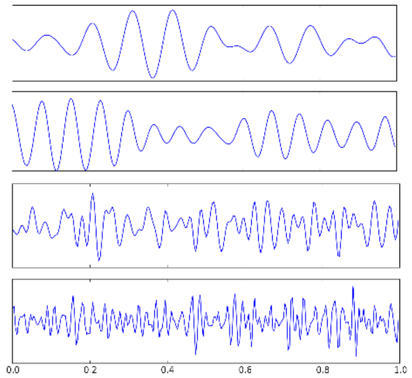
New Opportunities from BMI for VR/MR

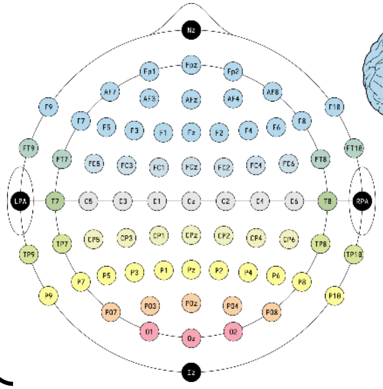
VR/MR Headsets

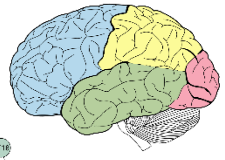
- **Electroencephalogram (EEG)**
  - Brain's electrical activity
- **Brain-Machine Interface (BMI)**
  - Brain activity tracking
    - Active control
    - Reactive control
    - Passive control

Interaction Methods



EEG waves





Applications

Gaming

Movie/Shopping

Office

Motivation and Challenges

VR headset

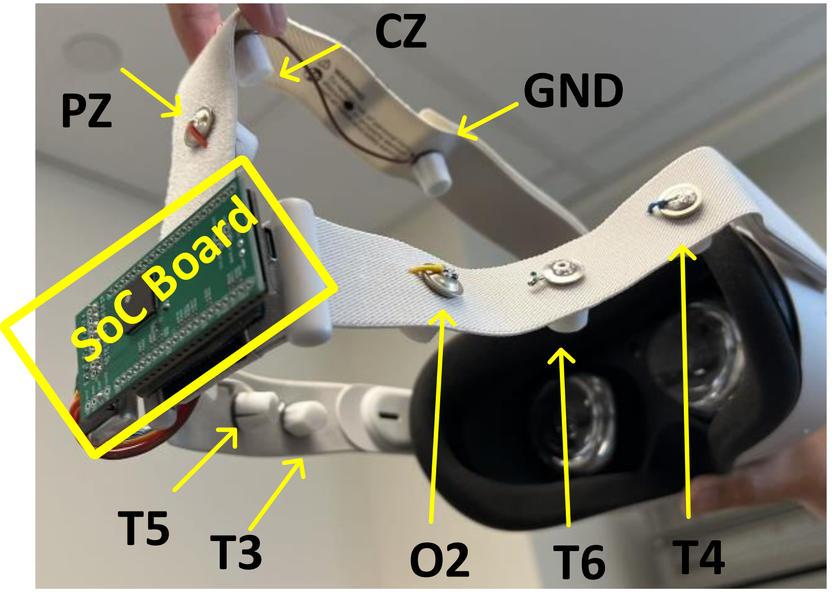
EEG electrode cap

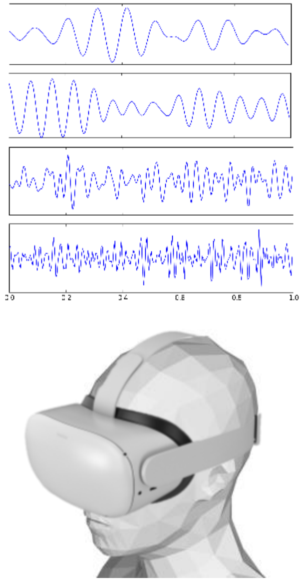
Desktop

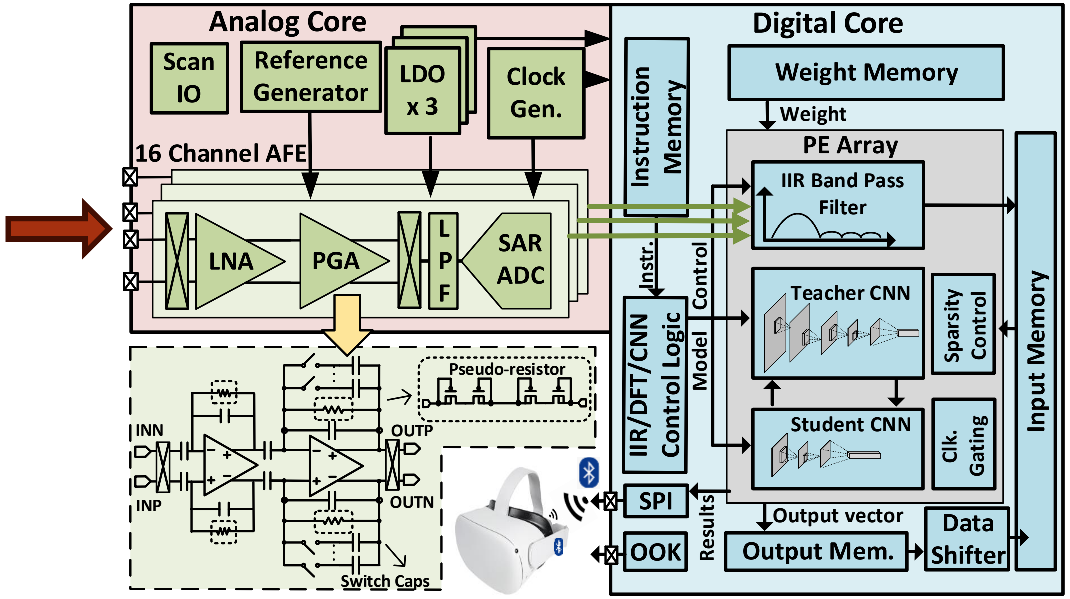
Immersive virtual environment & brain activity combination

- **Cumbersome wearing**
- **High power for AI models**
- **Lack of low-latency computing support**
- **Lack of real-time feedback control**

This Work

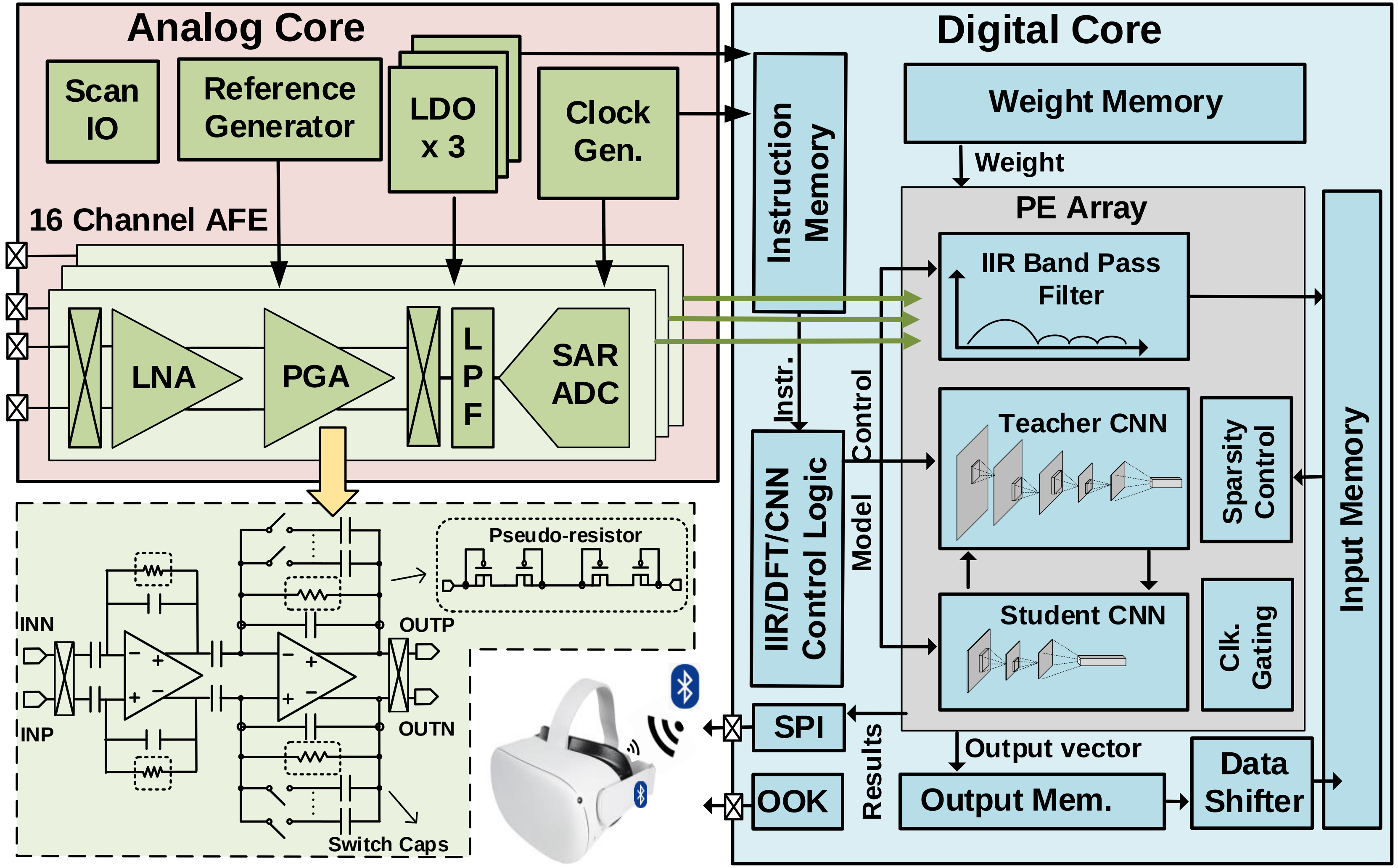






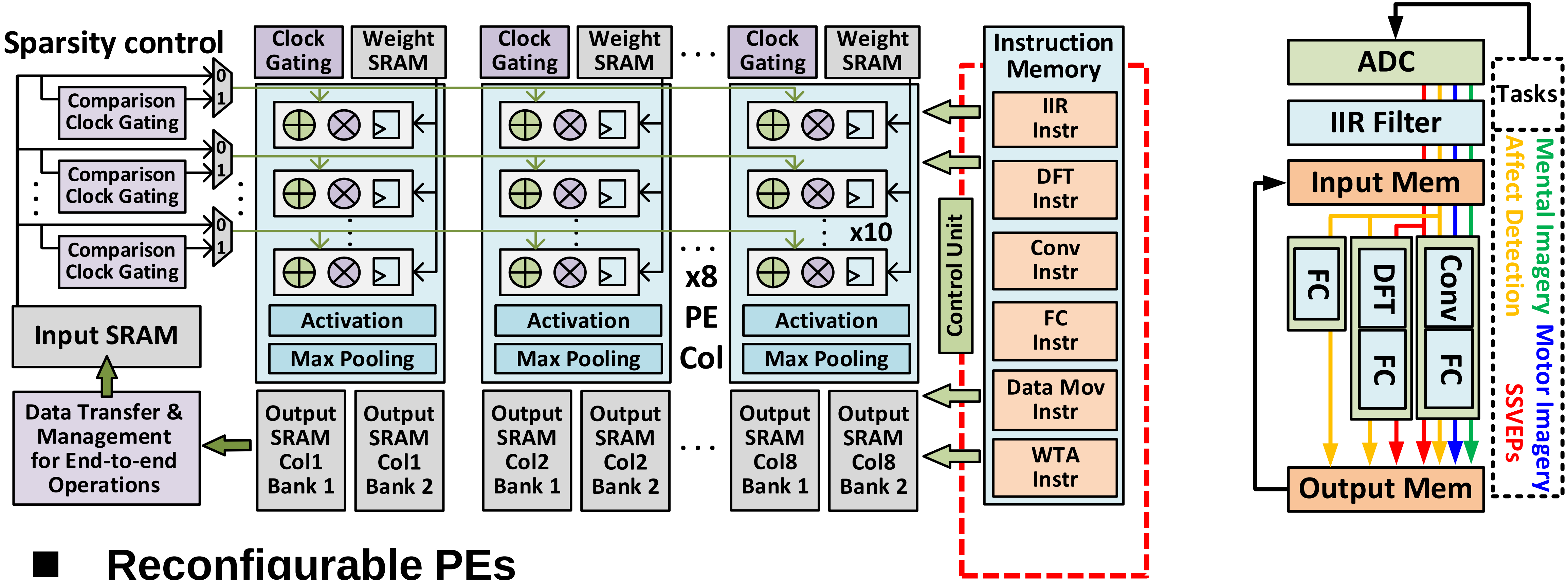
- The First SoC supporting mind imagery control for VR/MR
- Integration with VR headset and optimized channel placement
- ISA and AI architecture for general-purpose mind imagery tasks
- Teacher-Student CNN and sparsity enhancement for power saving

System Overview



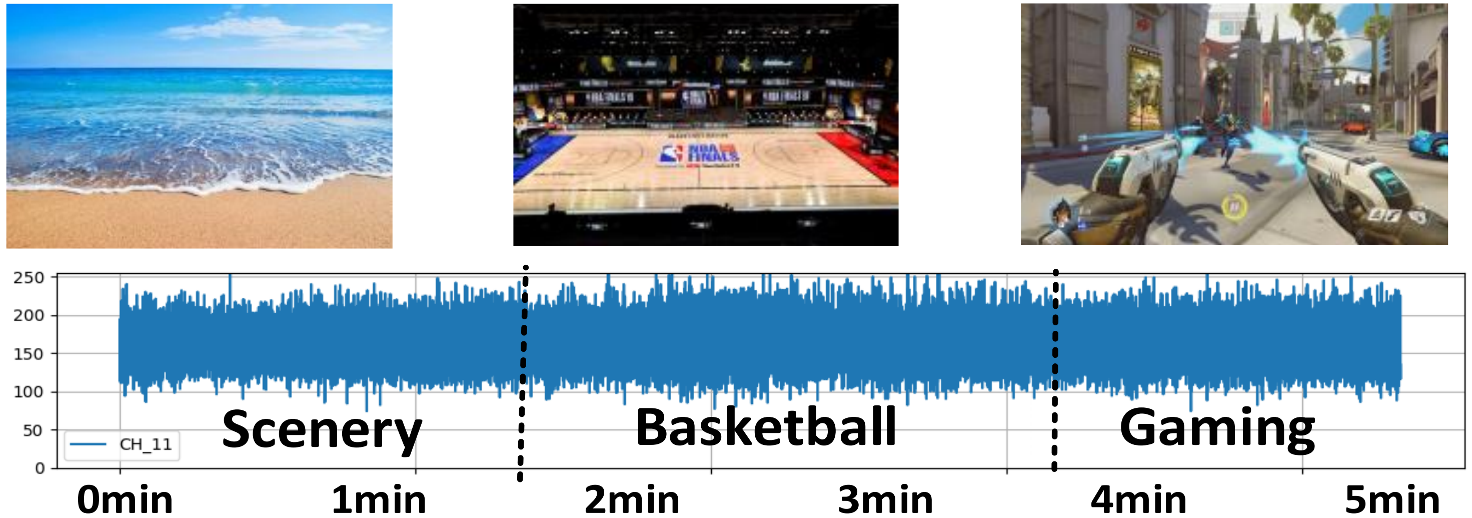
- **16-ch AFE for EEG**
  - Two-stage chopper amp.
  - 45-72dB gain
  - 0.05-400Hz bandwidth
- **8x10 MAC PE array**
- **IIR band pass filter**
- **Discrete Fourier trans.**
- **Convolutional NNs**
- **Instruction Mem.**
- **Customized inst.**
- **Control VR by ext. BLE**

Neural Processor Architecture and Configuration

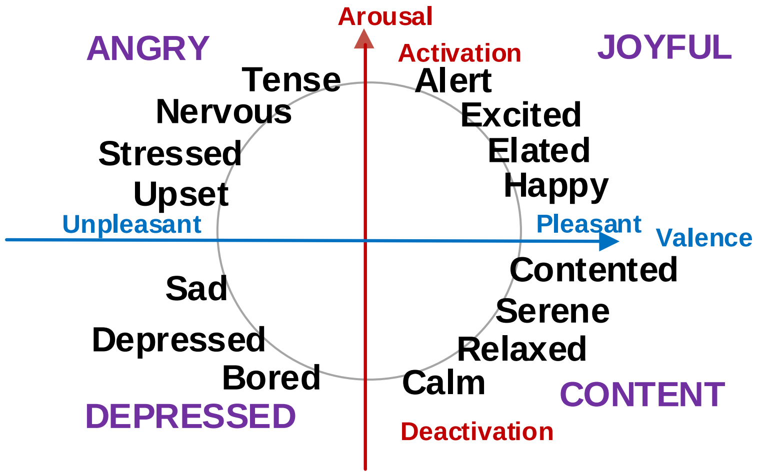


- Reconfigurable PEs
- Flexible solutions for EEG tasks
- End-to-end flow without Off-Chip data reloading

Teacher-Student CNN for Affect Monitoring



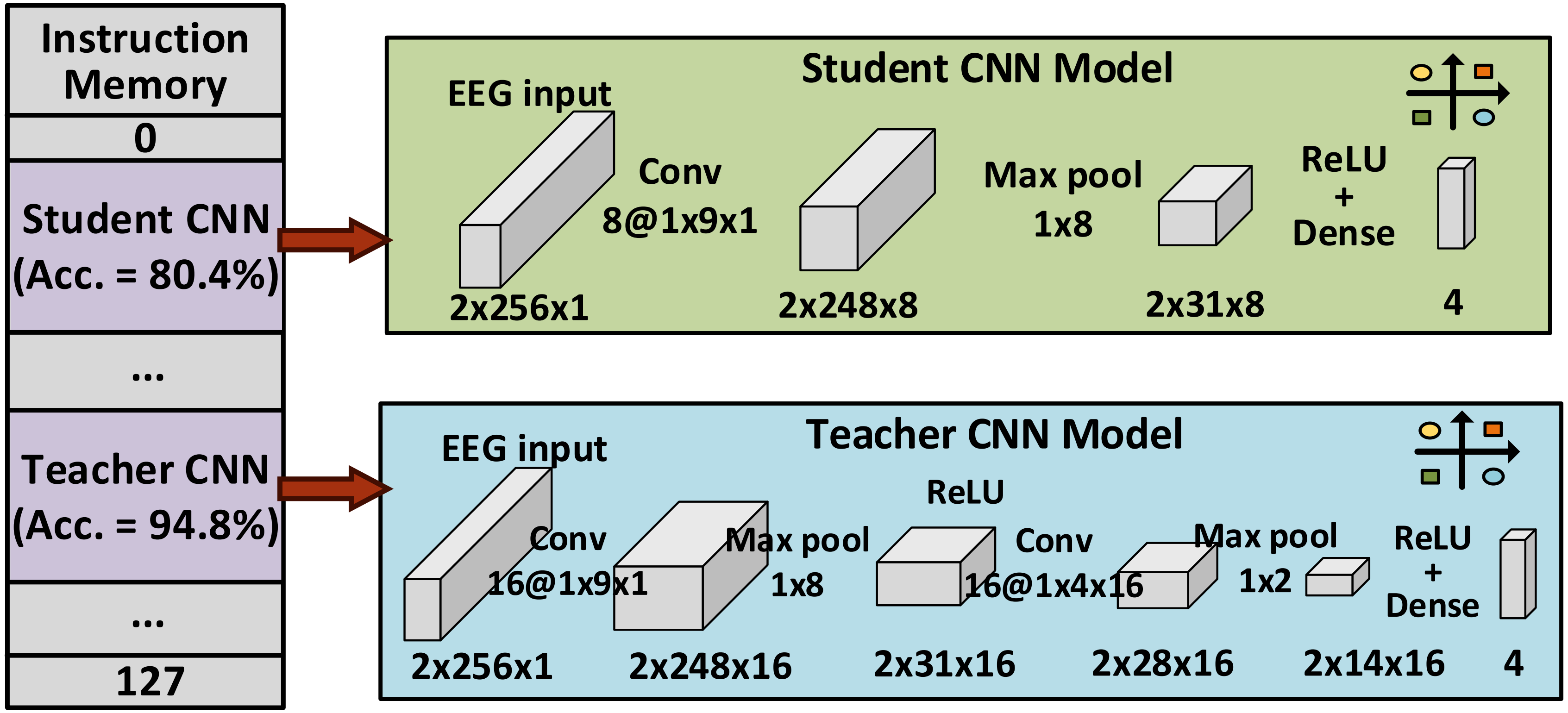
EEG recorded during YouTube watching



Russell circumplex model on emotion

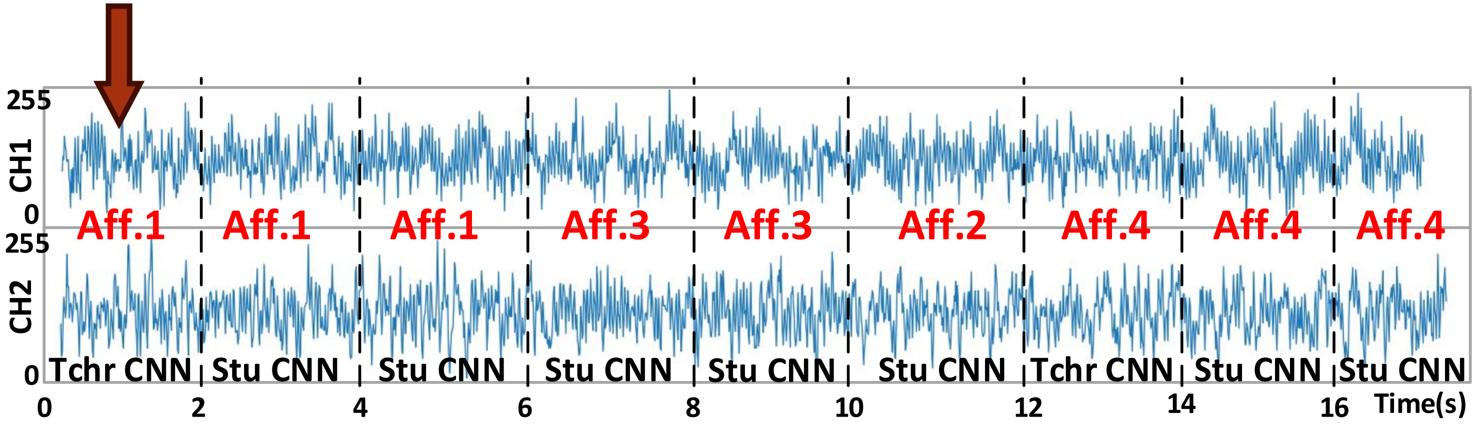
- **Affect changes at a slow pace over a long period**
- **Integrated circuits run at a much faster speed**
- **Teacher-Student CNN scheme based on temporal locality**
  - Two CNN models with different cost and accuracy
  - Balance between computational power and accuracy

Confusion Matrix Guided CNN Scheme



- **Affect classification**
  - Four classes
- **Student CNN model**
  - 3x faster
  - 70% less energy
  - 14% lower accuracy
- **Teacher CNN model**
  - Higher cost
  - Higher accuracy

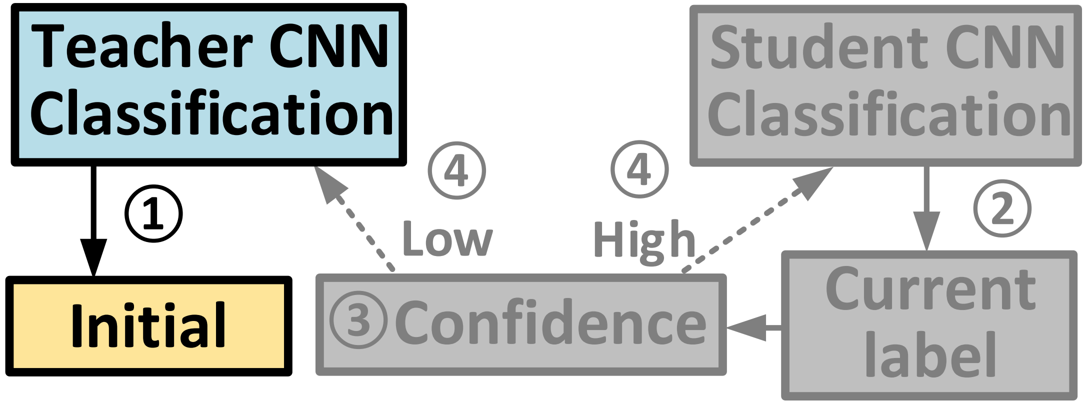
Confusion Matrix Guided CNN Scheme

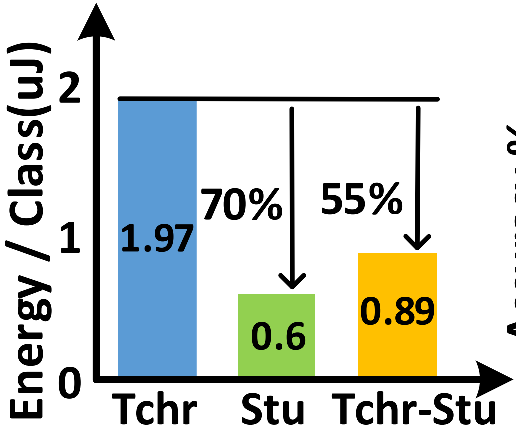


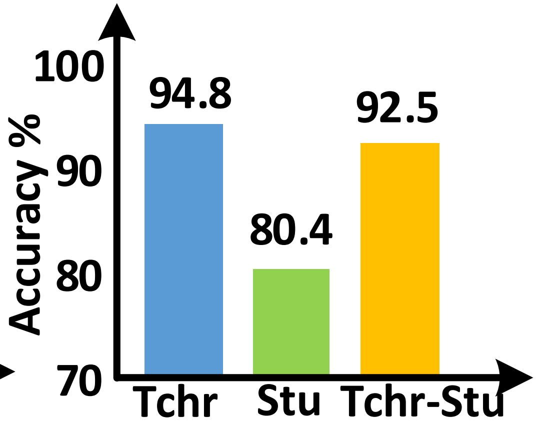
Predicted

Actual	Aff.1	Aff.2	Aff.3	Aff.4
Aff.1	0.986	0.014	0	0
Aff.2	0.014	0.966	0	0.02
Aff.3	0.027	0	0.932	0.041
Aff.4	0	0.667	0	0.333

Student confusion matrix

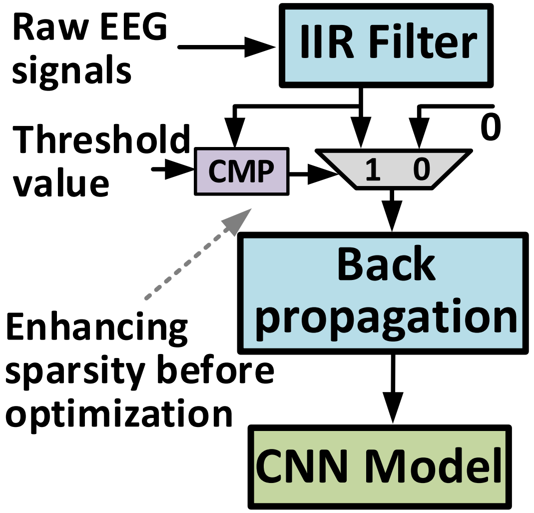




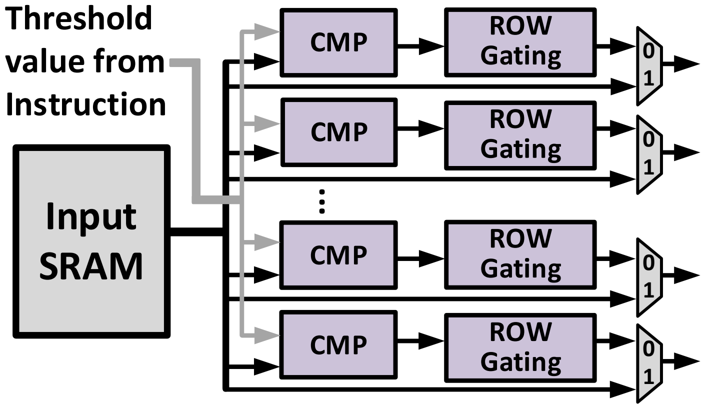


- Teacher CNN for initial prediction
- Student CNN for monitoring

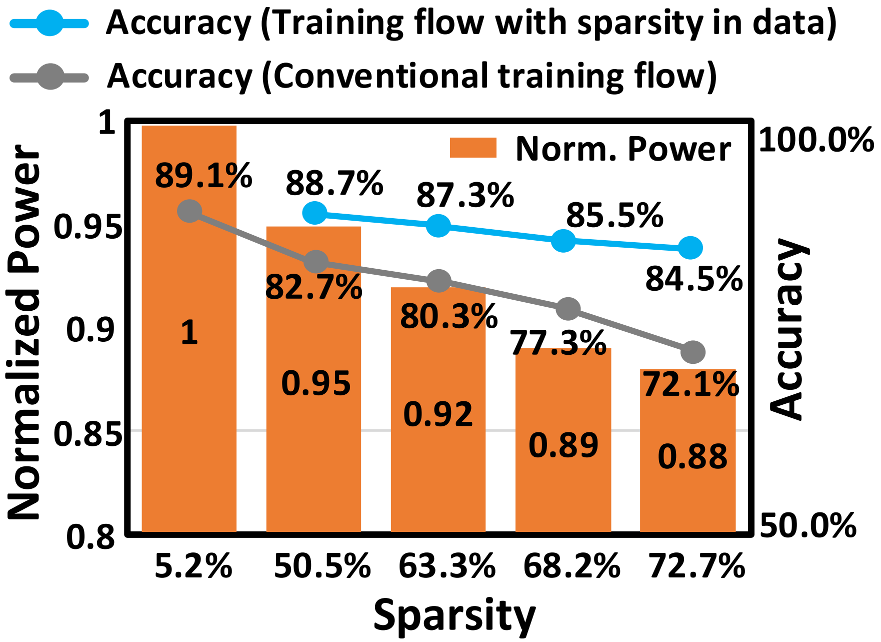
Sparsity Enhancement



Sparsity-Enhanced training flow



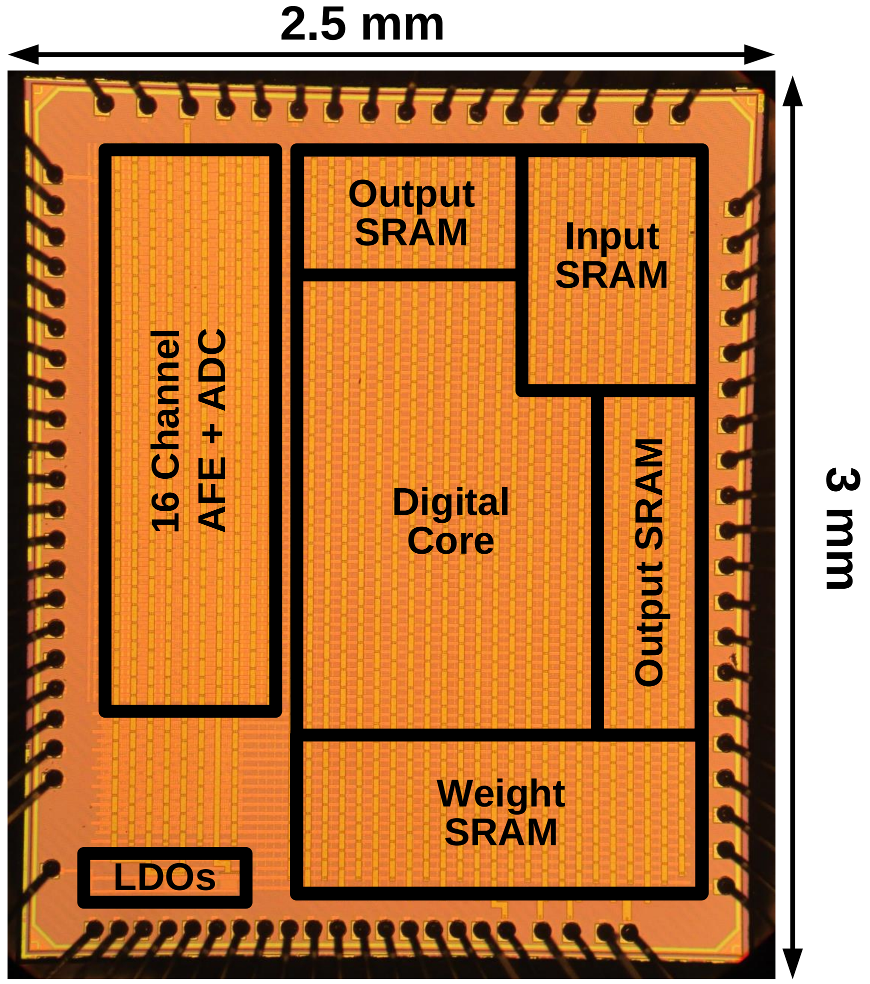
On-Chip Inferencing

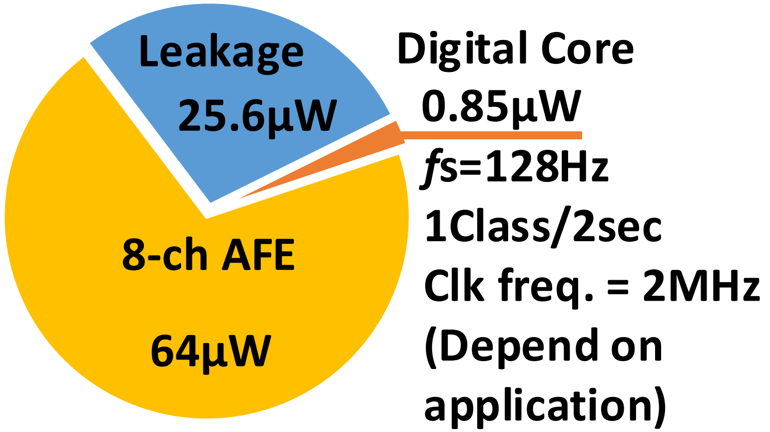


Binary affect classification

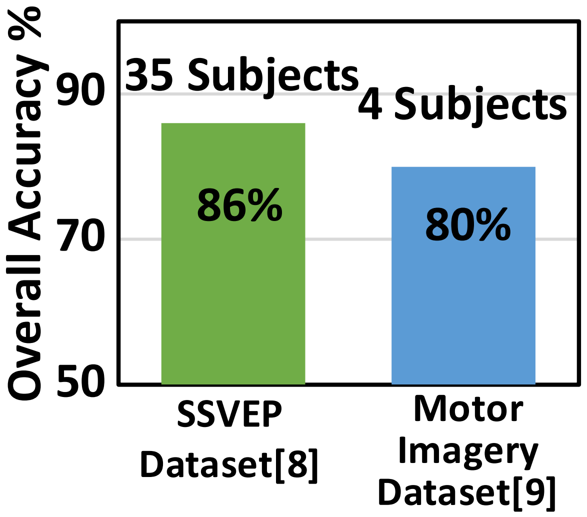
- **Increase data sparsity and accuracy w/ sparsity-aware training**
  - 12% power saving
  - 12.4% accuracy improvement by sparsity-aware training

Chip Implementation & Measurement Results





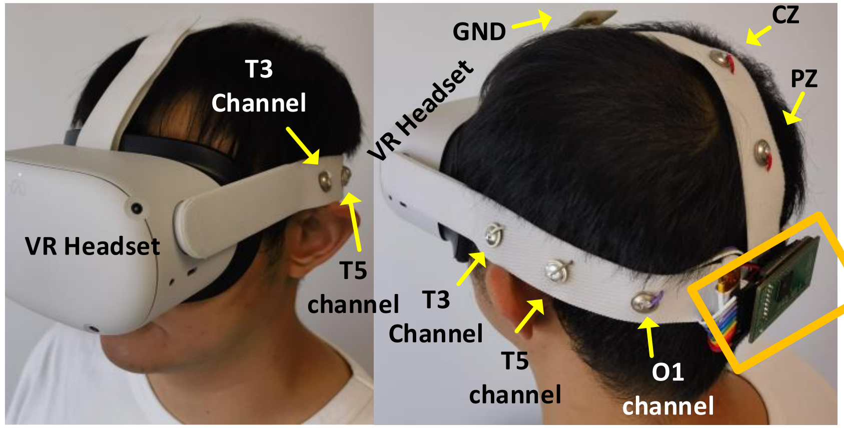
Average power in affect monitoring

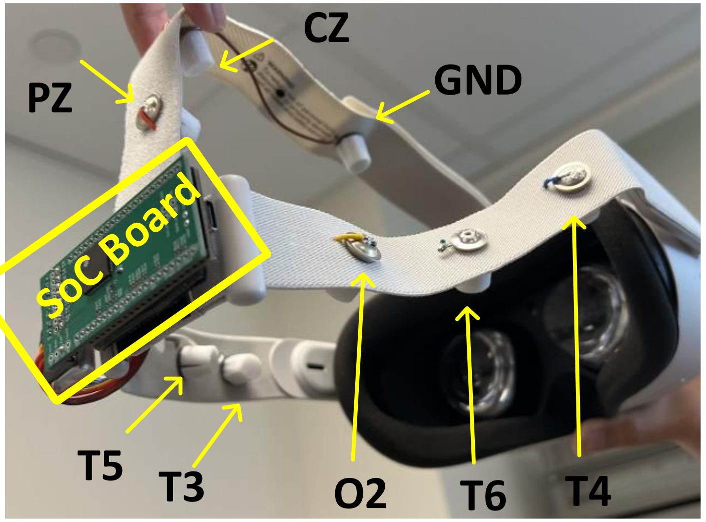


Public dataset results

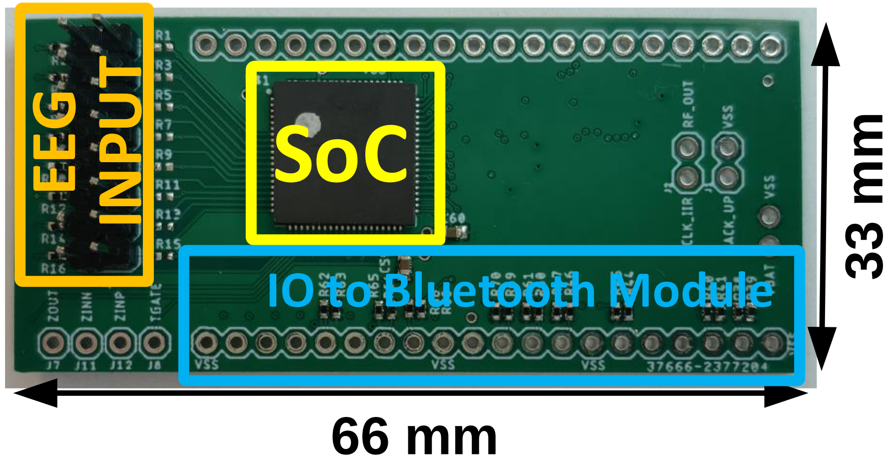
Chip fabricated In TSMC 65nm

System Setup and Applications





- Meta Quest 2 VR
- Customized VR scene and games
- Chip communicated with VR through BLE



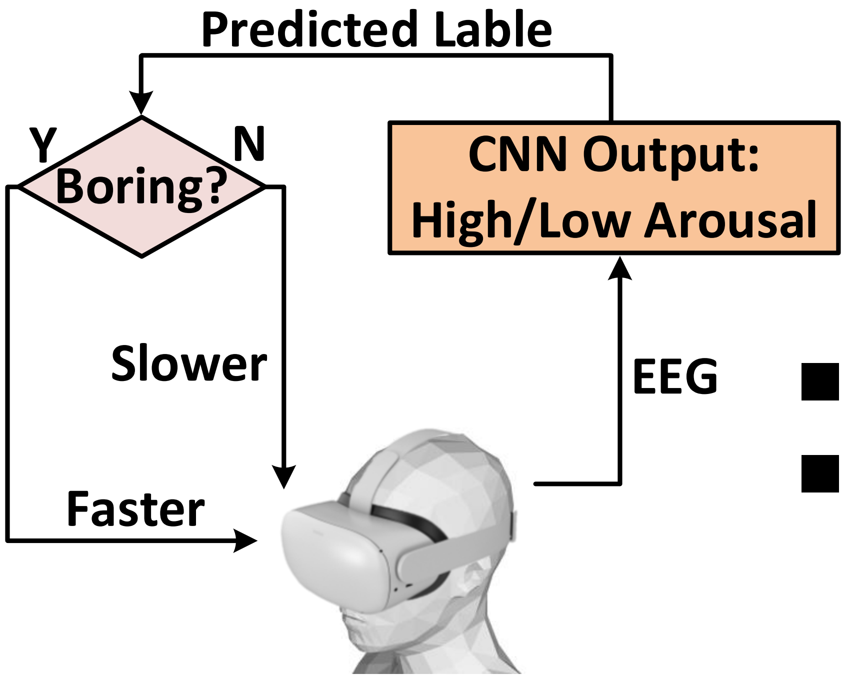
Real-time Affect Tracking and Control for VR Game

① **Collect EEG signals as training and validation data**

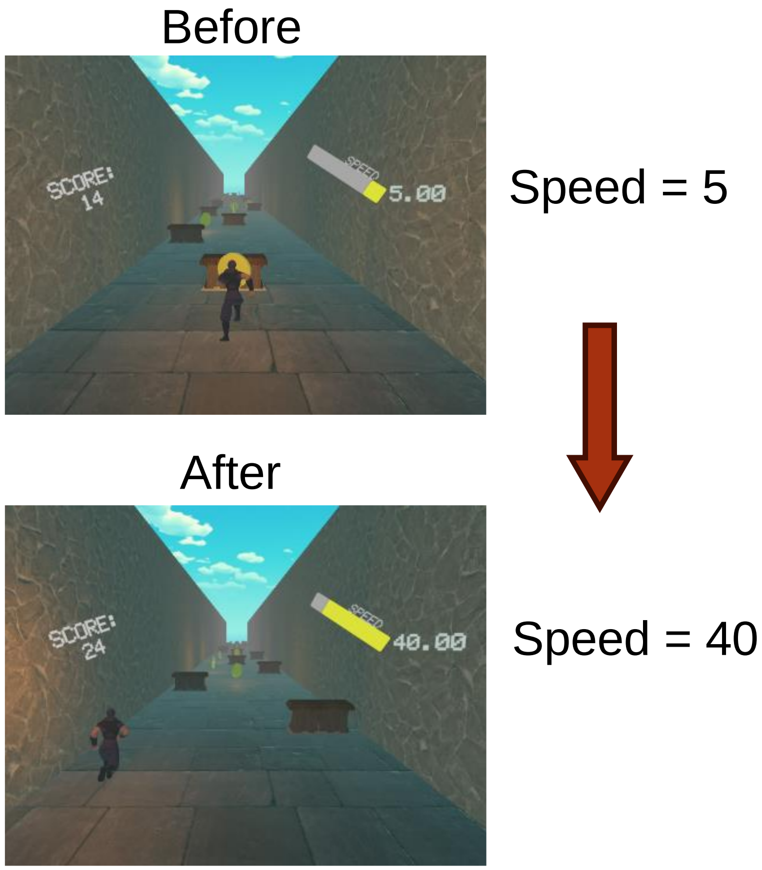
Easy Gaming	Rest	Intense Gaming	Rest	Easy Gaming	Rest	Intense Gaming	Rest

0 min · 1 min · 2 min · 3 min · 4 min

② **Change the game speed based on gaming experience**



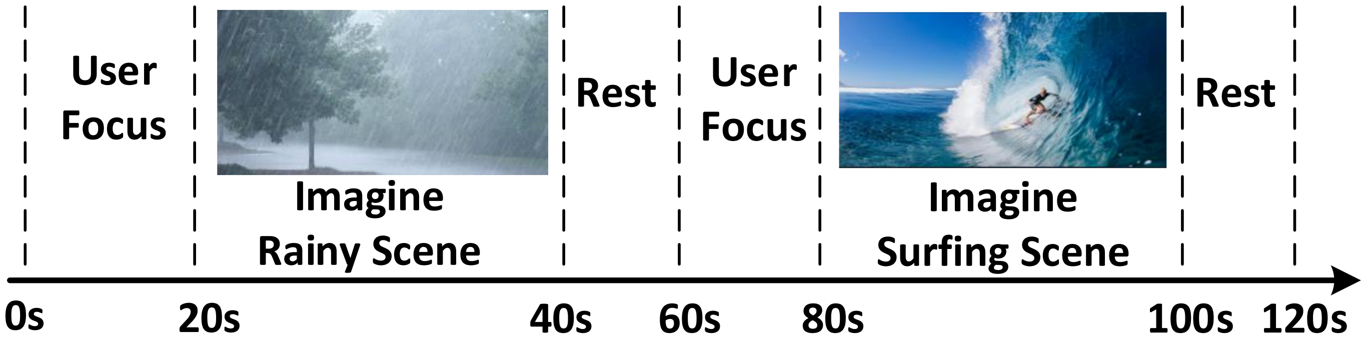
- **Passive speed control**
- **~90% accuracy**



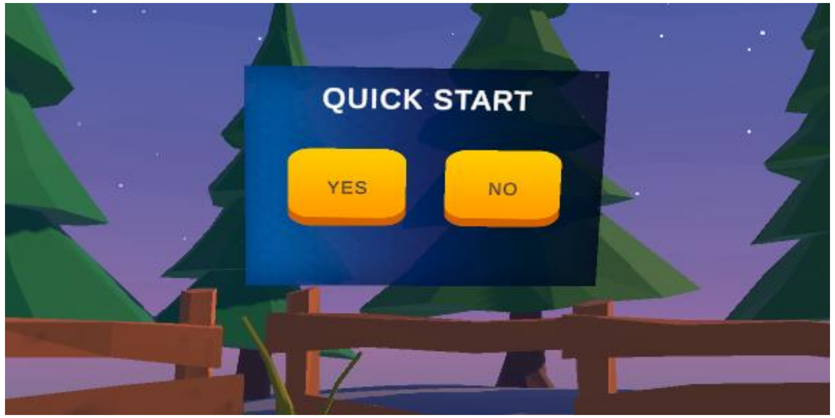
Customized Endless-Runner VR game

Mental Imagery Controlled Menu Selection

① Collect EEG signals as training and validation data



② Issue commands to VR by actively changing mental states



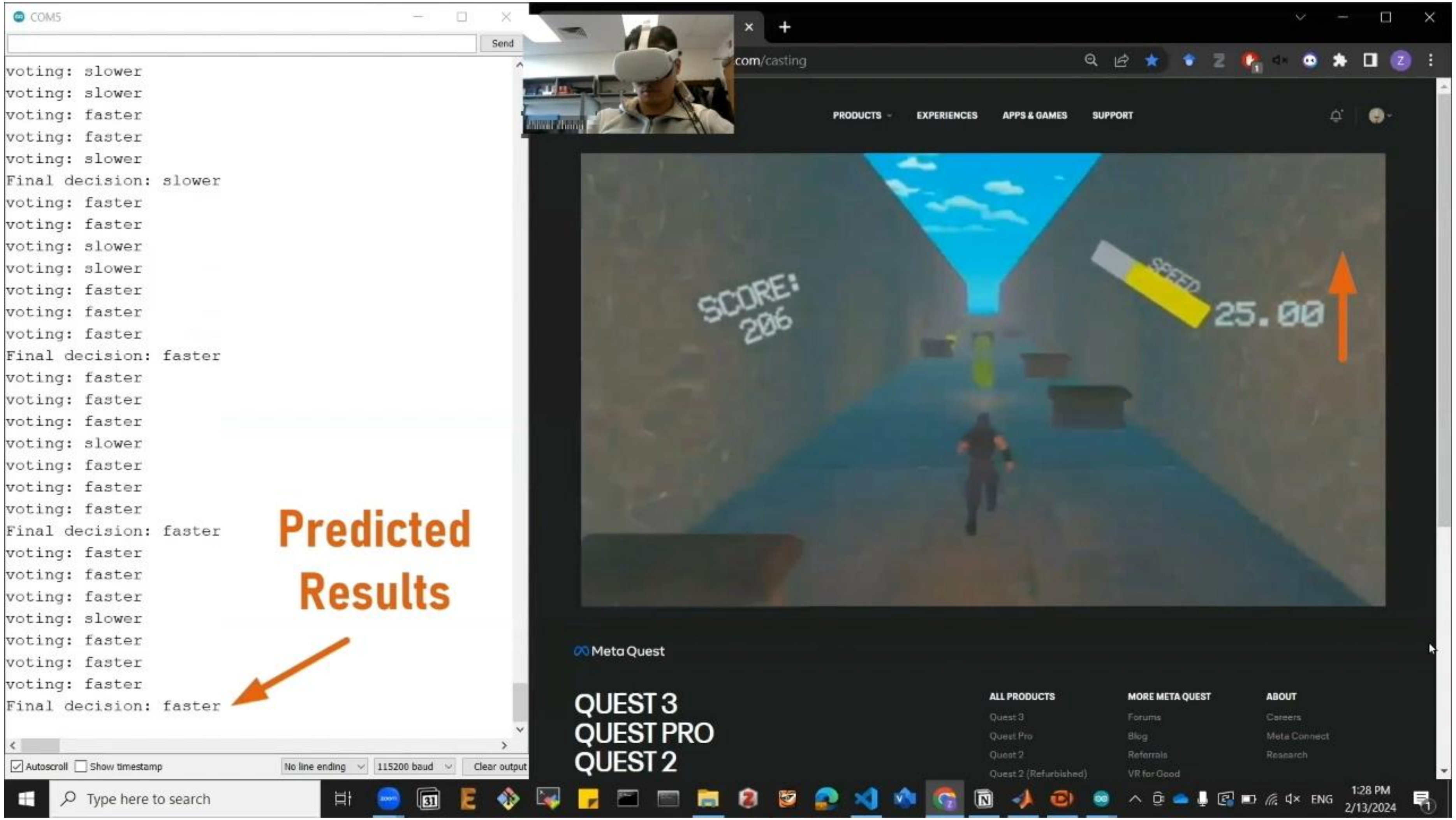
Focus: open menu

Surfing (intense): YES

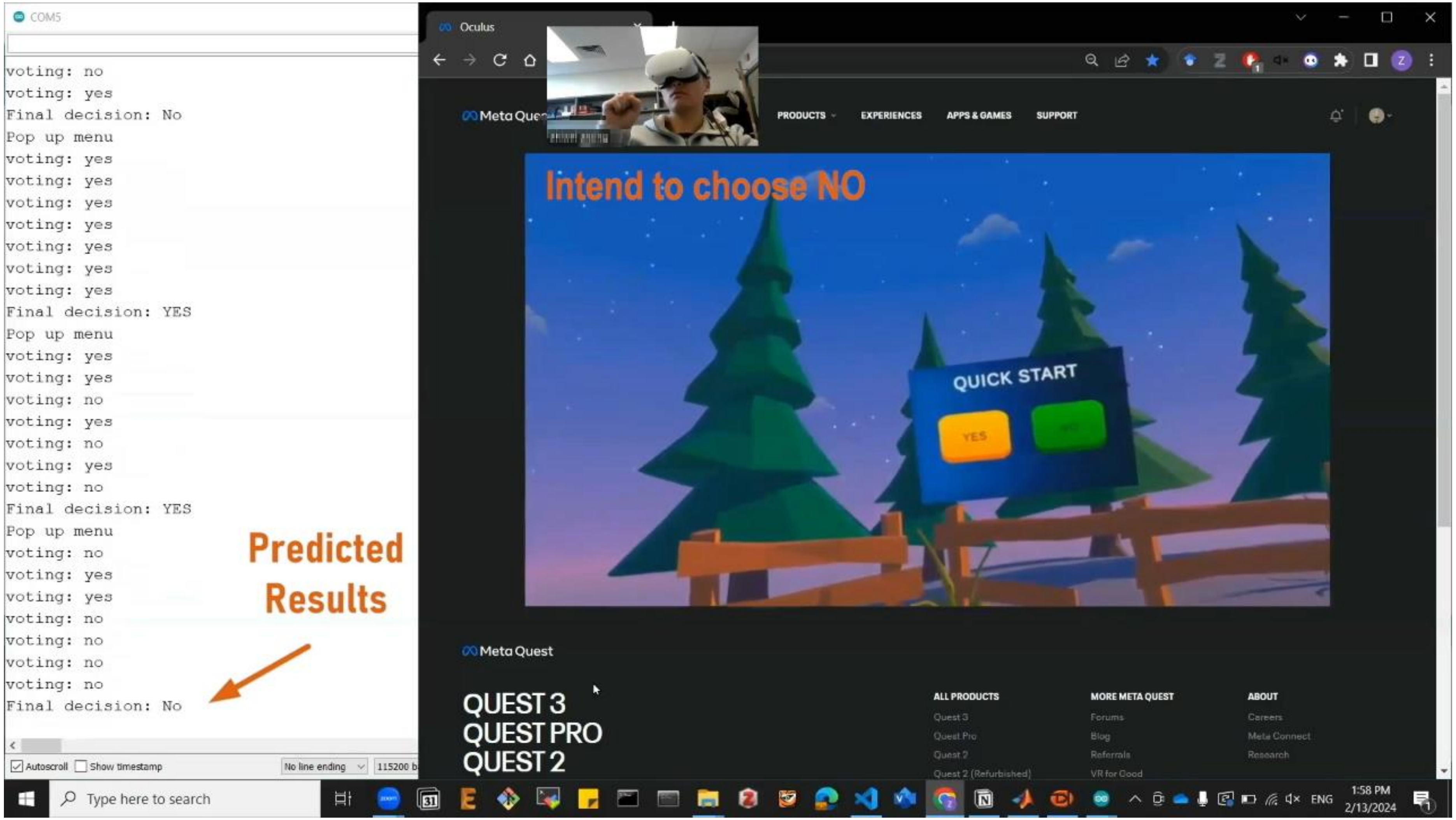
Rainy (relaxed): NO

- Active control by mind states
- Scenario-aided imagery
- ~80% accuracy

Real-time Affect Tracking and Control for VR Game



Mental Imagery Controlled Menu Selection



Summary

- **The first SoC for Mind Activity Monitor and Control for VR/MR**
  - Integration with VR headset and optimized EEG electrodes placement
  - Instruction Set and reconfigurable architecture for various brain activity tasks
- **Special Low-power Features**
  - Teacher-Student CNN guided by confusion matrix with 55% energy saving
  - Sparsity-aware training flow with 12% power saving
- **65nm Test Chip and System Demonstrations**
  - Mental imagery and control for VR menu operation
  - Affect tracking and control of gaming scenes
  - Achieved lowest energy per class for CNN operation among biomedical ICs

Thank you!