Inter-brain coupling for learning in real classroom settings
基于真实课堂脑电超扫描的学生学习过程研究

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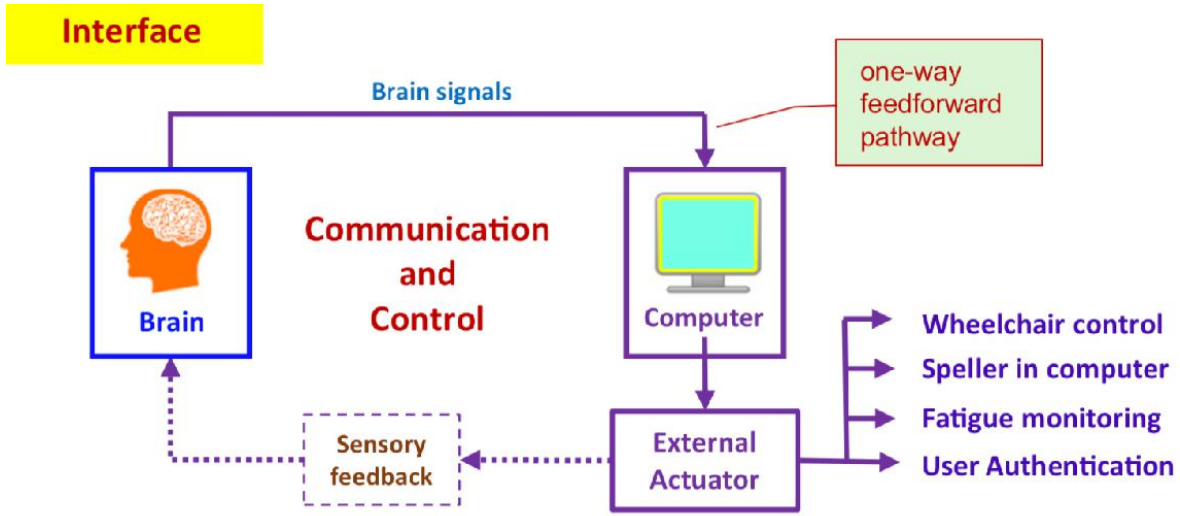
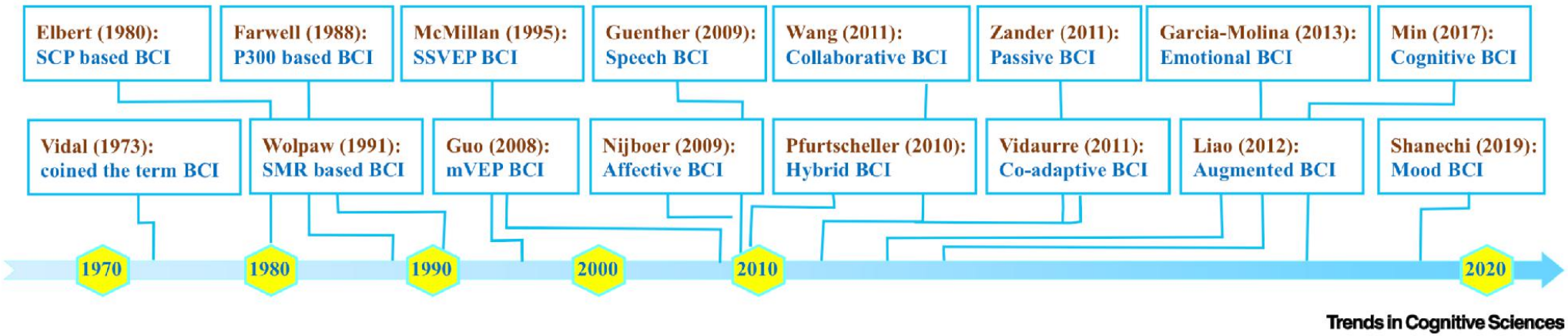
清华大学心理与认知科学系
Department of Psychological and Cognitive Sciences
Aug 28th @ 2025第七屆學習科學與科技研討會

脑机接口
Brain-Computer Interface (BCI)





Gao et al. Interface, interaction, and intelligence in generalized brain–computer interfaces, TICS 2021

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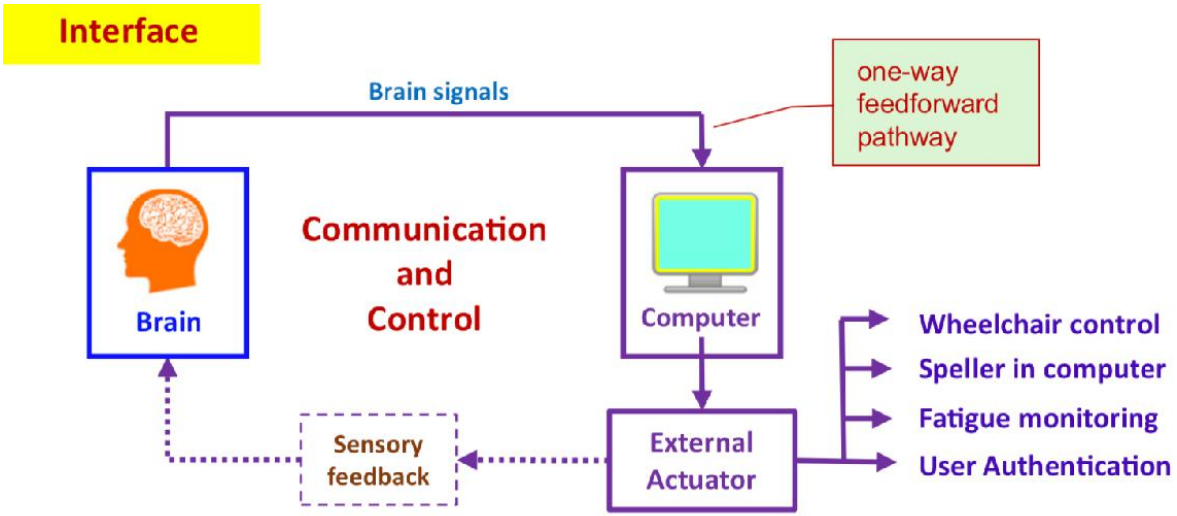
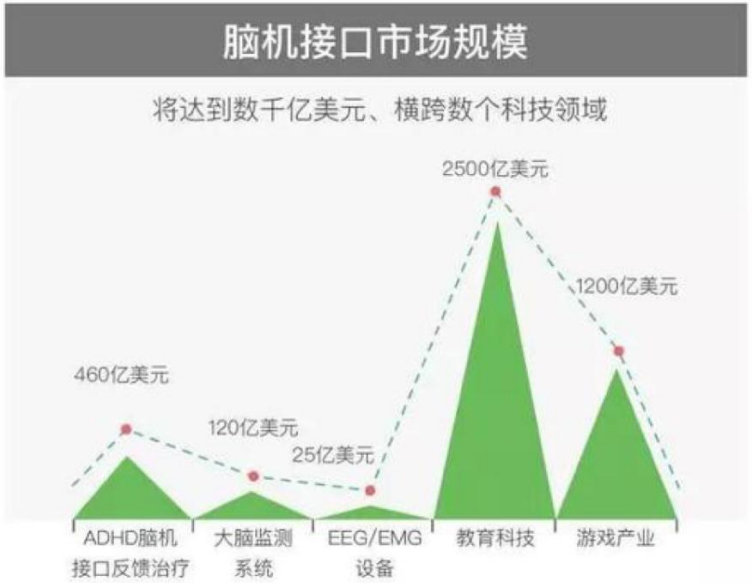
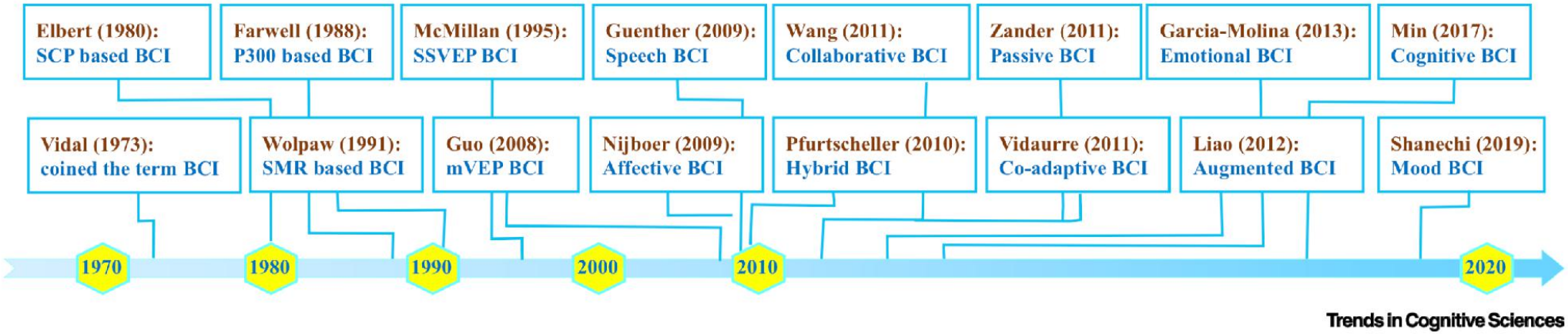




脑机接口研究报告, 硅谷Live 2017



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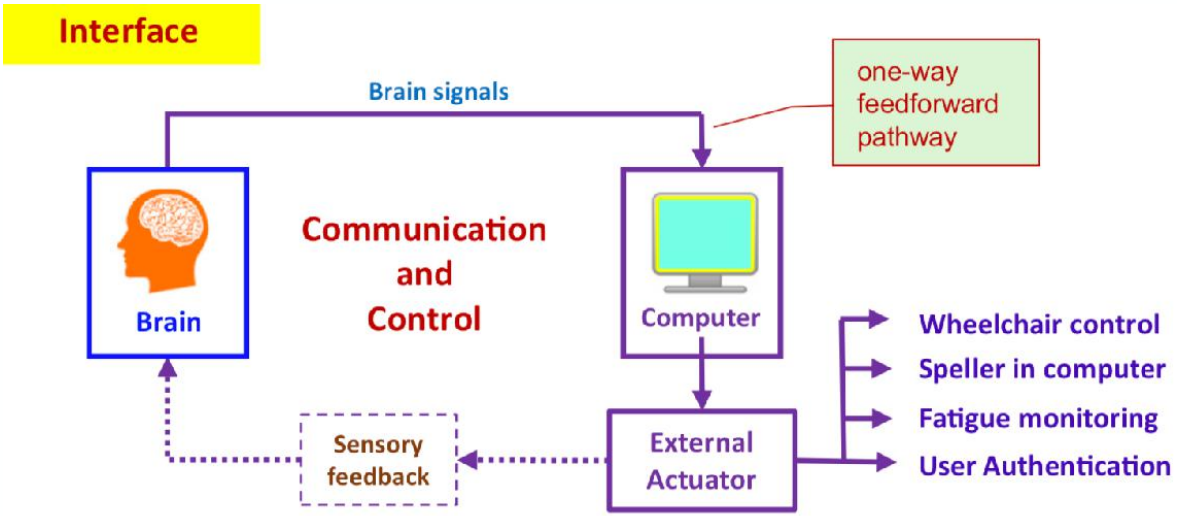

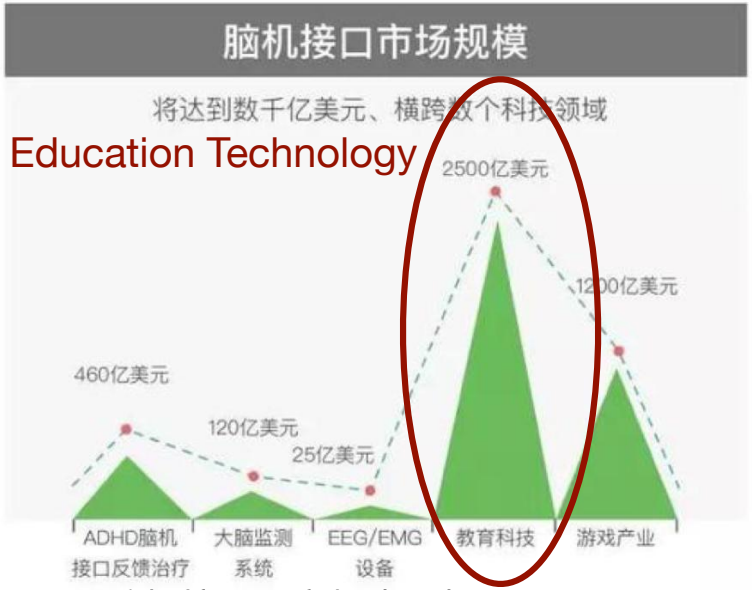

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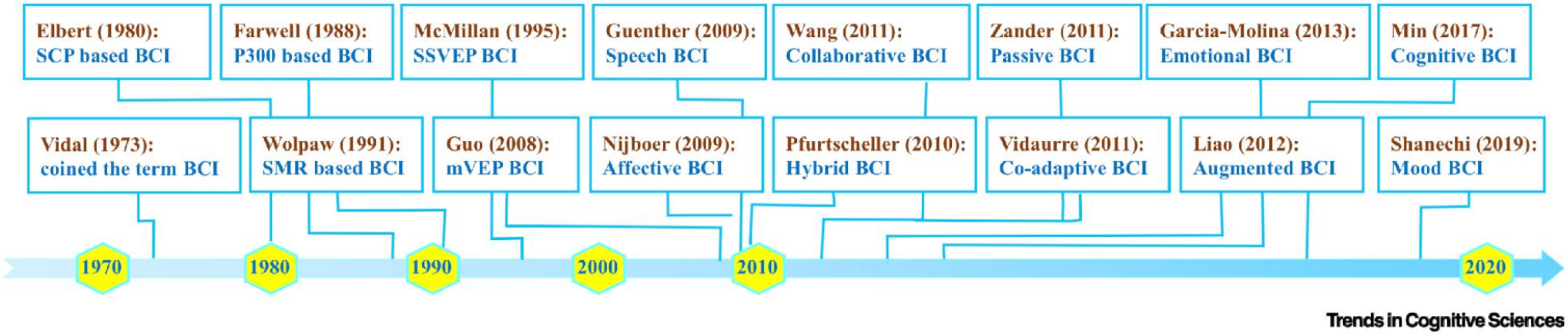
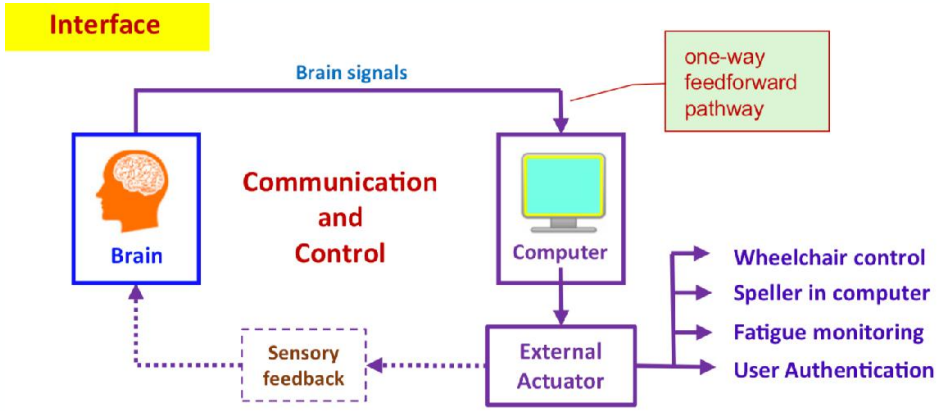
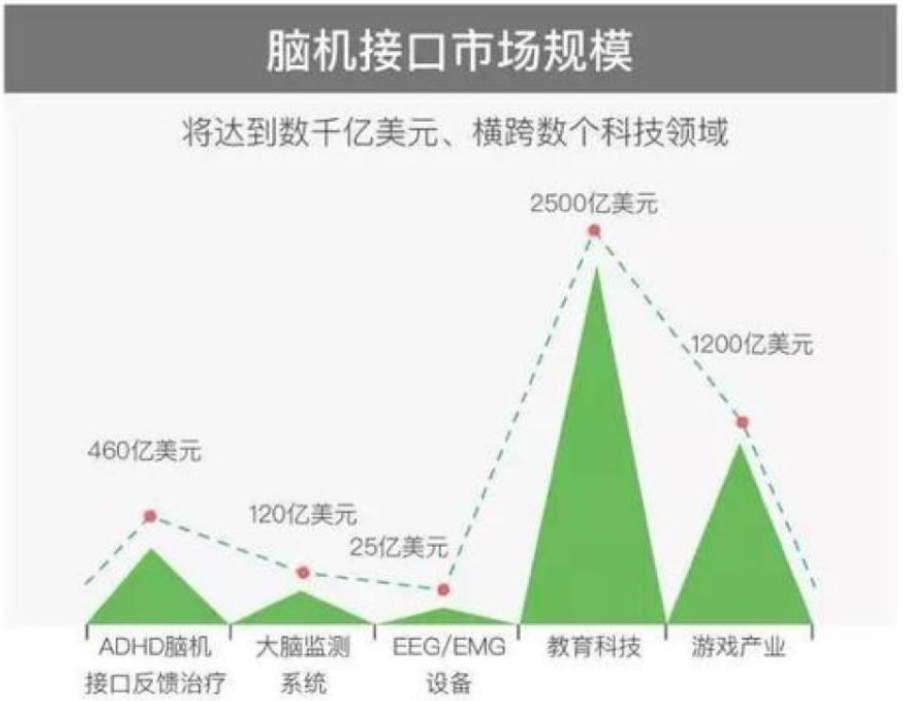


BCI for education: brain state decoding





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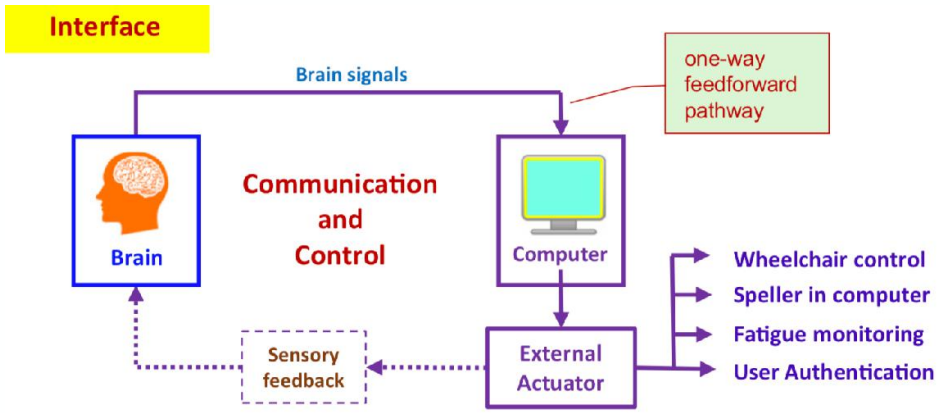

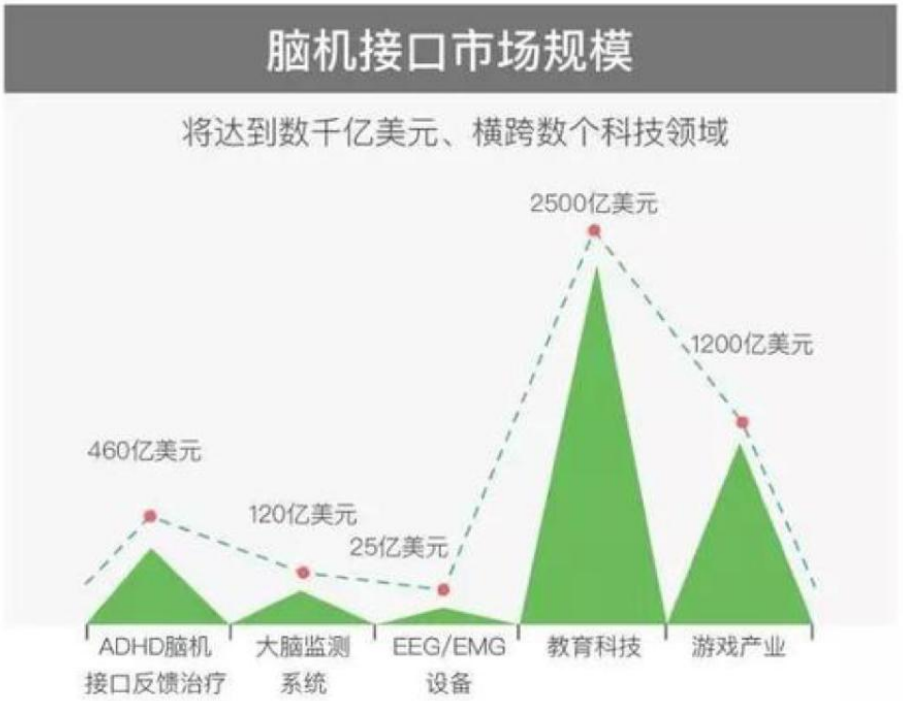

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  - Being attended?
  - Being positive?
  - Being confused?
  - … …

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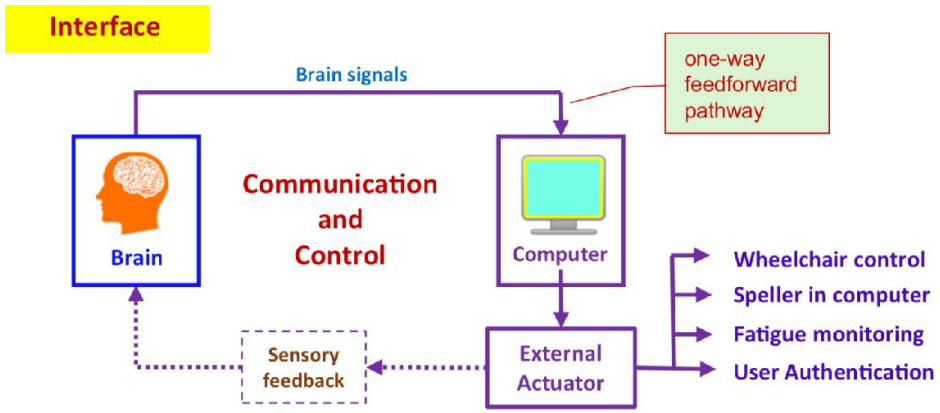

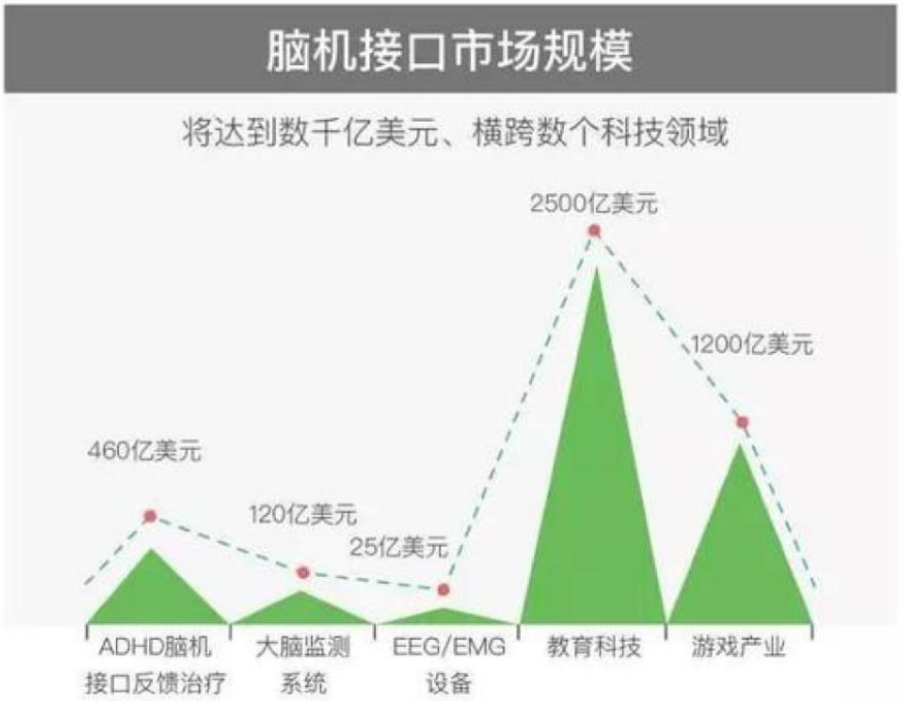

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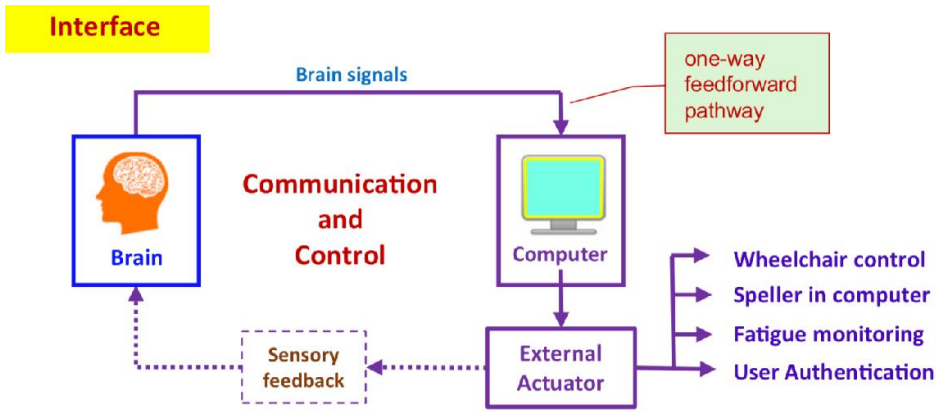

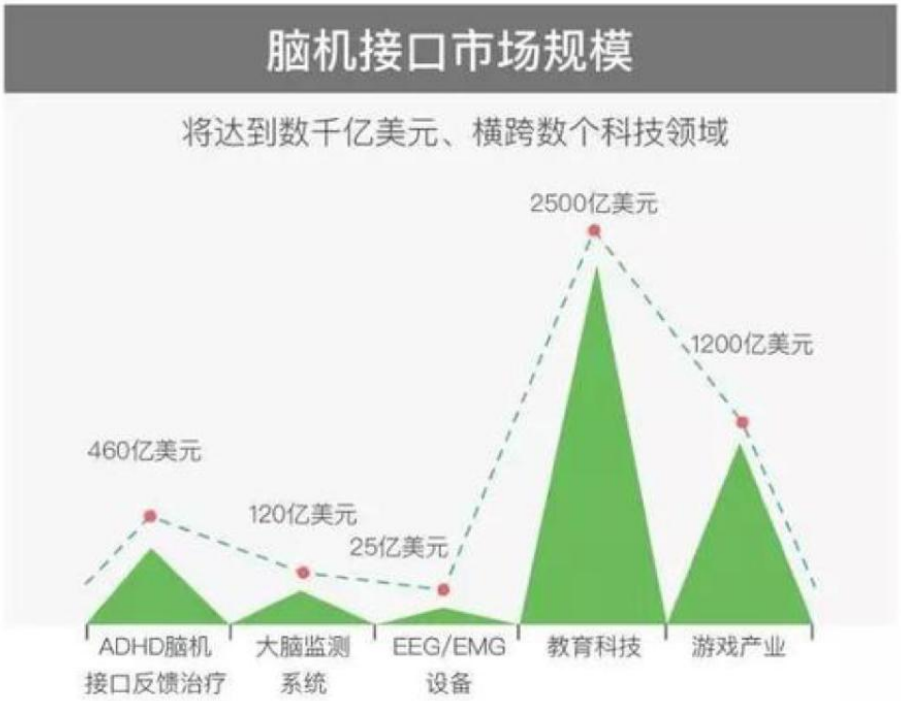

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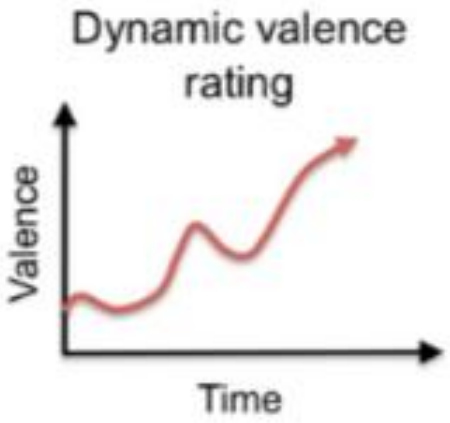

Who is paying attention in class?

Image by DeepAI

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From subjective to objective evaluation

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Teacher observation / student self-report

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Behavioral metrics
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Bio-signal sensing

PPG, GSR -> EEG … [BCI]

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"The classroom is an ideal starting point for real-world neuroscience. It provides a practically important and ecologically naturalistic context but also a semi-controlled environment, governed by a sequence of activities led by a teacher. "

Dikker et al. Curr Biol 2017

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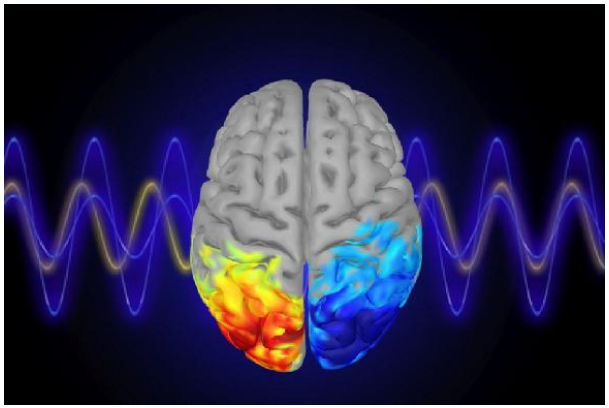
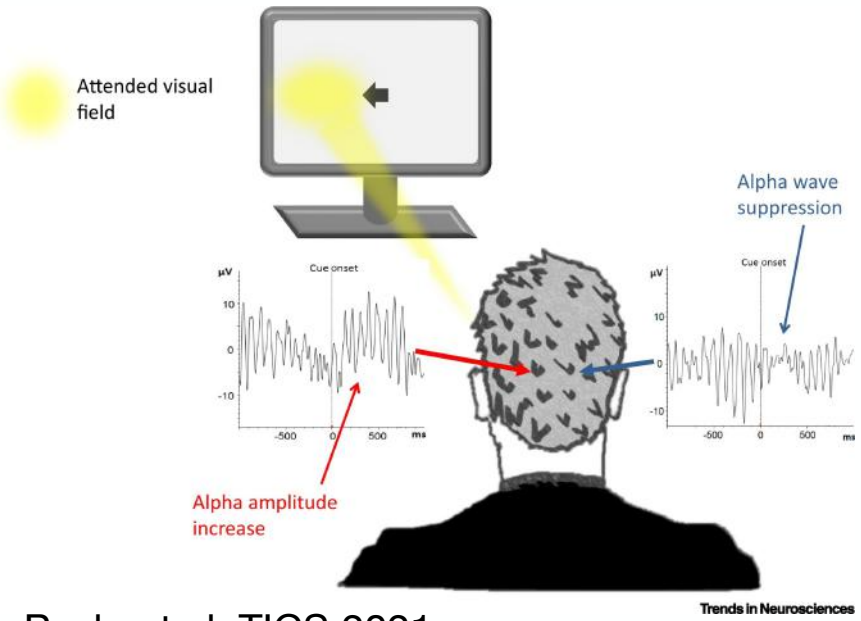
Decoding brain activities for attention

Attention: Parietal/Occipital Alpha





Peylo et al. TICS 2021

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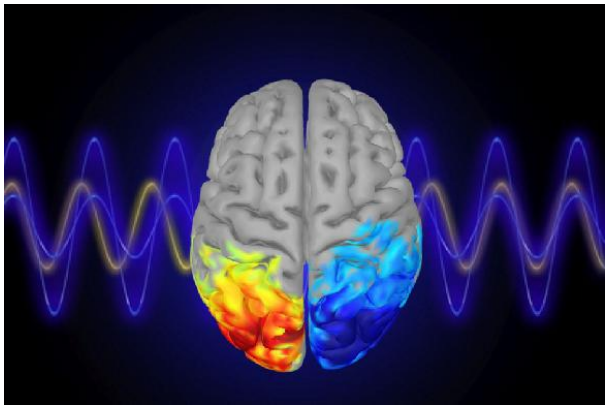

EEG decoded attention state
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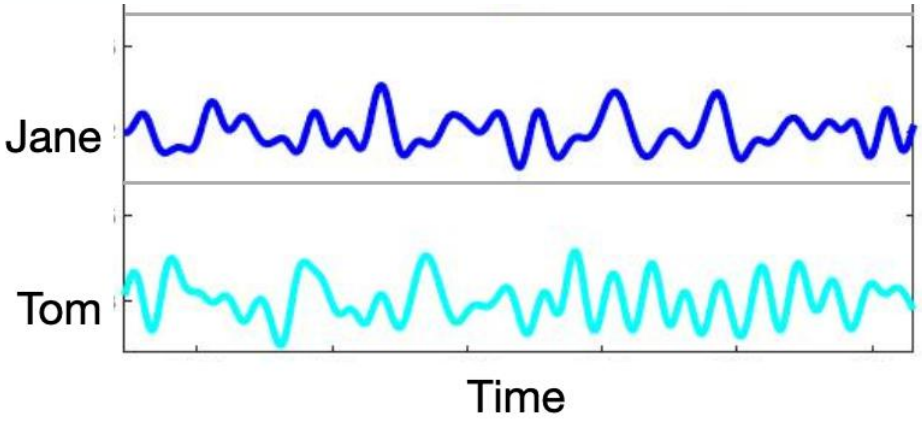

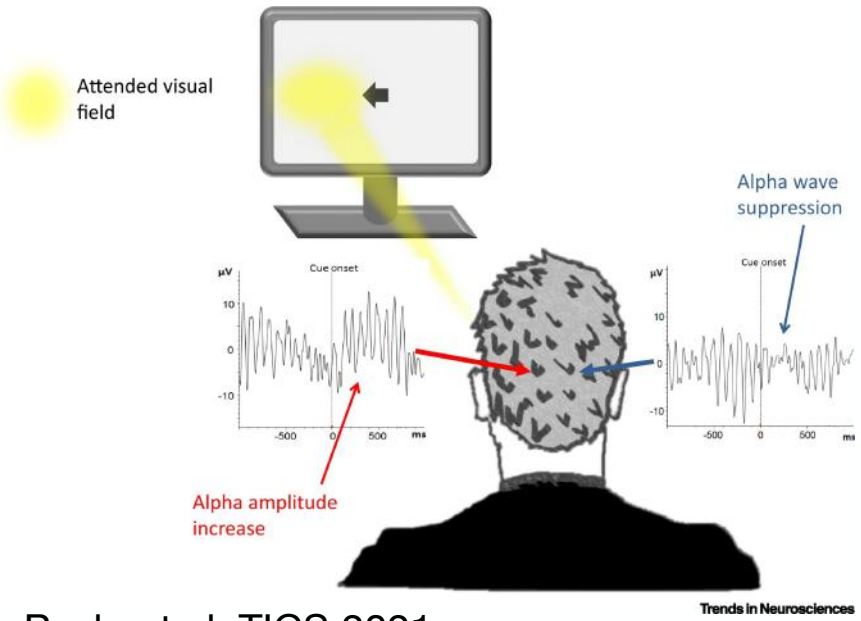

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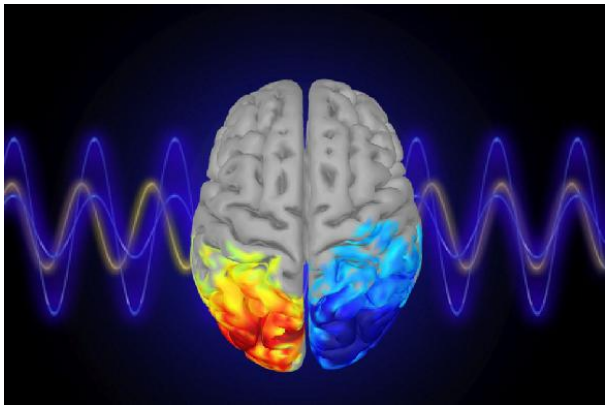

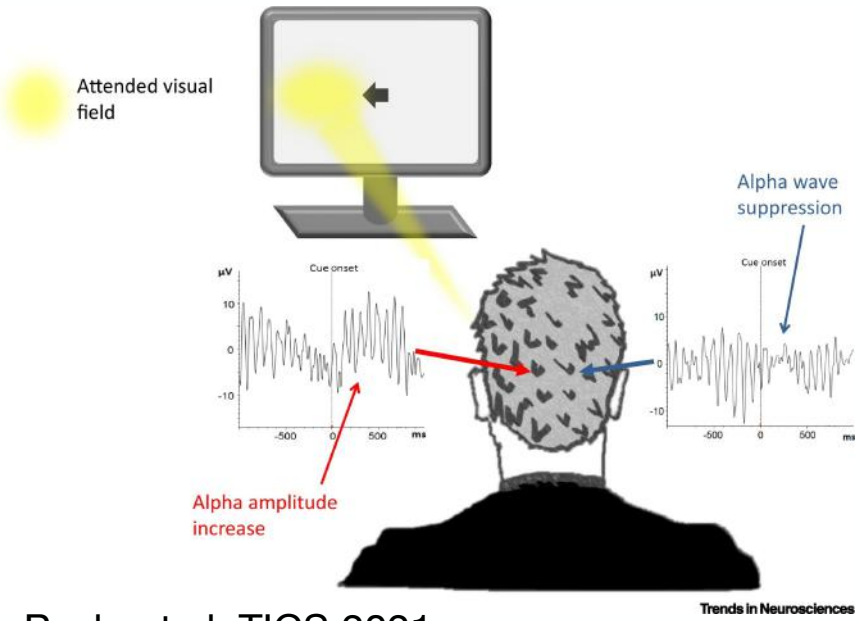

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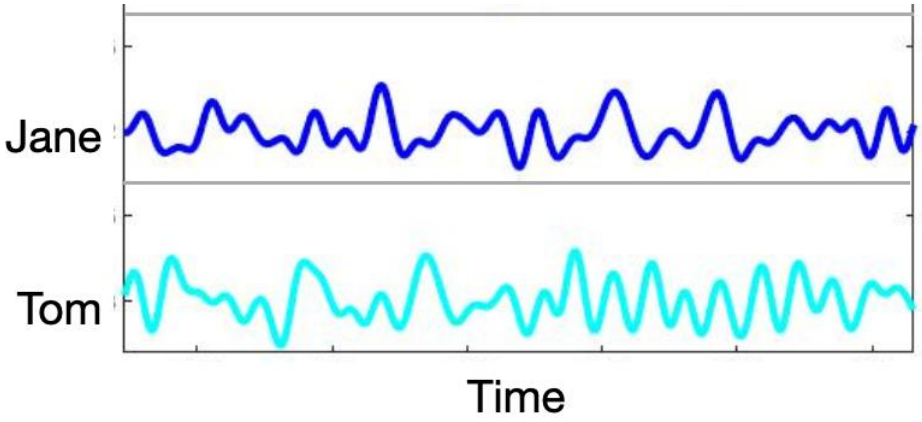

Who is less attentive?

Peylo et al. TICS 2021

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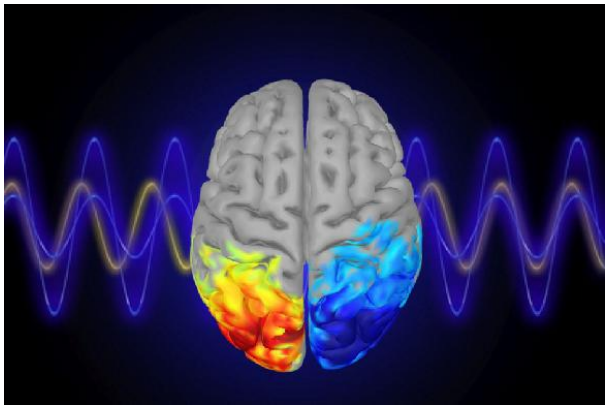

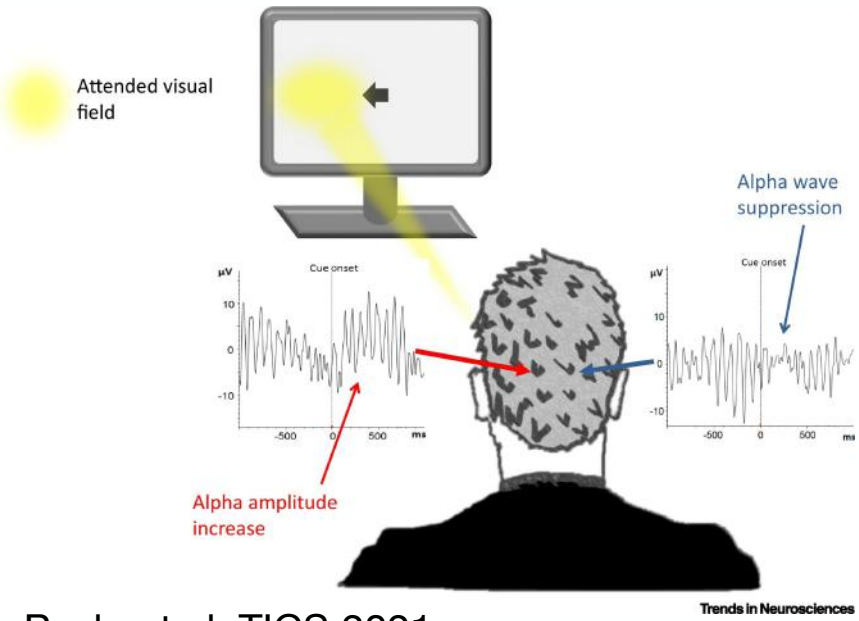

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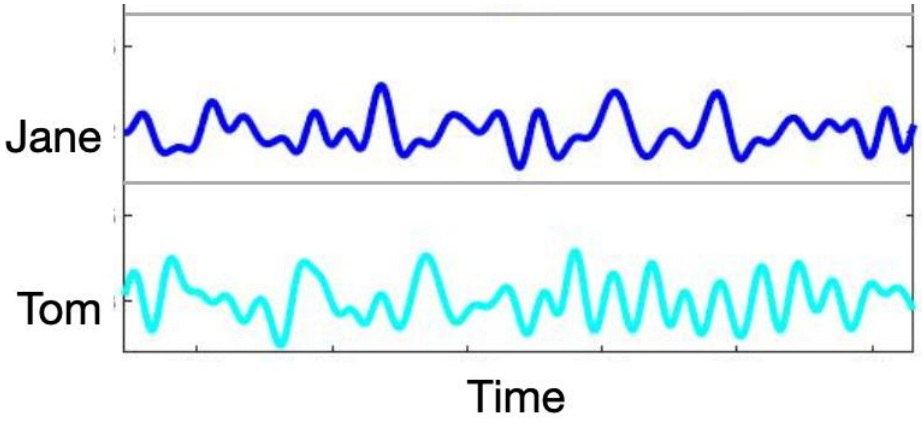

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Peylo et al. TICS 2021

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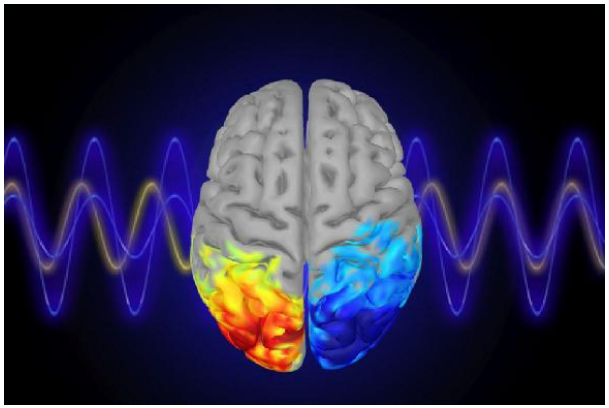

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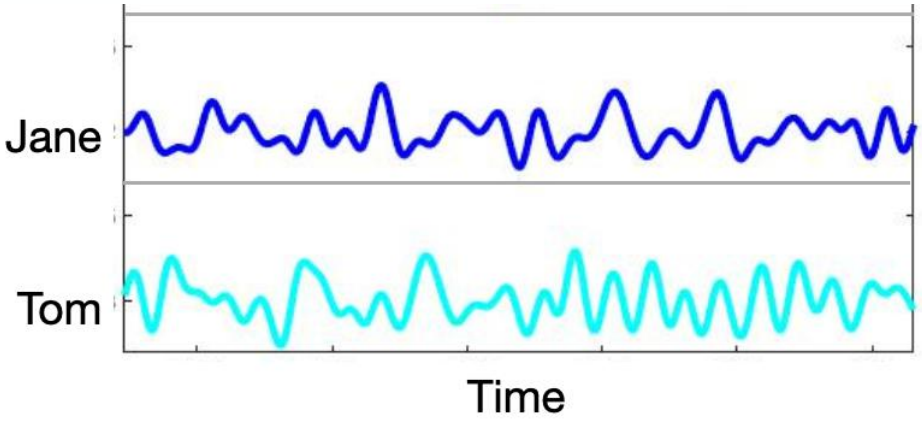

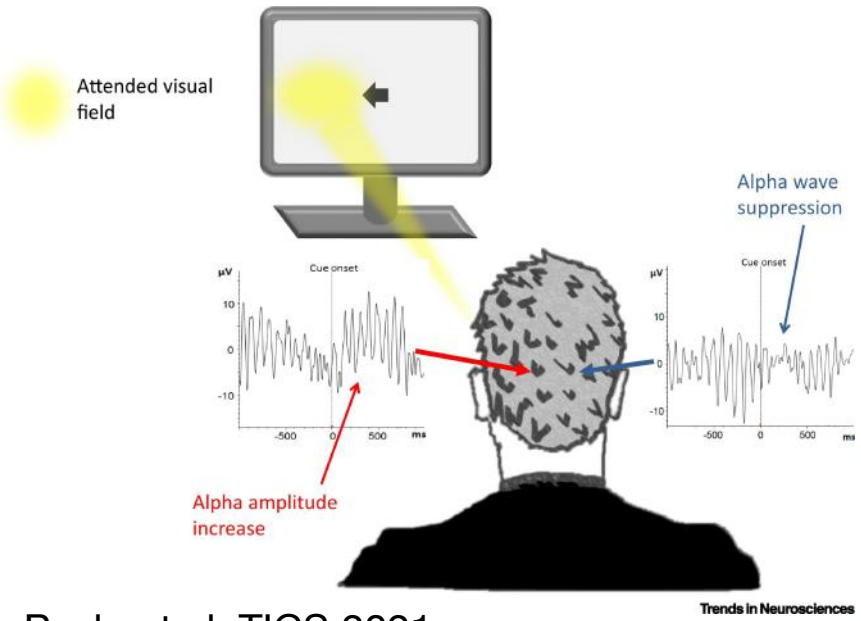

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Peylo et al. TICS 2021

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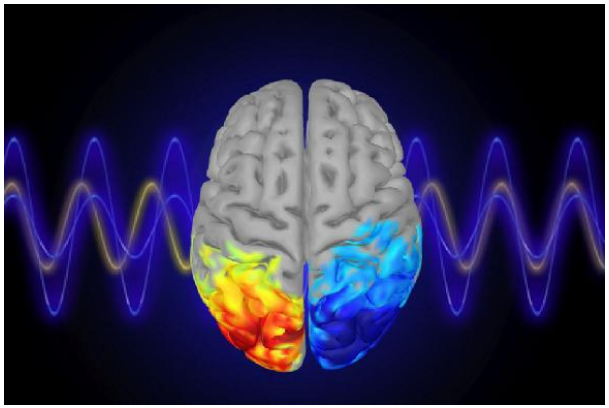

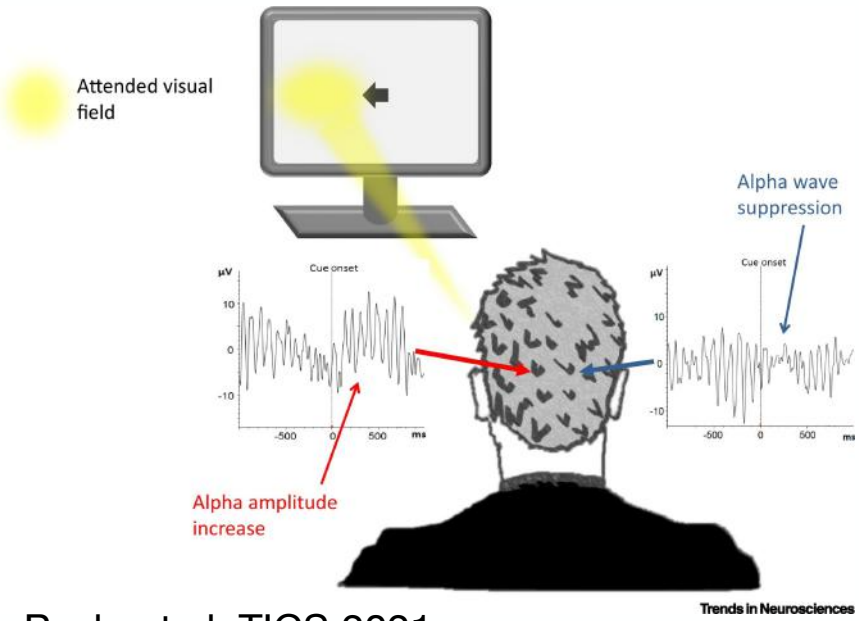

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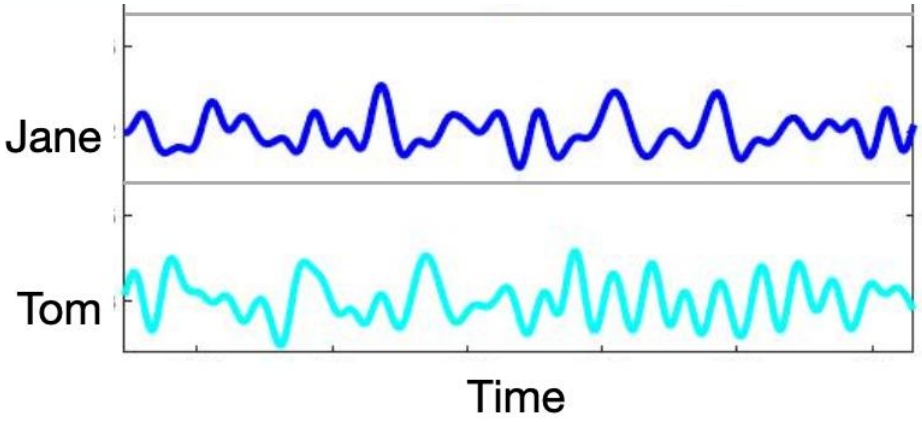

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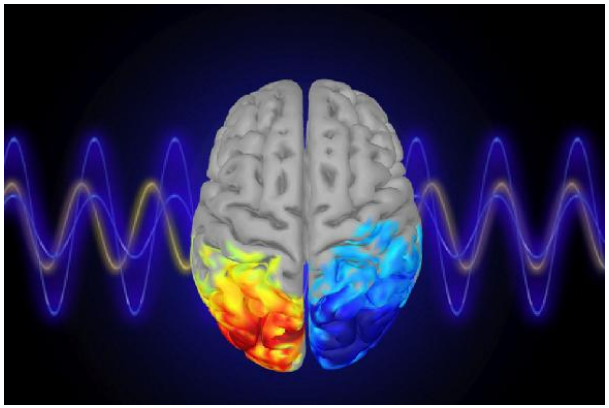

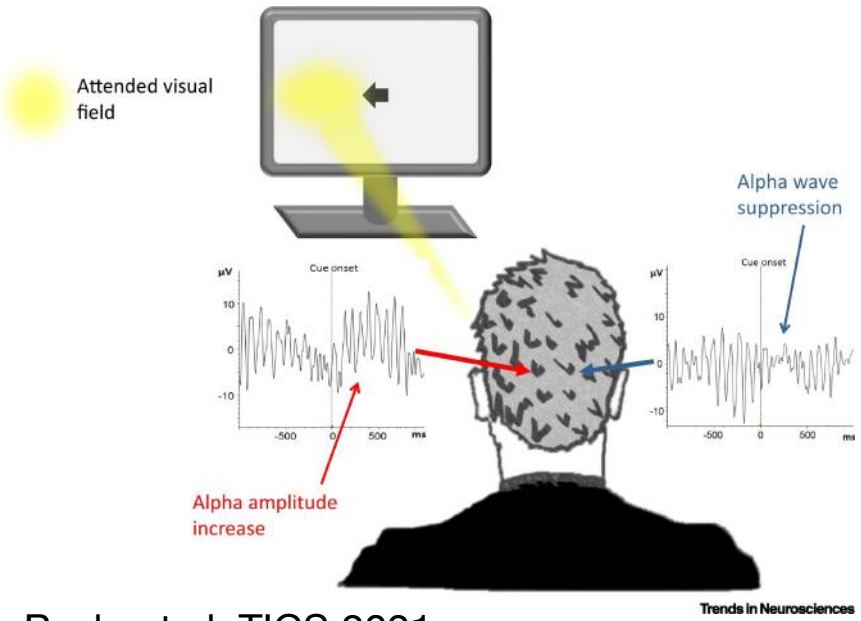

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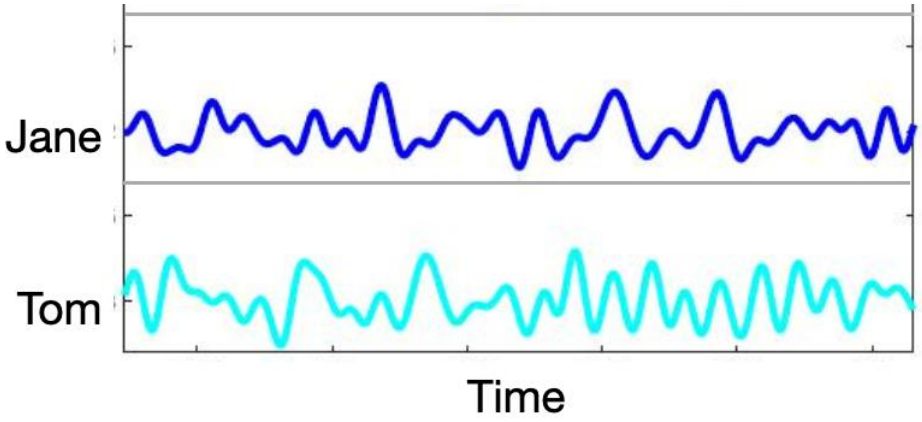

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Peylo et al. TICS 2021

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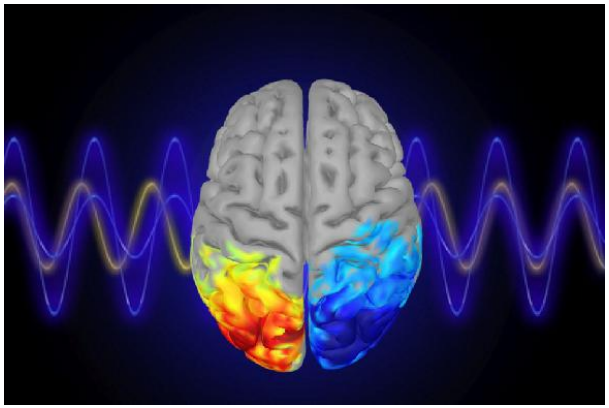

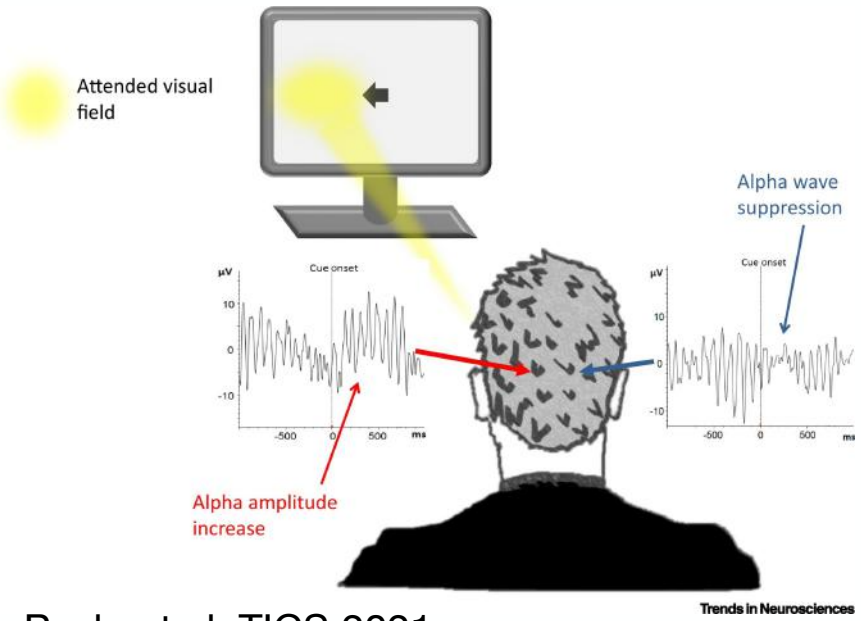

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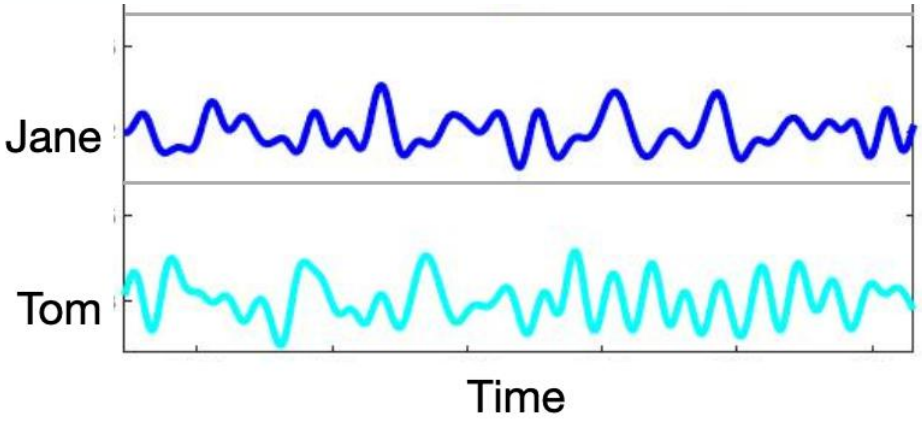

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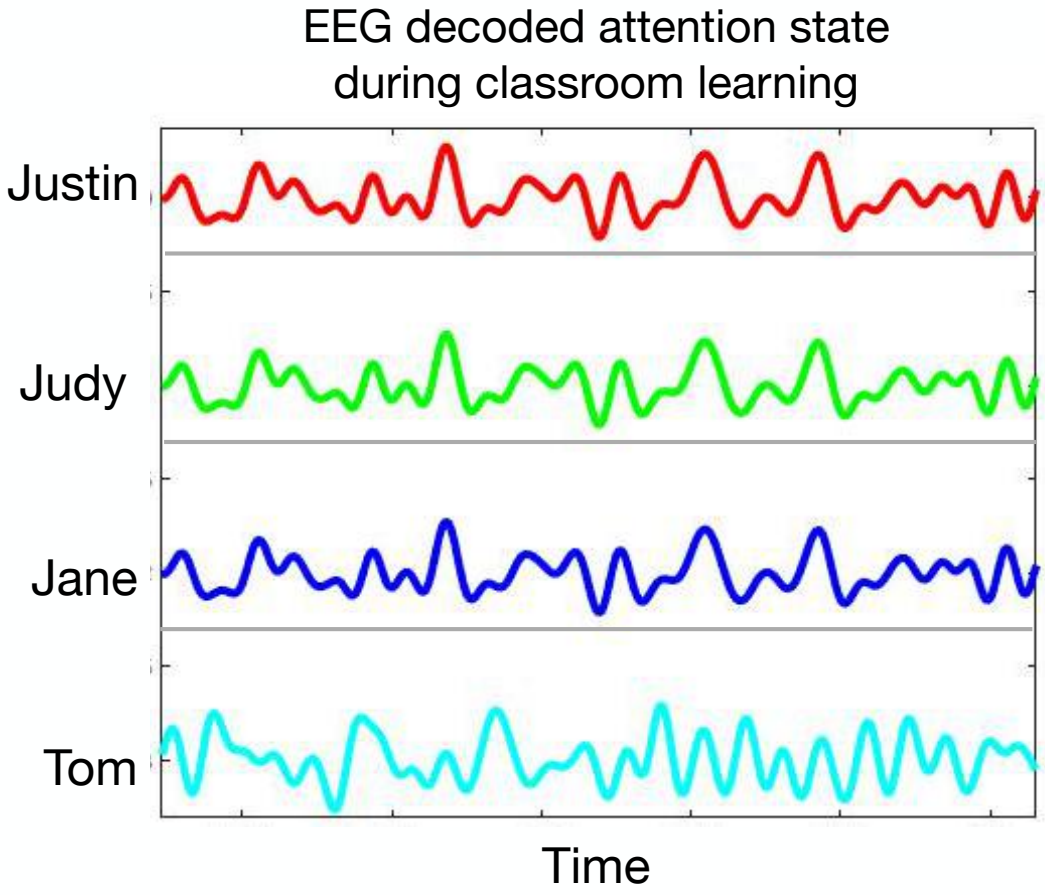
The Challenge

How to relate the attention state to classroom learning?

Pursuing learning-related attentional state



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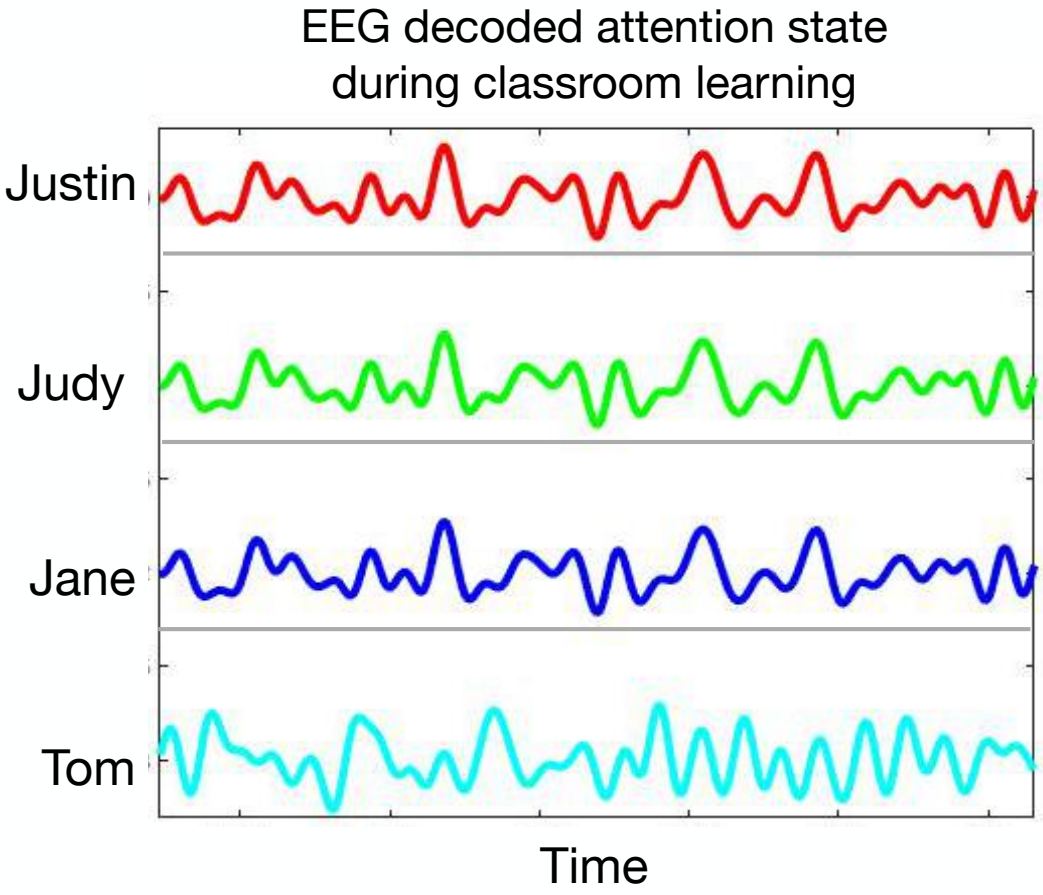

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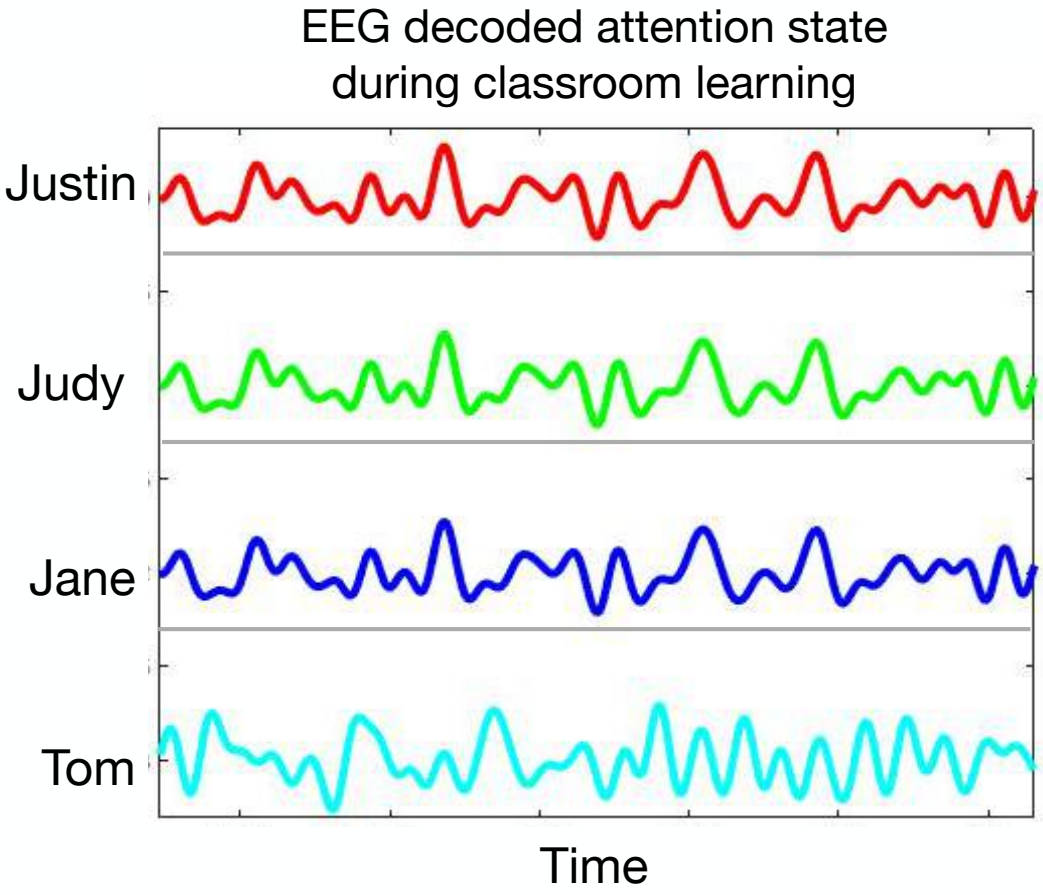

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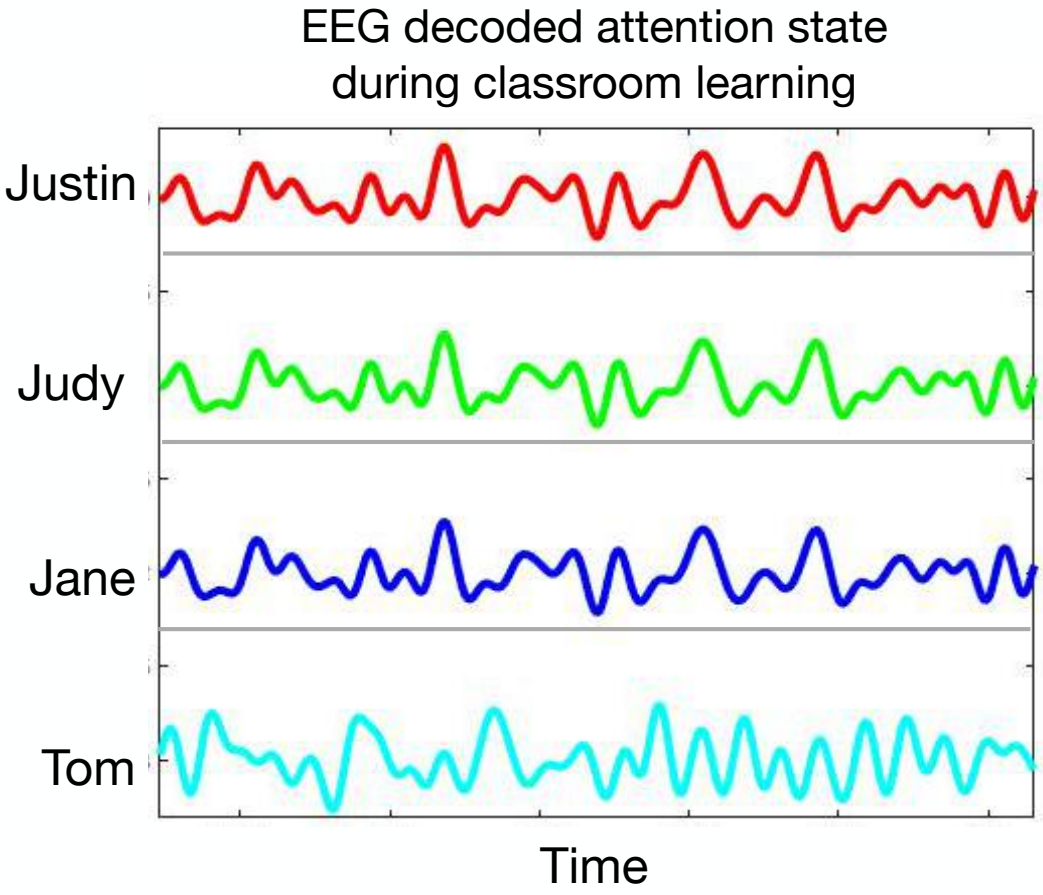
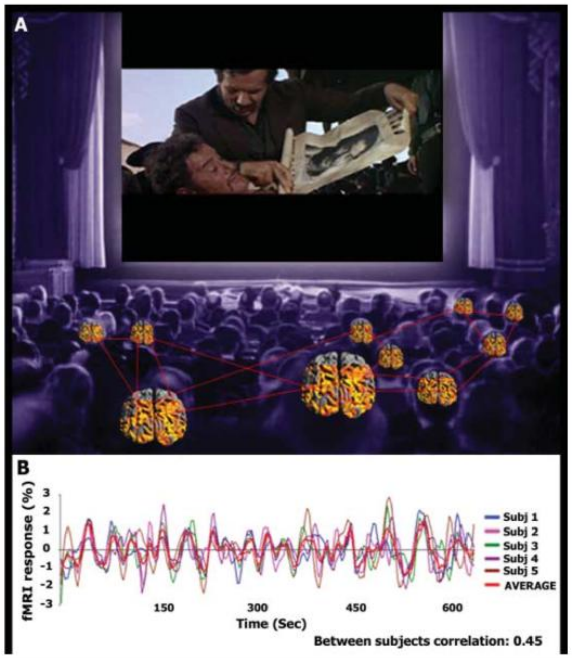
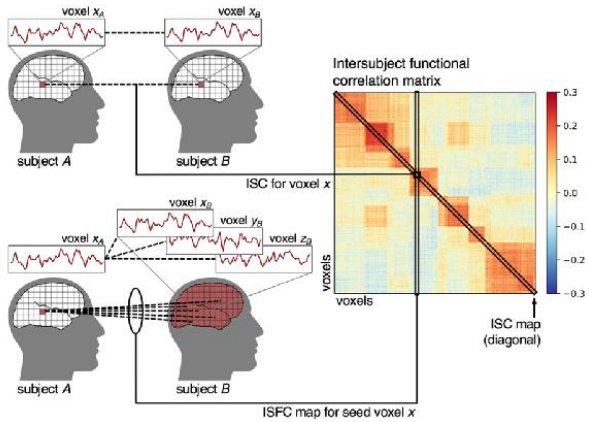


Who is less attentive?

Why?

The inter-brain perspective for describing neural activities in naturalistic settings





Hasson et al. Science 2004
Nastase et al. SCAN 2019

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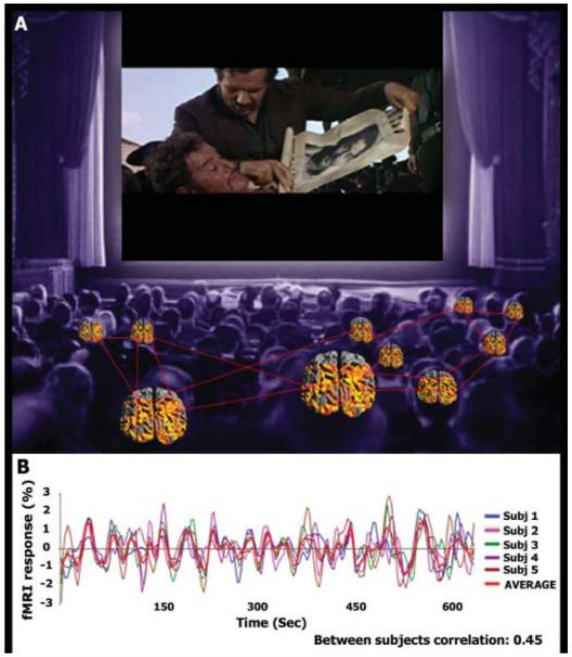

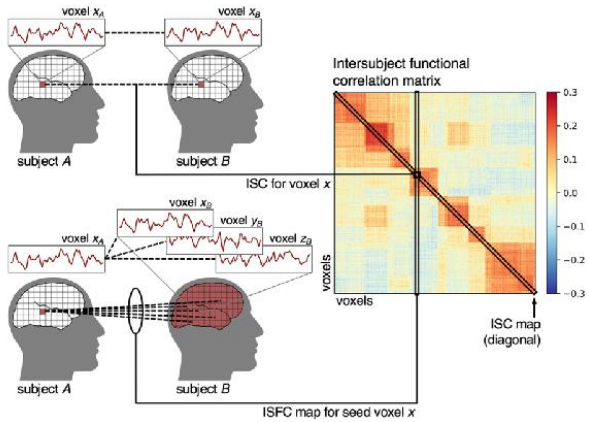

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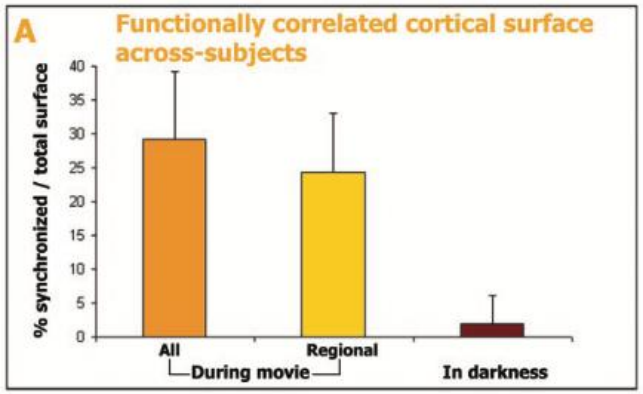

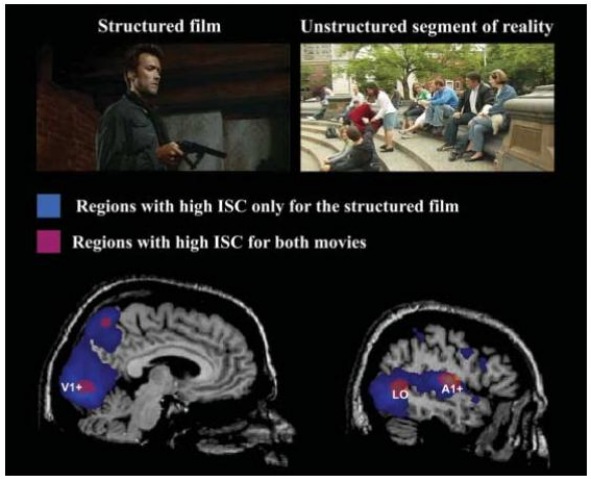

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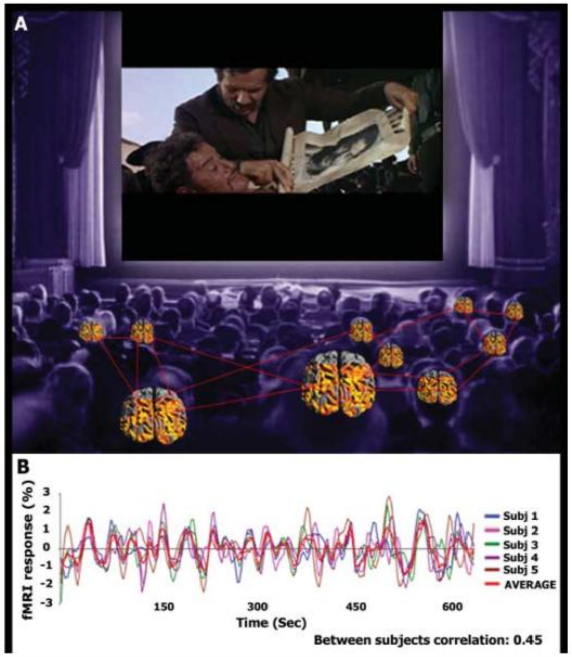
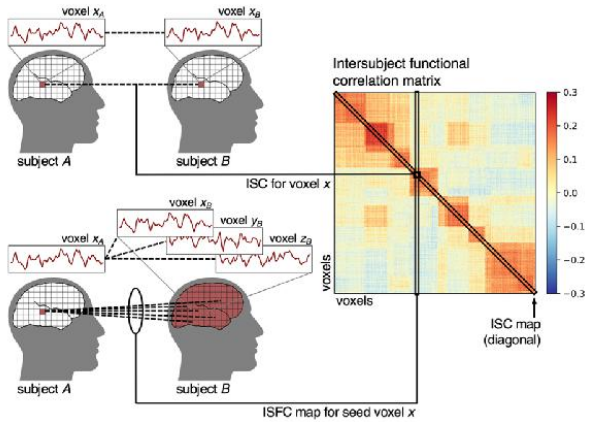
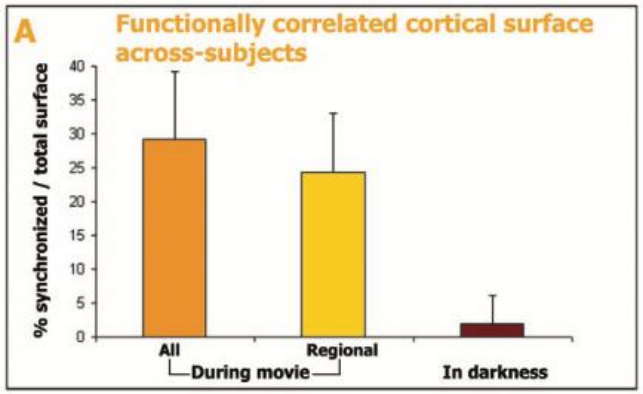
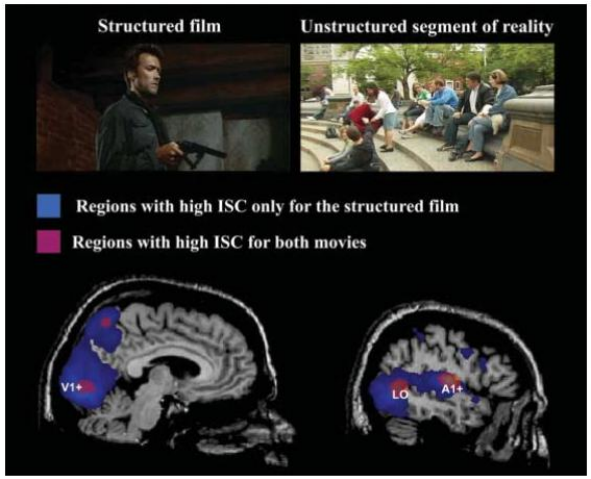
The inter-brain perspective for describing neural activities in naturalistic settings





Hasson et al. Science 2004
Nastase et al. SCAN 2019





Hasson et al. 2008

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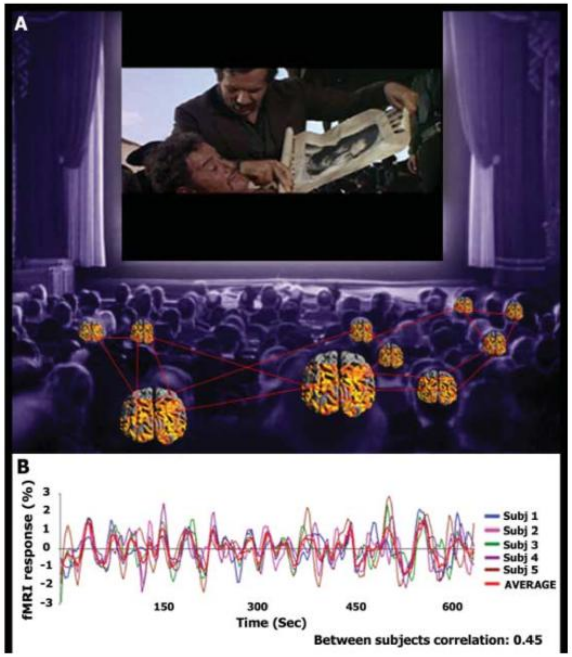

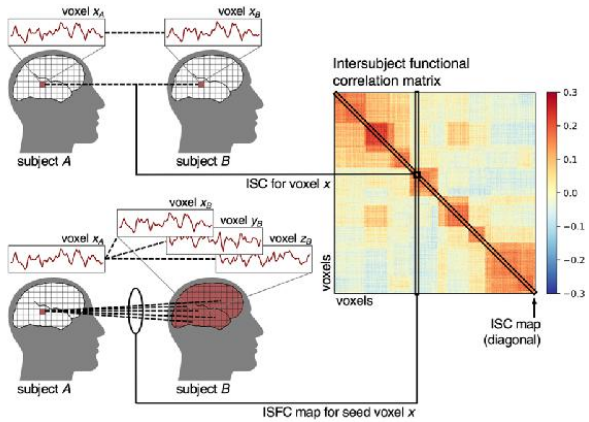

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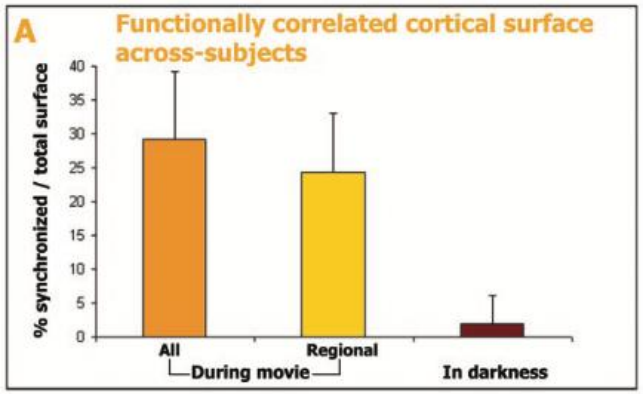

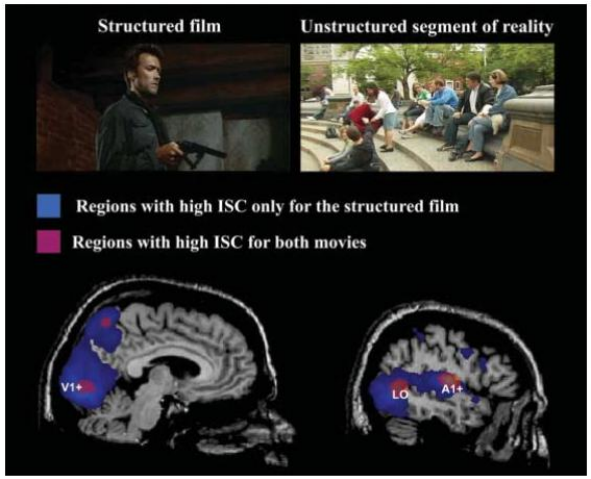

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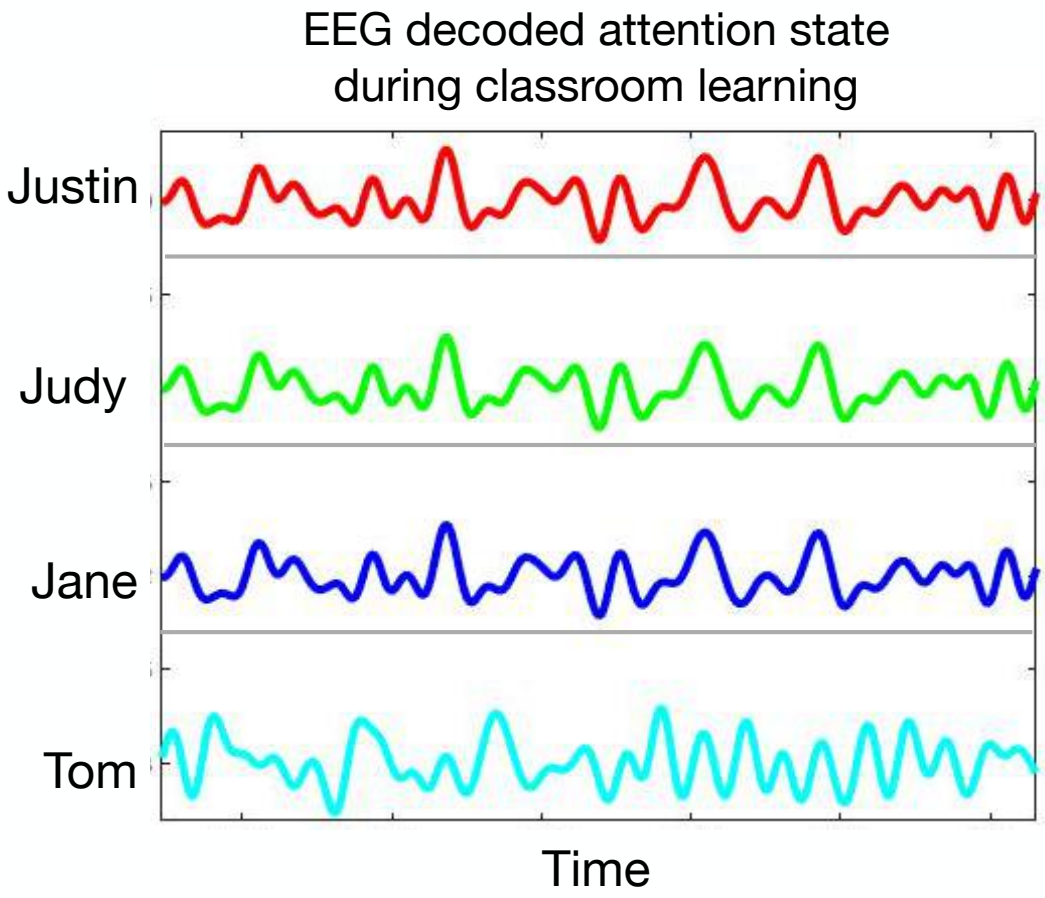
Inter-brain coupling provides a **model-free** method to characterize neural responses in naturalistic scenarios with complex and dynamic events that cannot be easily coded.

Pursuing learning-related attentional state

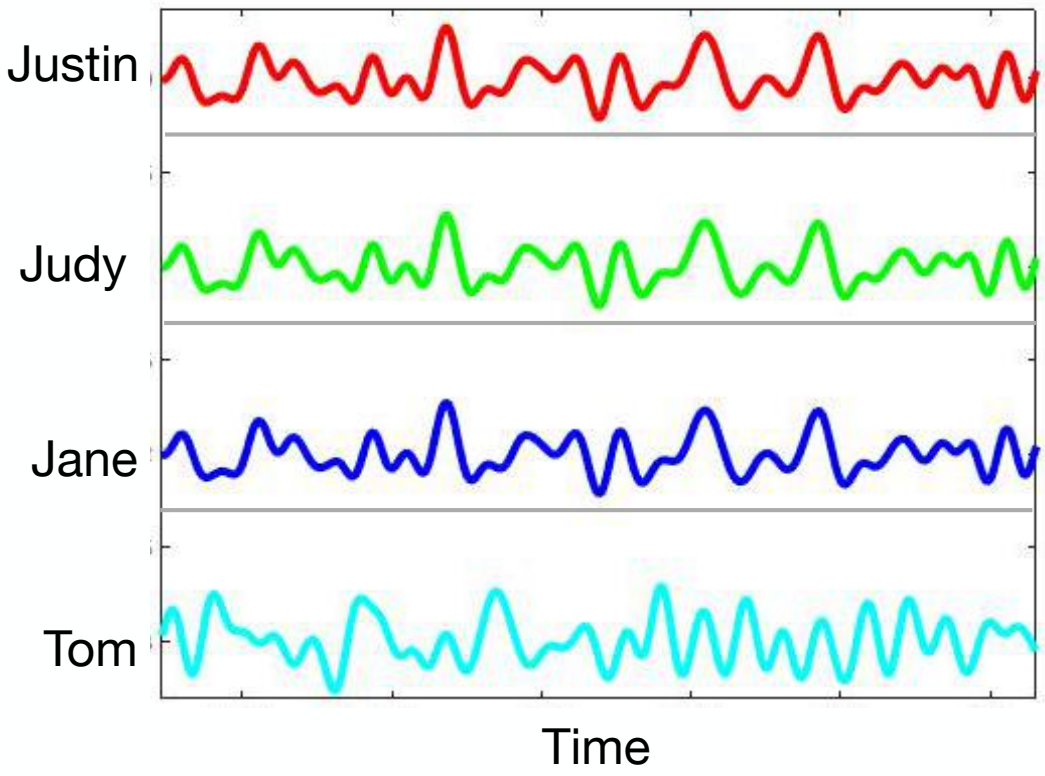


Who is less attentive?

Why?

Pursuing learning-related attentional state

EEG decoded attention state
during classroom learning



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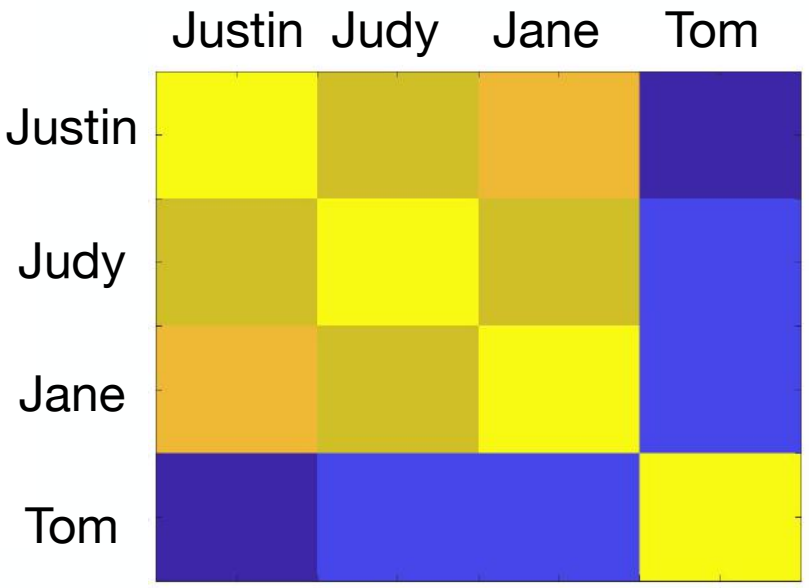
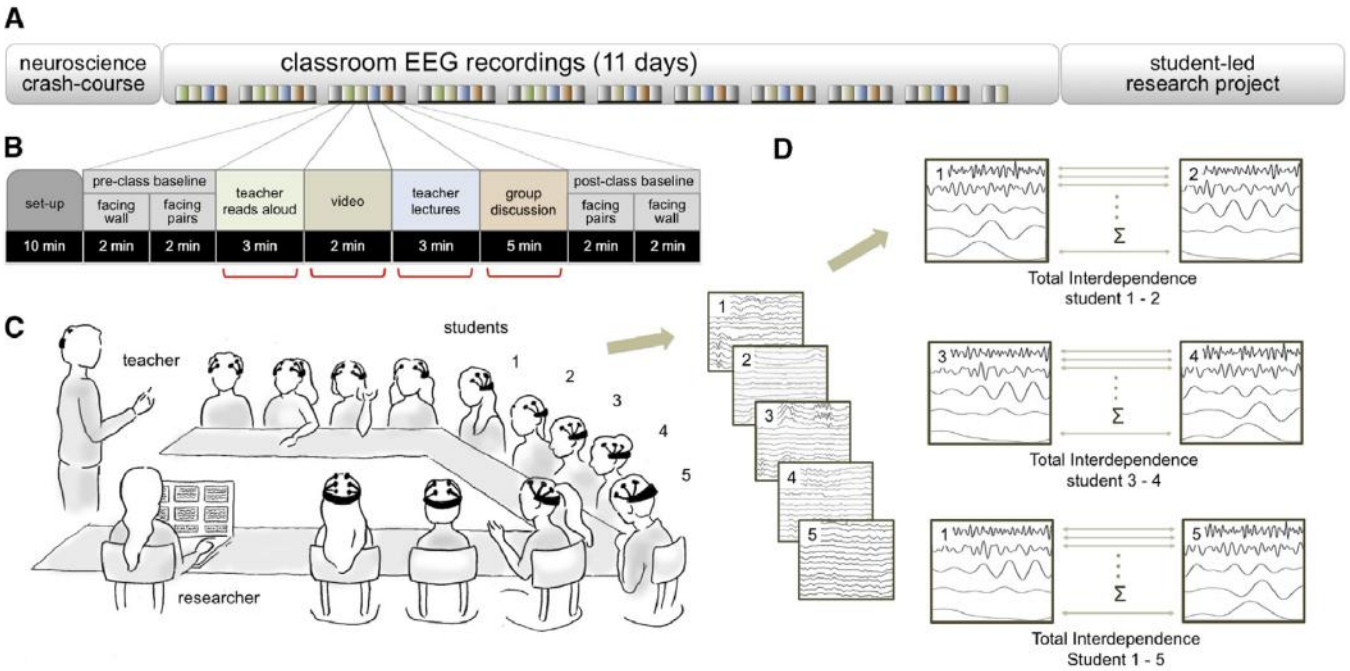


Inter-brain coupling among students

Inter-brain coupling in real classroom: the first study



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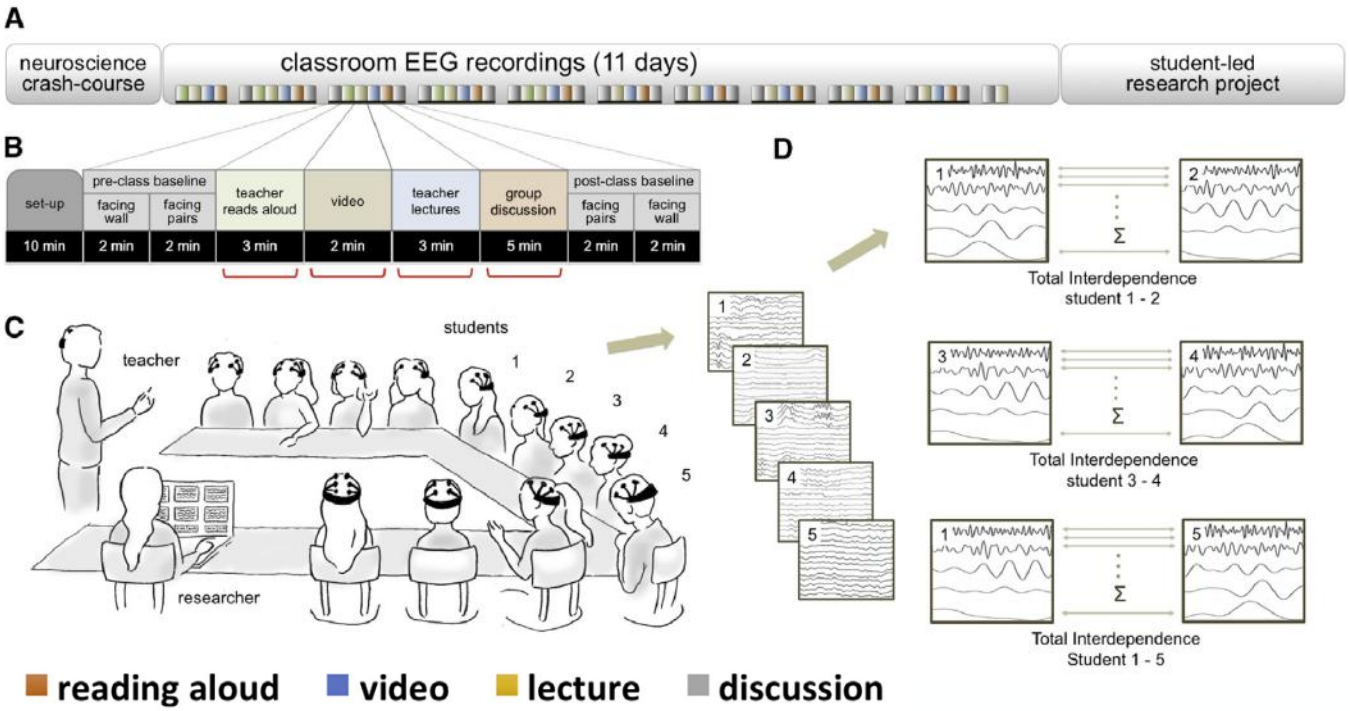

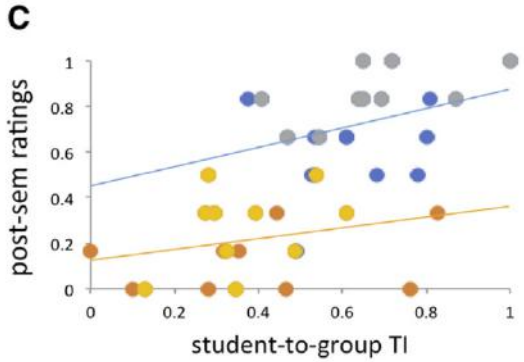

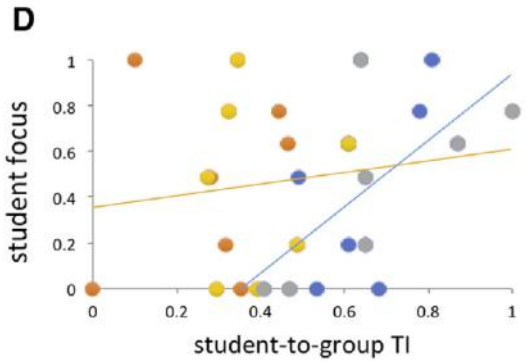

The students' brainwaves are more in sync with each other when they are more engaged during class.

Dikker et al. Curr Biol 2017 (NYU)

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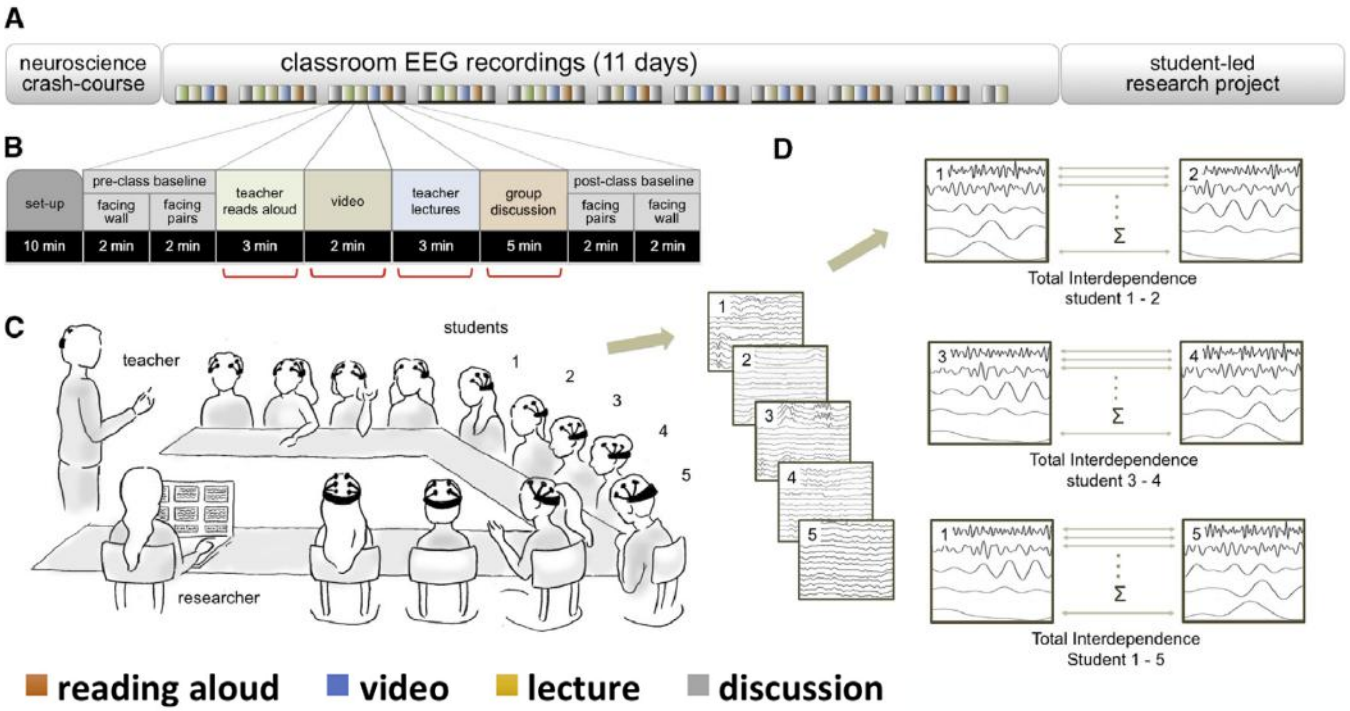

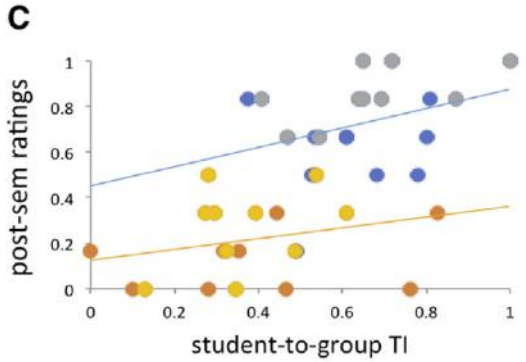

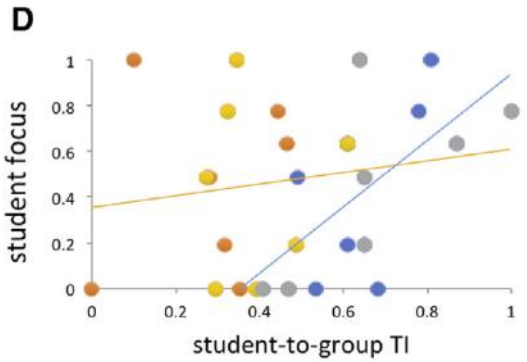

The students' brainwaves are more in sync with each other when they are more engaged during class.

Engagement -> Learning outcome?

Dikker et al. Curr Biol 2017 (NYU)

Study 1

Inter-brain coupling for learning-related attention

Exploring the learning-related attention from an inter-brain perspective

28 Grade-3 primary school students (16 females, average 10 years old)

Single-channel frontal EEG recordings over five sessions of a brain science introduction course

Built-in Attention decoding algorithm by the EEG device (NeuroSky)

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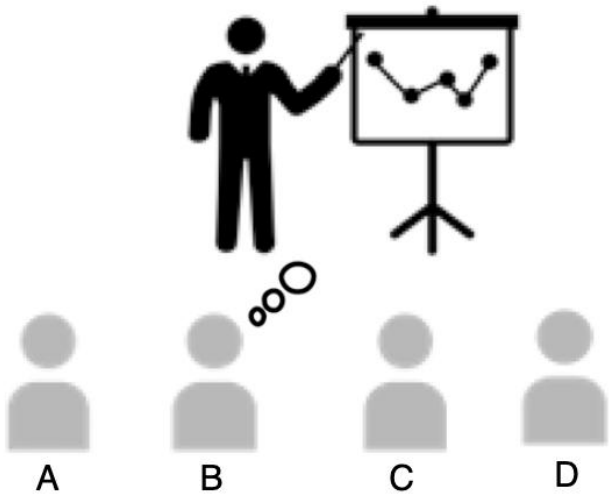

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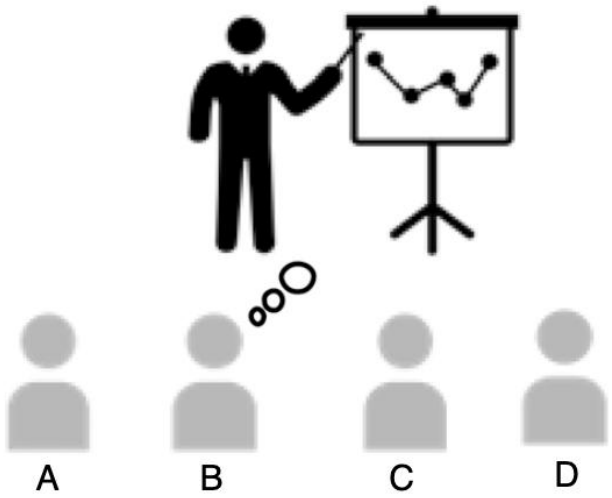

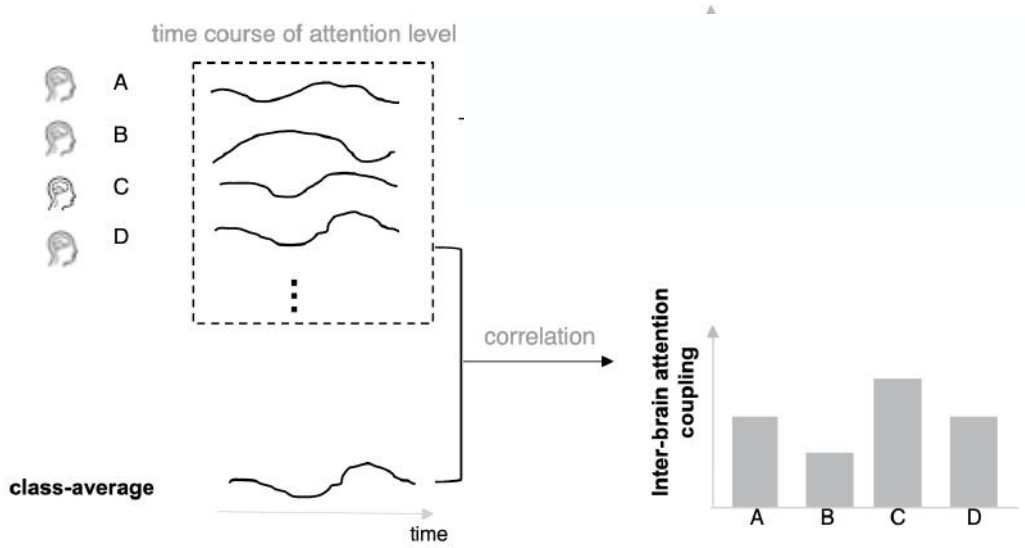

Student-class inter-brain coupling

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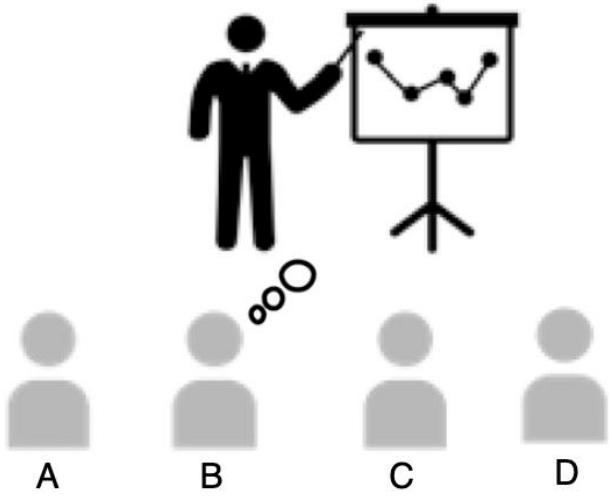

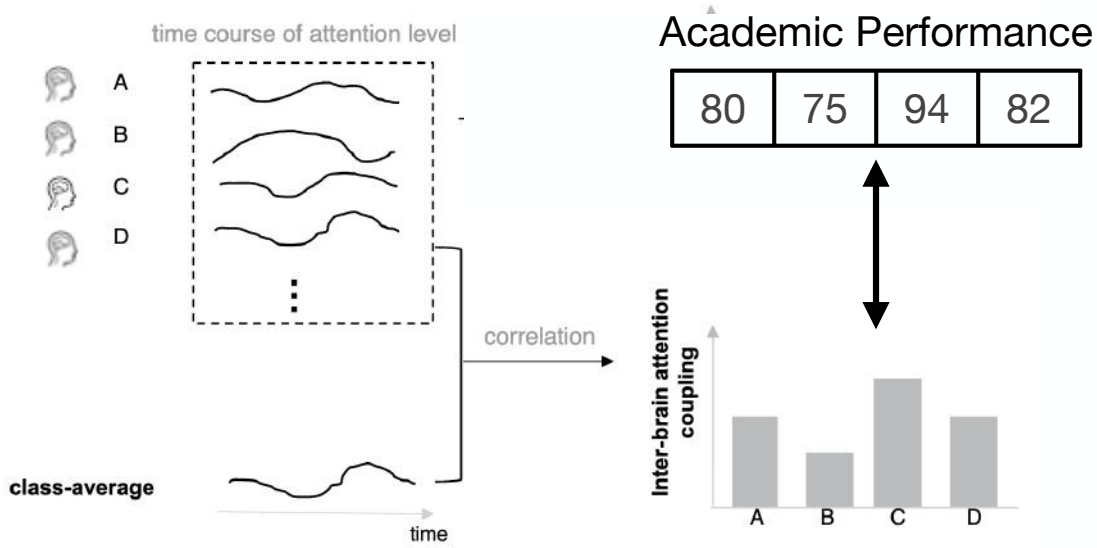

Student-class inter-brain coupling

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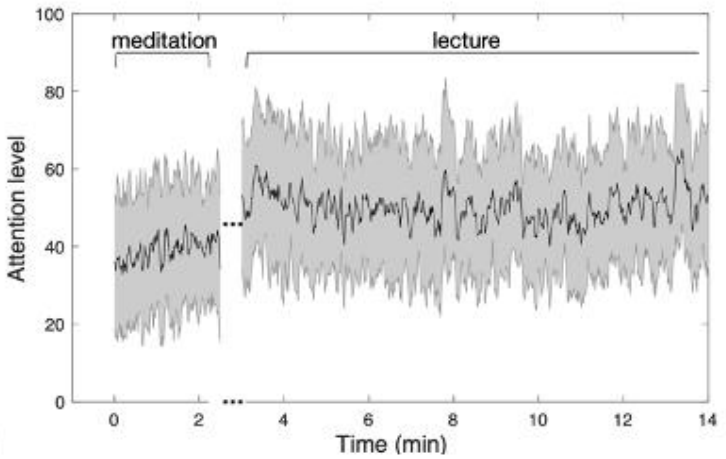
Validation of the EEG-based attention level



Validation: significantly increased attention level during lecture (vs. meditation)

Study 1

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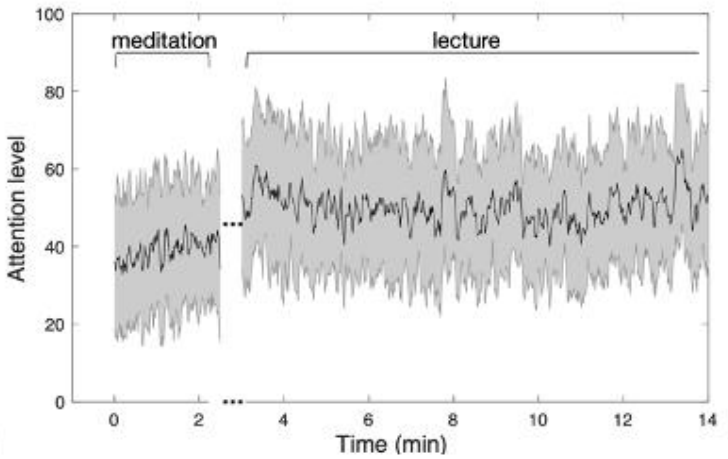

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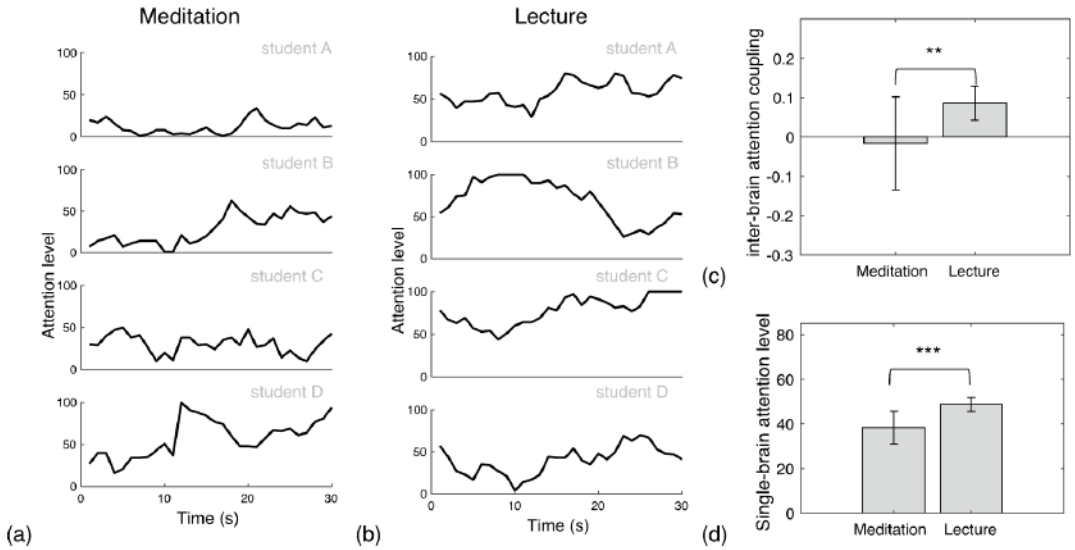
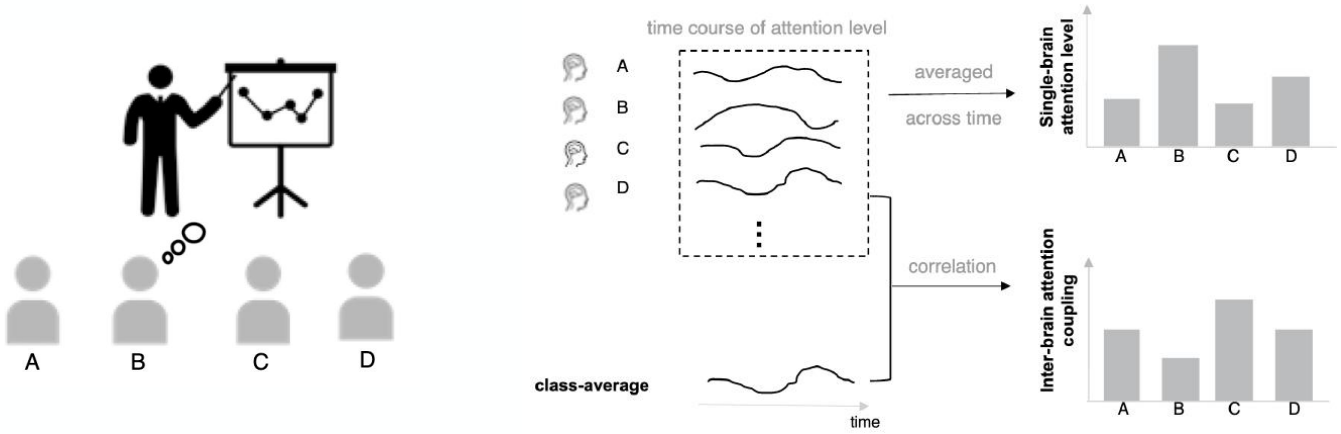


From single-brain to inter-brain:

Significantly increased and above zero inter-brain coupling during lecture (vs. meditation)

Study 1

Inter-brain coupling for academic performance



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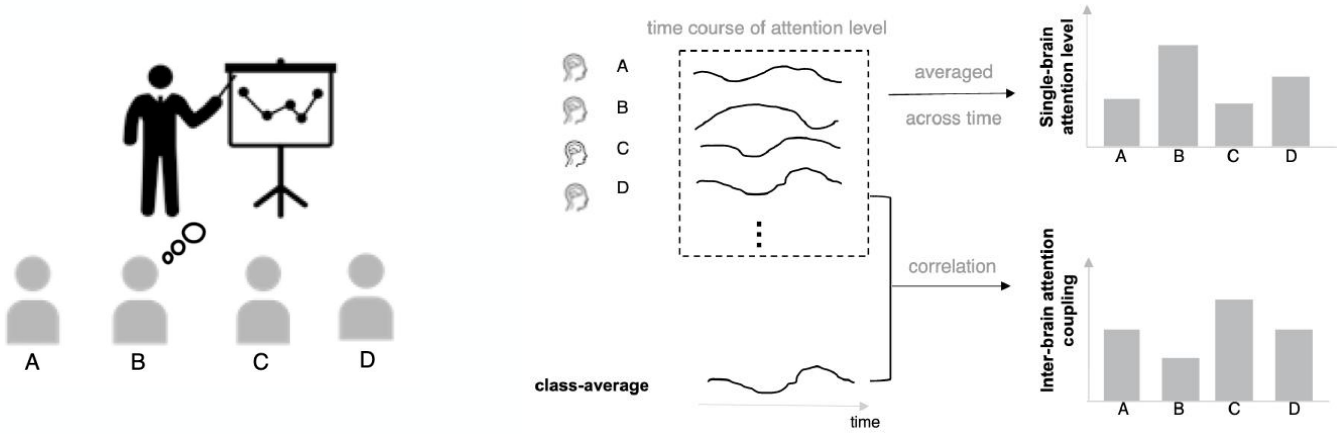

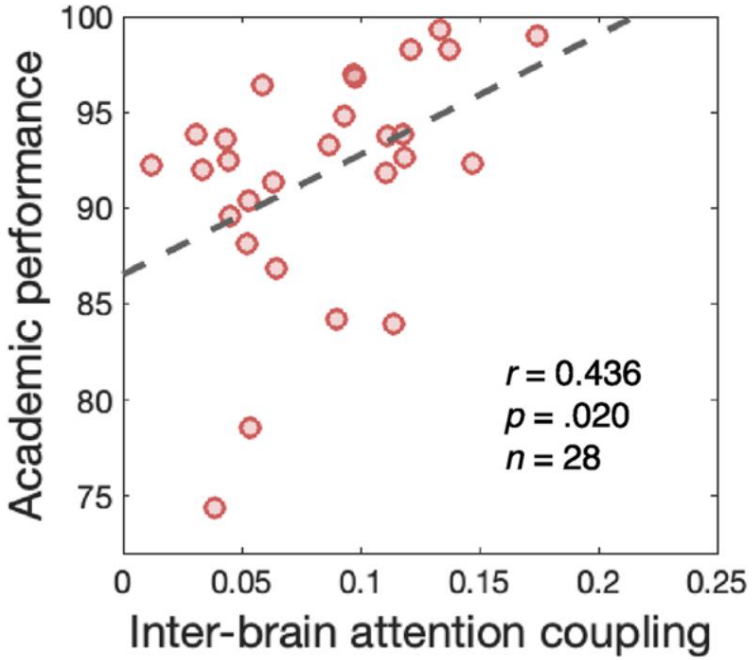

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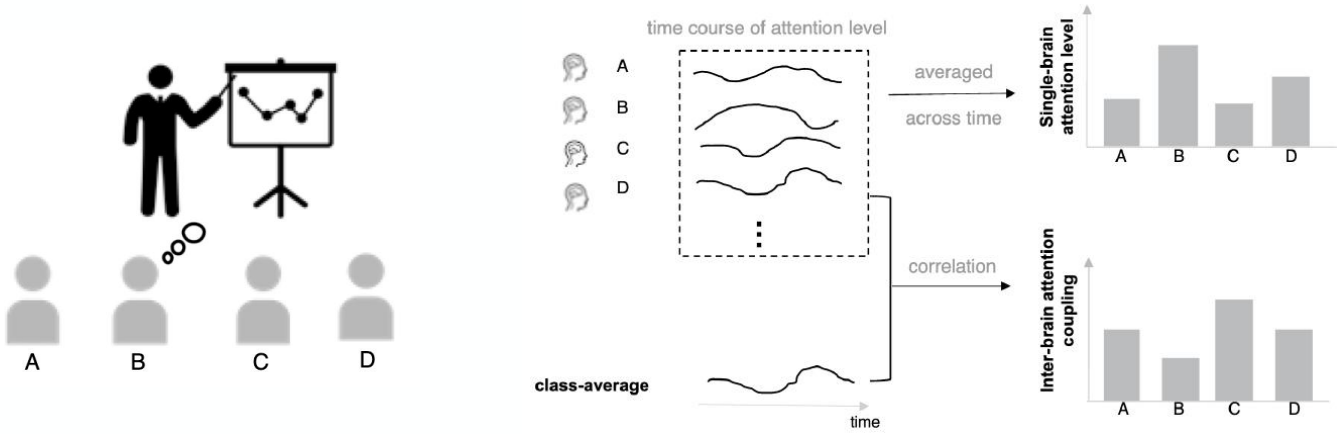
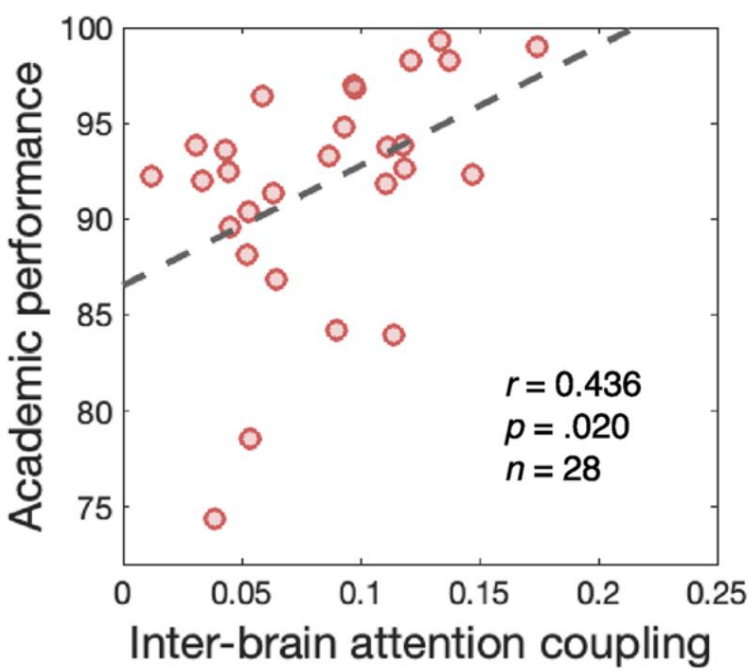
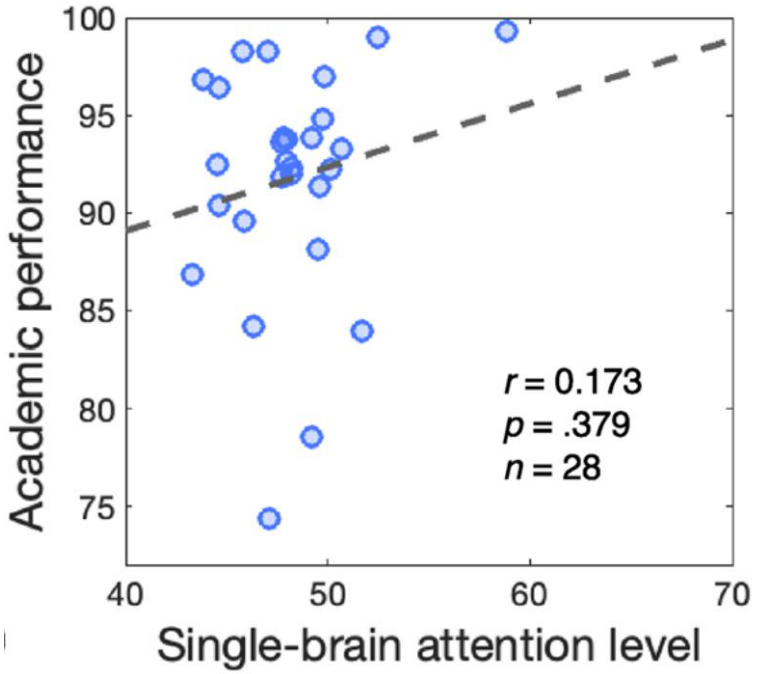
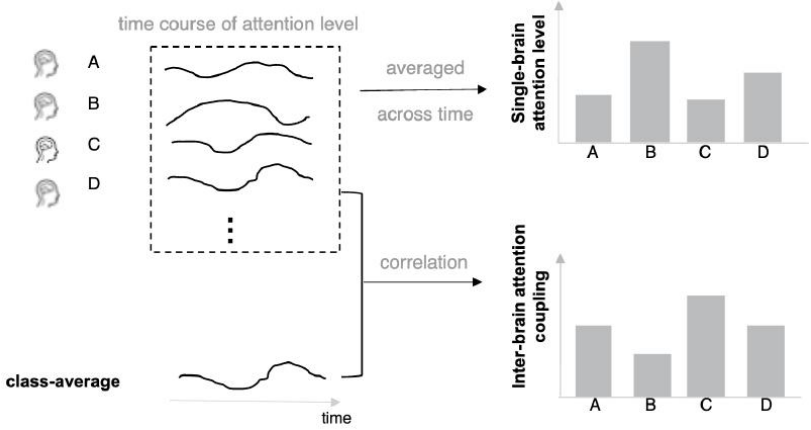


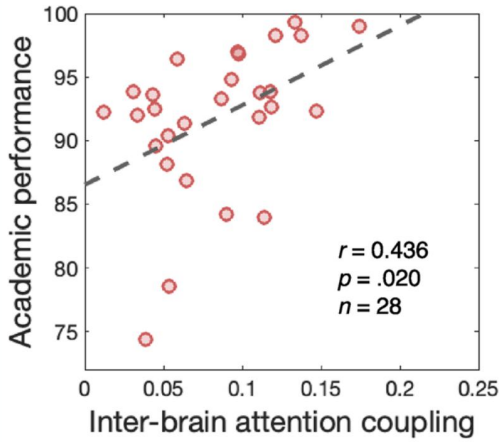




Study 1

Interim Summary





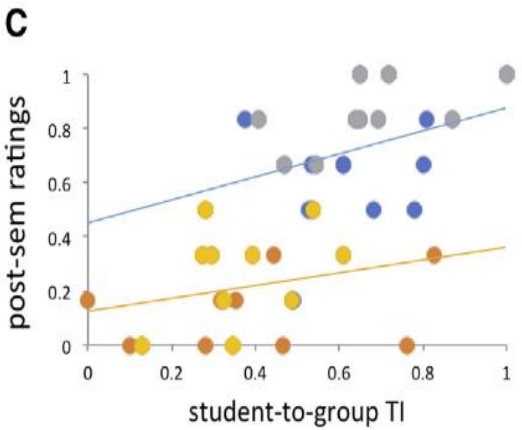
- One's inter-brain attention coupling was positively correlated with academic performance: higher performances are associated with higher coupling to the class-average attention dynamics
- The inter-brain coupling outperforms as an indicator of academic performance compared with the widely-used single-brain attention level

- **Class-average as a good reference for effective learning**

Chen et al. Education Tech Research Dev 2024 (Ours)

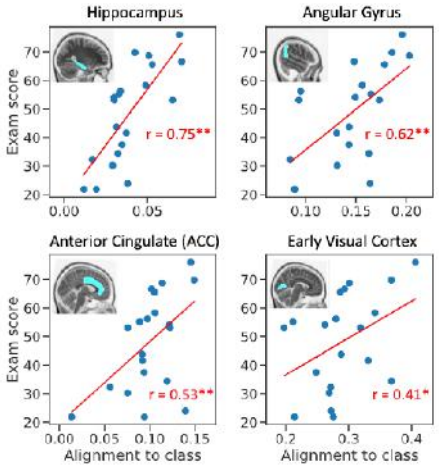
Class-average as a good reference for effective learning?

Neuroscience



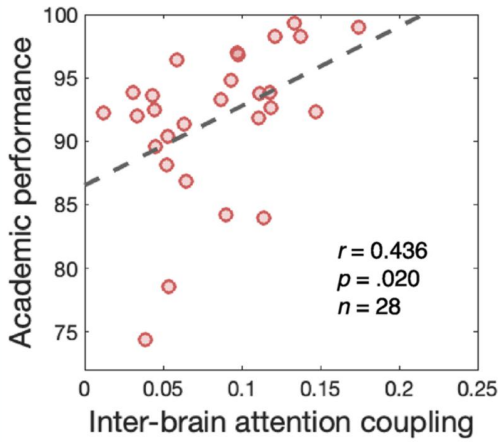
Dikker et al. Curr Biol 2017

Computer Science



Meshulam et al. Nat Comm 2021

Brain Science



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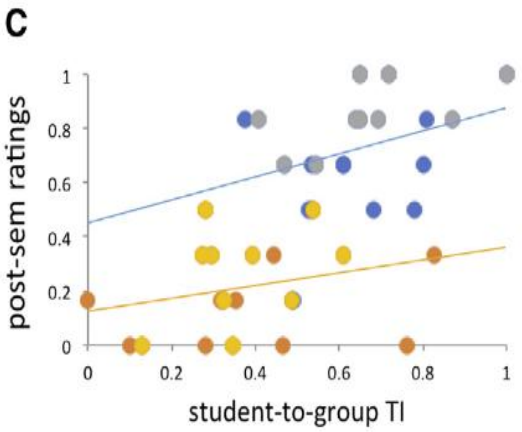

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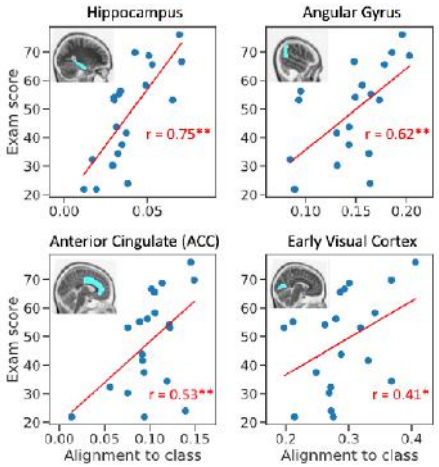

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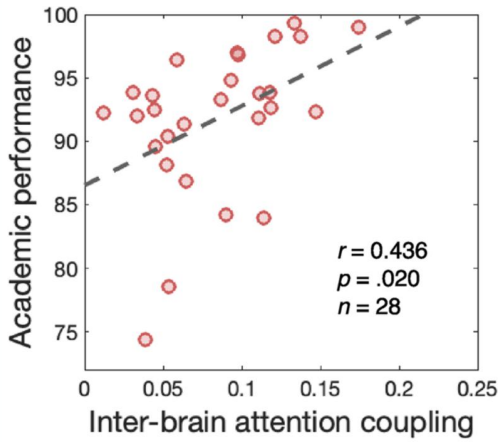

Chen et al. 2024 (Ours)

Class-average as a good reference for learning knowledge in a variety of fields: neuroscience, computer science, brain science, etc.

Meshulam et al. 2021 further suggest **class-average is similar to 'expert'**

Can we generalize the finding to all types of courses?

Study 2

References for effective learning of different disciplines

Math

Chemistry

Chinese

Music

AI-generated images

Study 2

References for effective learning of different disciplines

Math

Chemistry

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The commonalities in teaching and learning of neuroscience, computer science, brain science, etc.?

AI-generated images

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Hard disciplines

Relatively hierarchical, linear knowledge structure and straightforward, uncontentious learning contents **->** prioritize attending to knowledge from teachers **->** ‘class-average’ could well reflect the collective attention dynamics

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loose-structured, non-linearknowledge and contents **->** requiring more constructive and interpretative activity **->** less consistency among students

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Reference for effective learning of soft disciplines?

AI-generated images

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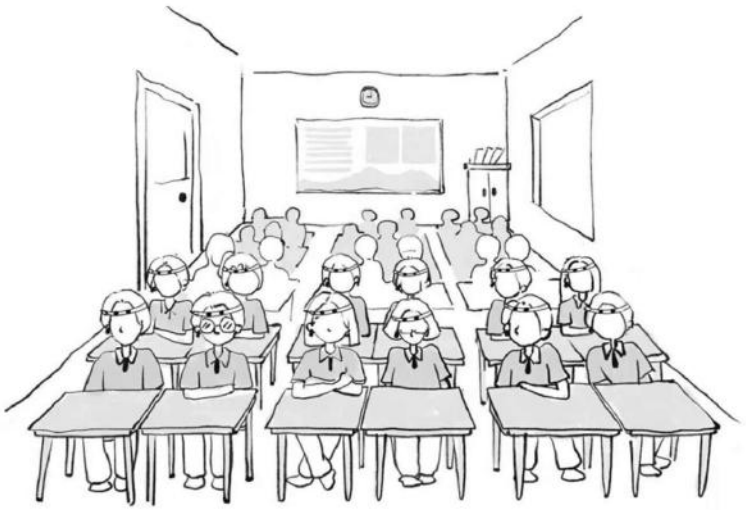
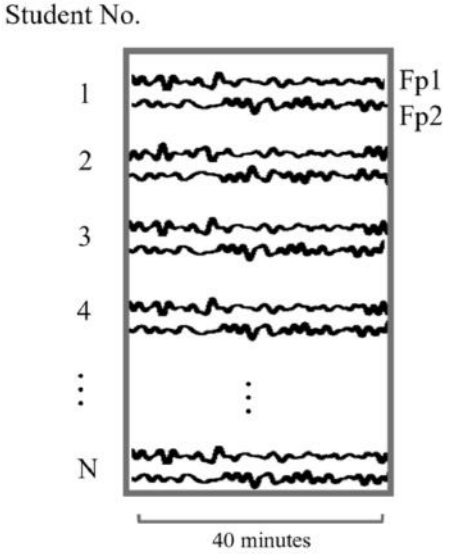
The data collection





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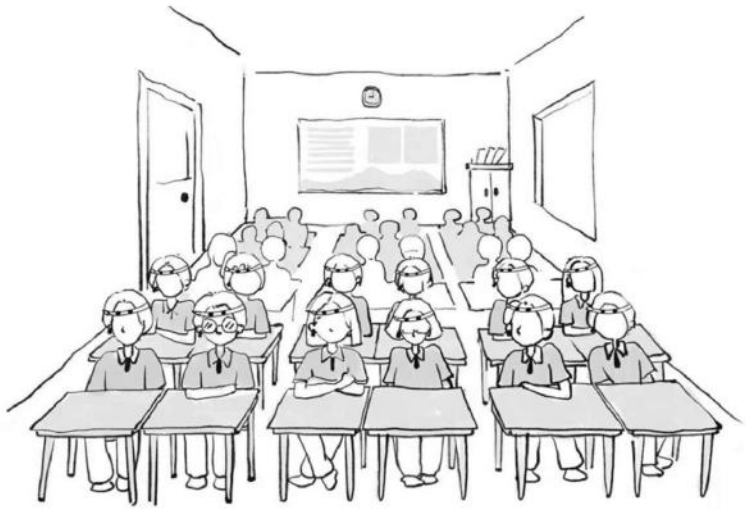
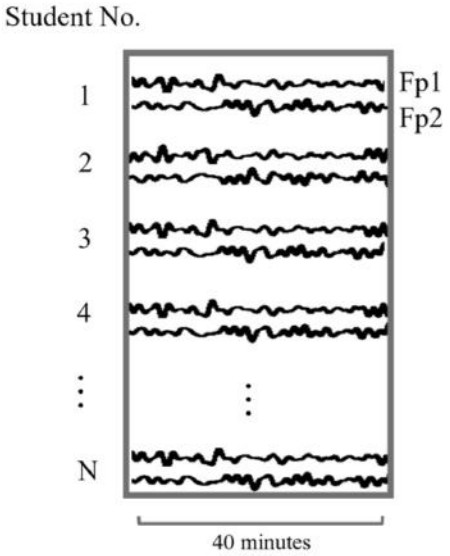
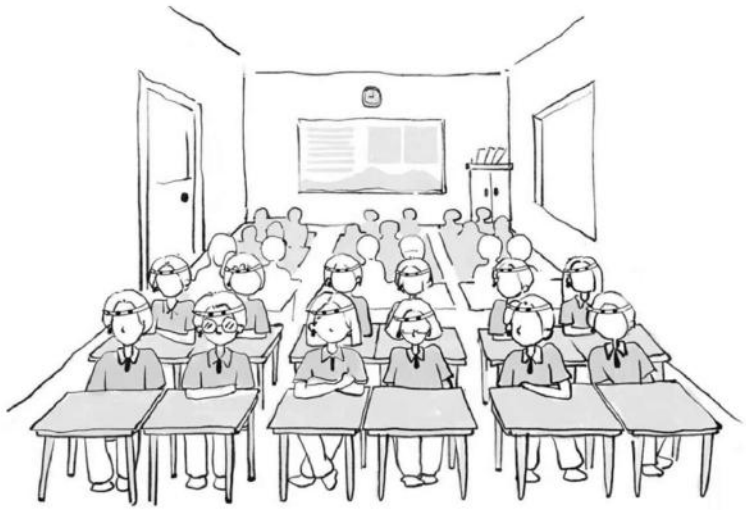


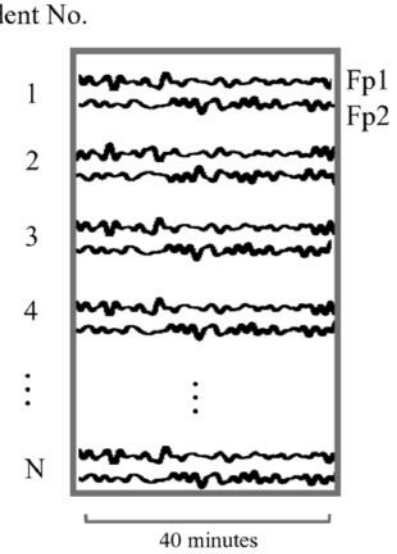


A class of students from grade 10 from a high school in Beijing (34 in total, 16 females, 15-16 years old)

Study 2

The data collection





A class of students from grade 10 from a high school in Beijing (34 in total, 16 females, 15-16 years old)

Wearable EEG headbands (Brainno, SOSO H&C, South Korea) with two dry electrodes covering Fp1/2 at the sampling rate of 250 Hz

Study 2

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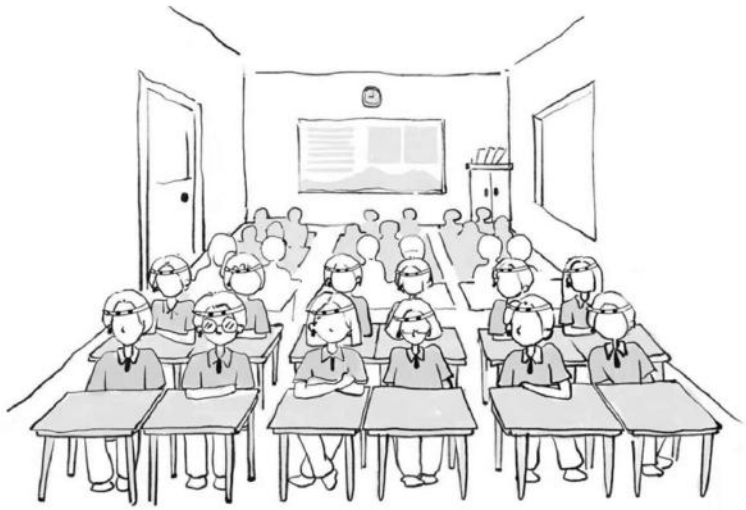

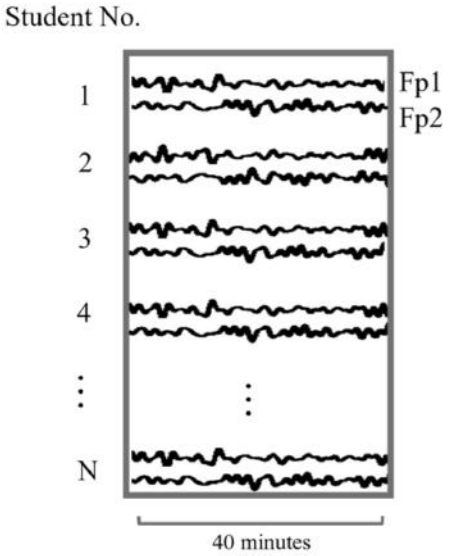

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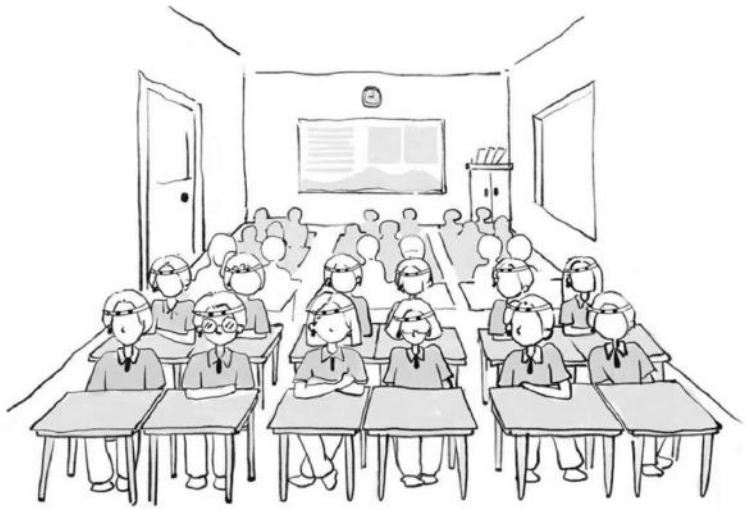
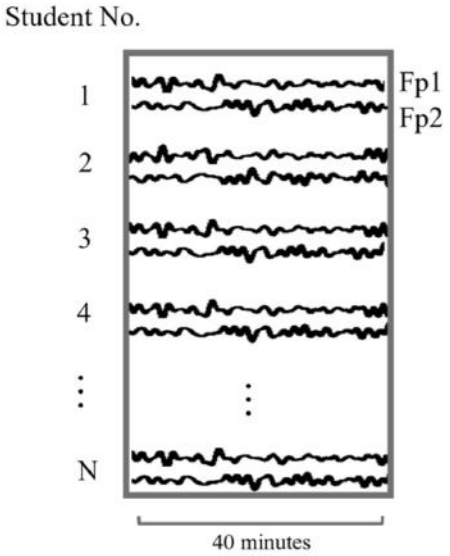
Students' brain signals recorded during their regular Math and Chinese sessions in the classroom throughout one semester (one week per month, in total **18 Chinese sessions and 20 Math sessions**)

Study 2

The data collection





A class of students from grade 10 from a high school in Beijing (34 in total, 16 females, 15-16 years old)

Wearable EEG headbands (Brainno, SOSO H&C, South Korea) with two dry electrodes covering Fp1/2 at the sampling rate of 250 Hz

Students' brain signals recorded during their regular Math and Chinese sessions in the classroom throughout one semester (one week per month, in total **18 Chinese sessions and 20 Math sessions**)

Math — Hard discipline; Chinese — Soft discipline

Study 2

Student-class coupling vs. student-top coupling

Study 2

Student-class coupling vs. student-top coupling

Hypotheses

Study 2

Student-class coupling vs. student-top coupling

Hypotheses

For Math sessions (Hard): class-average as a good reference of effective learning

Study 2

Student-class coupling vs. student-top coupling

Hypotheses

For Math sessions (Hard): class-average as a good reference of effective learning

The higher the inter-brain coupling to the class average, the better the academic performance

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Student-class coupling vs. student-top coupling

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Study 2

Student-class coupling vs. student-top coupling

Hypotheses

For Math sessions (Hard): class-average as a good reference of effective learning

The higher the inter-brain coupling to the class average, the better the academic performance

For Chinese sessions (Soft): top students as a good reference of effective learning

Study 2

Student-class coupling vs. student-top coupling

Hypotheses

For Math sessions (Hard): class-average as a good reference of effective learning

The higher the inter-brain coupling to the class average, the better the academic performance

For Chinese sessions (Soft): top students as a good reference of effective learning

The higher the inter-brain coupling to the top students, the better the academic performance

Study 2

Student-class coupling vs. student-top coupling

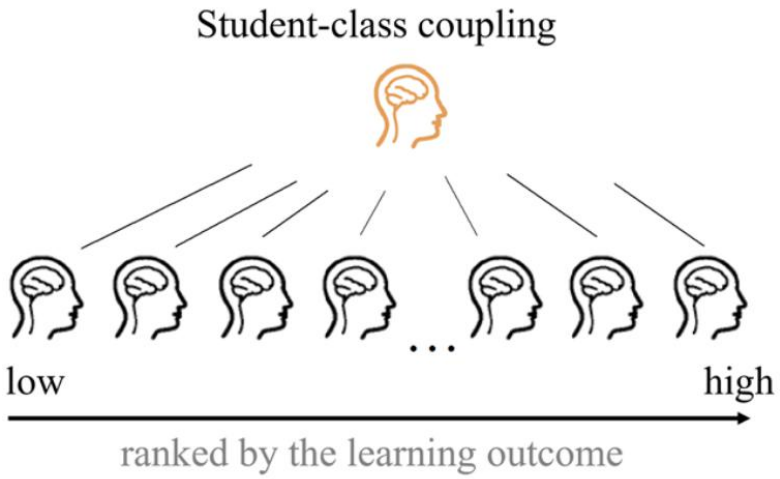
Hypotheses

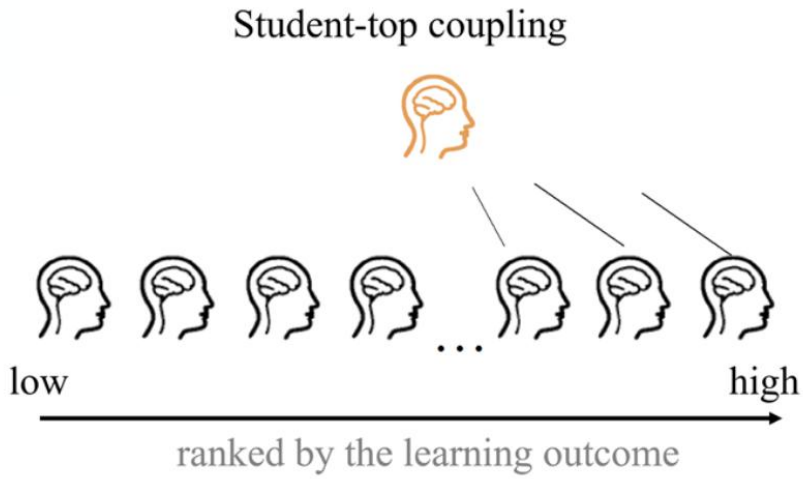
For Math sessions (Hard): class-average as a good reference of effective learning

The higher the inter-brain coupling to the class average, the better the academic performance

For Chinese sessions (Soft): top students as a good reference of effective learning

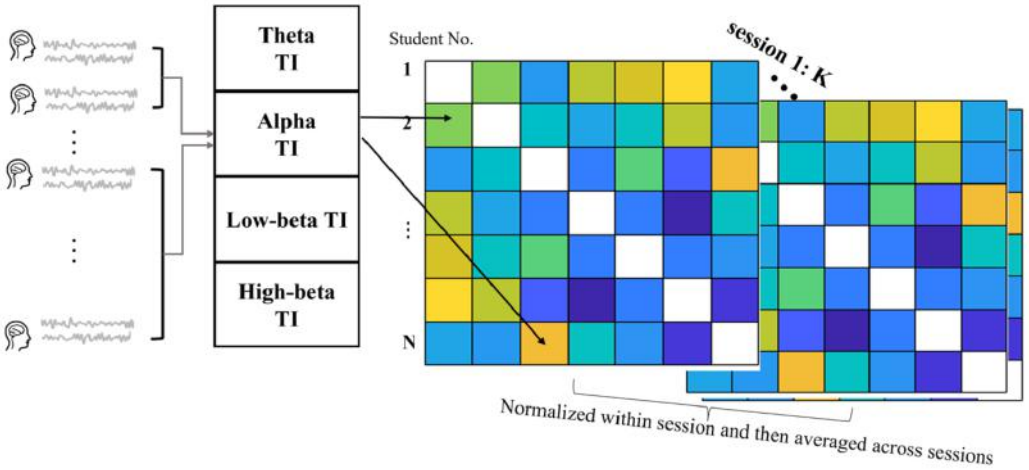
The higher the inter-brain coupling to the top students, the better the academic performance





Study 2

Computation of inter-brain coupling



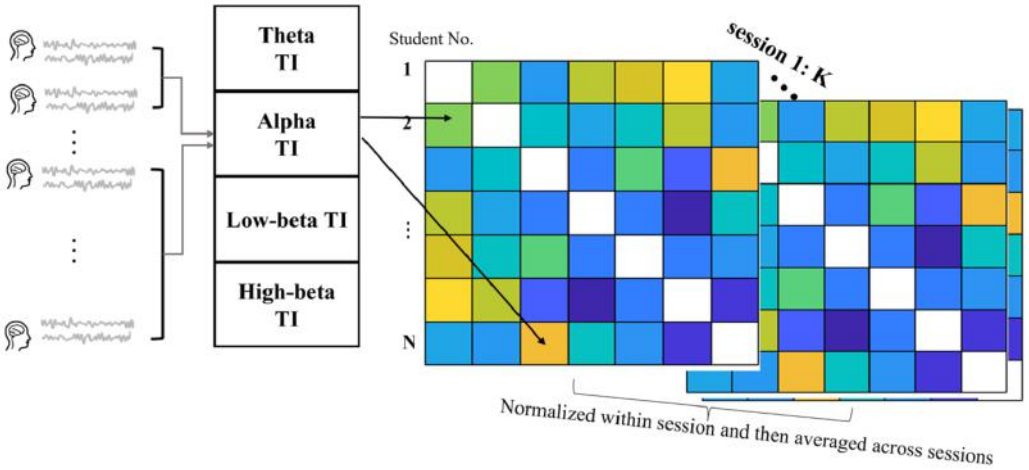
TI (total interdependence)

$$\mathrm{TI}_{X_i,X_j} = -\frac{2}{f_s}\sum_{m=1}^{M}\ln(1 - C^2_{X_i,X_j}(m\triangle f))\triangle f$$

$$\triangle f = \frac{f_s}{2(M-1)}$$

Study 2

Computation of inter-brain coupling



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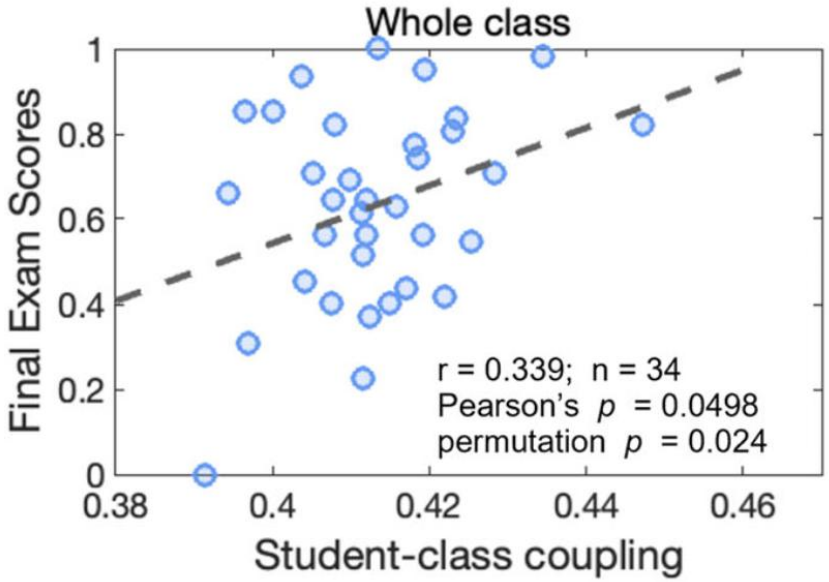
Math, theta-band



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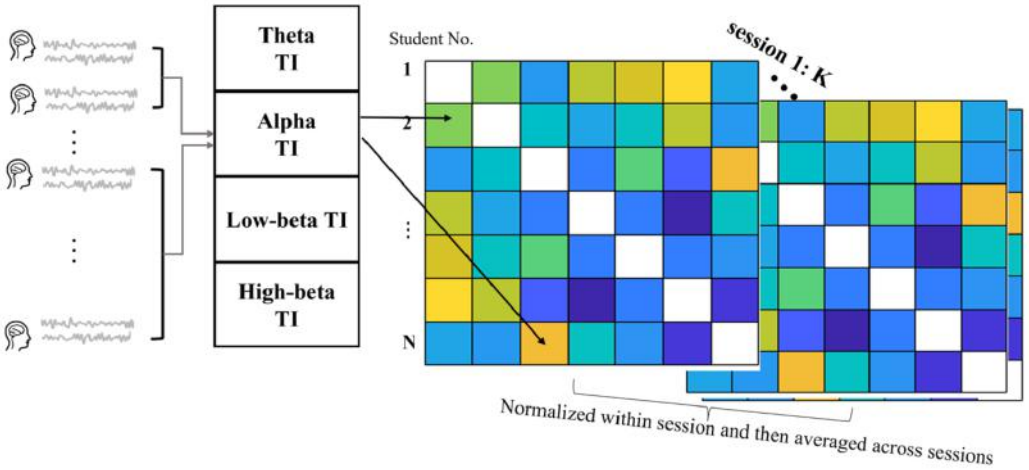

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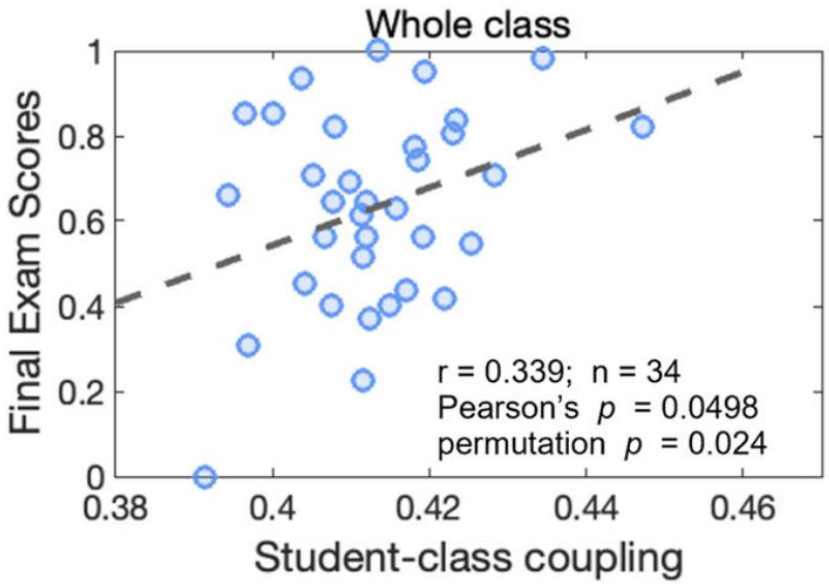
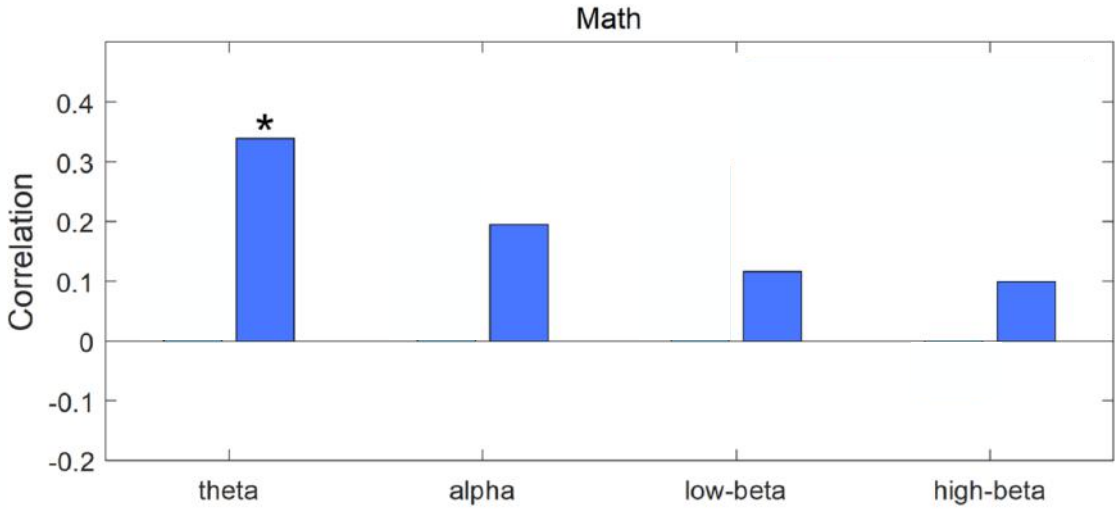
Math, theta-band

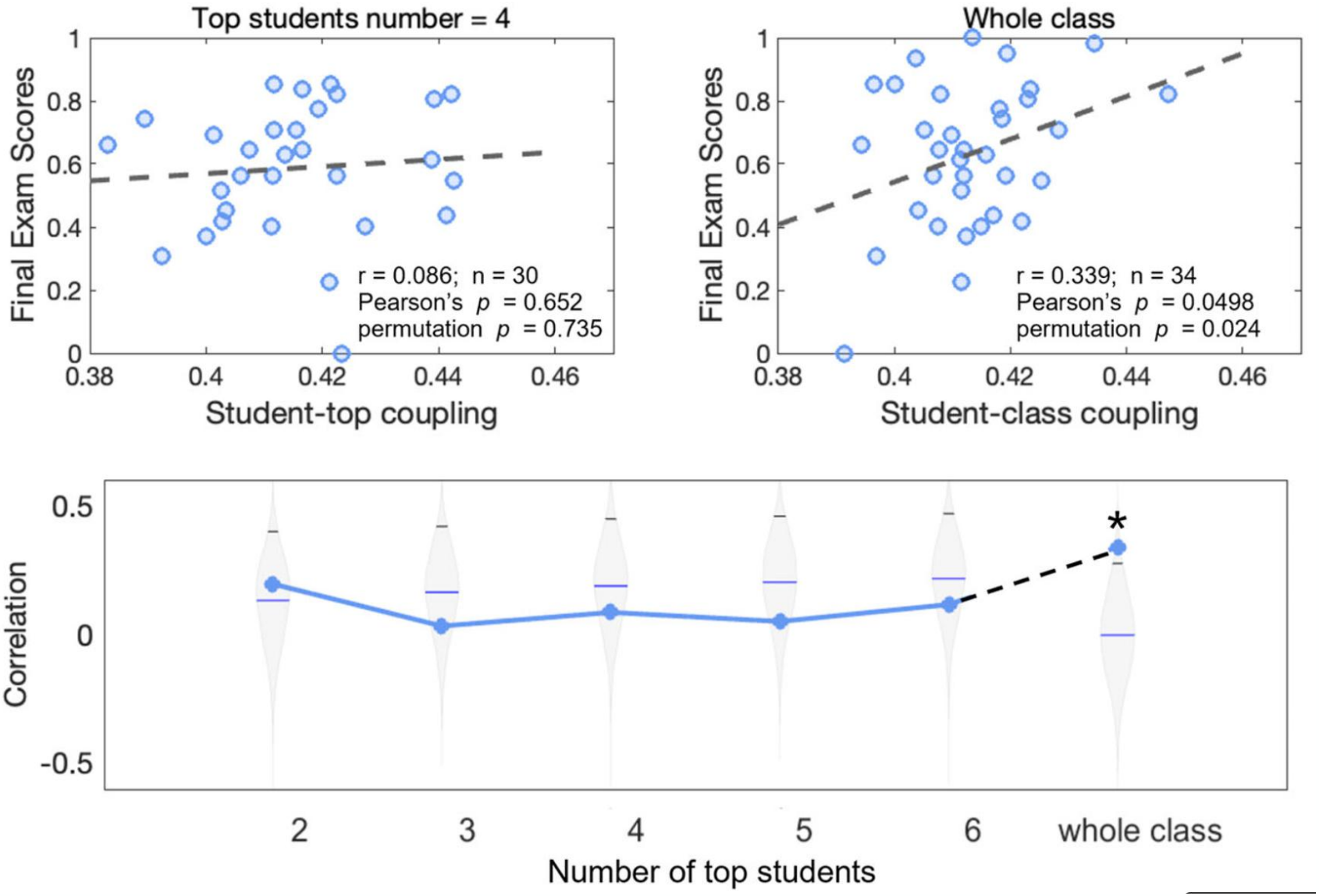




Study 2

Theta-band student-class coupling correlates with Math performance

Math, theta-band



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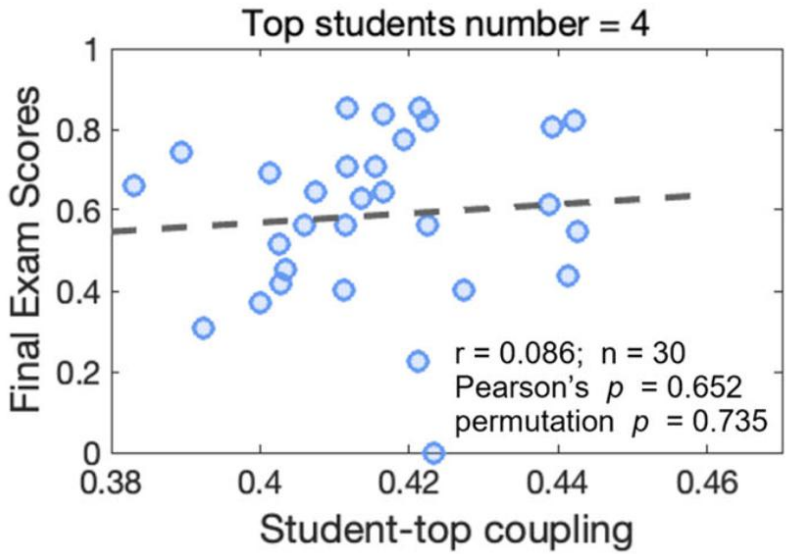
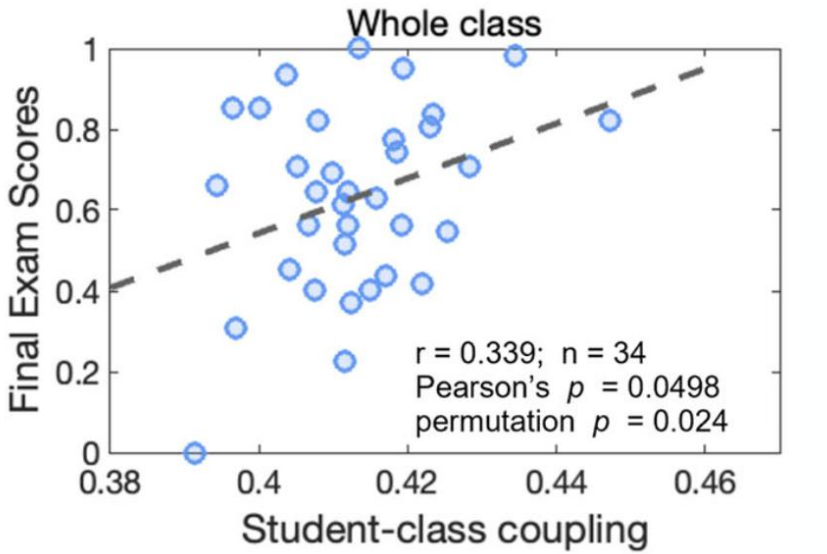
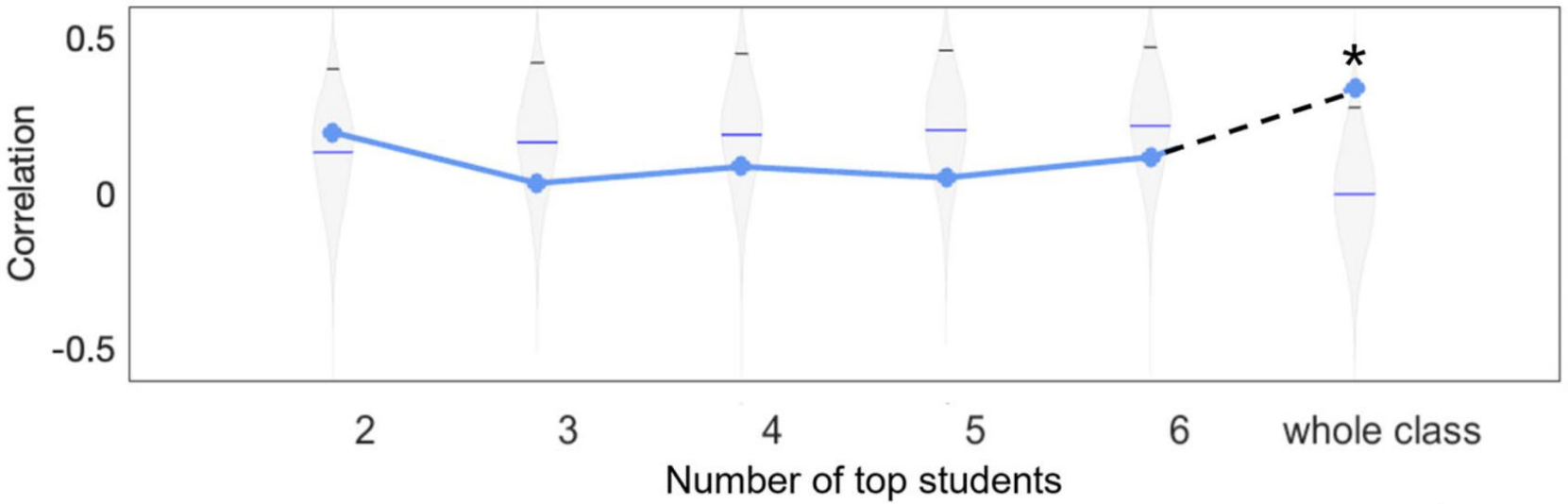


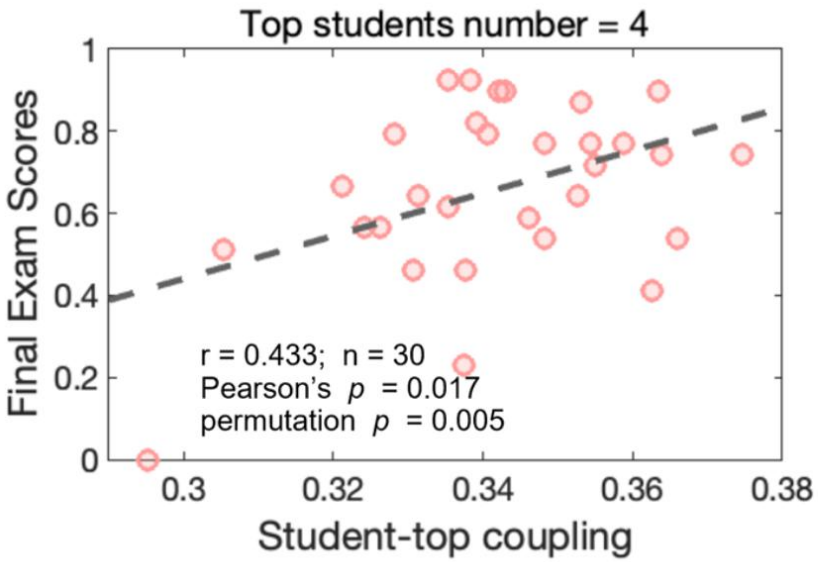


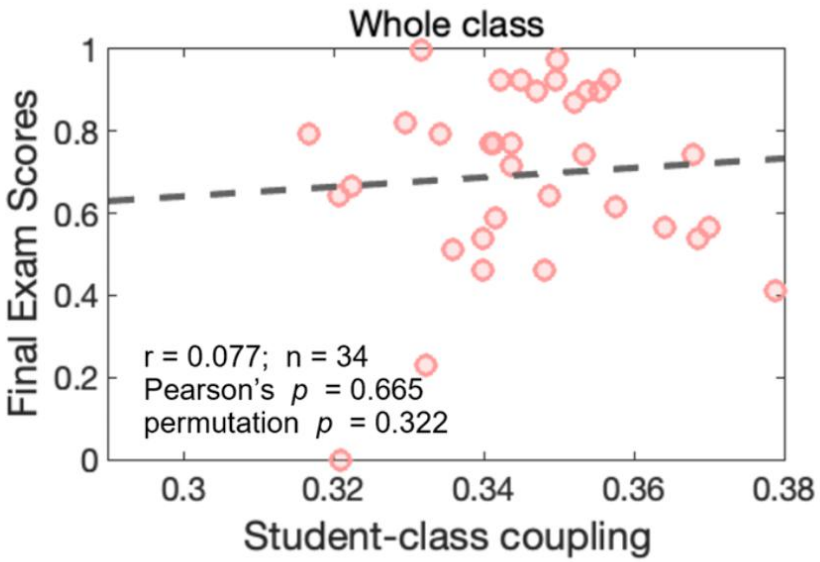


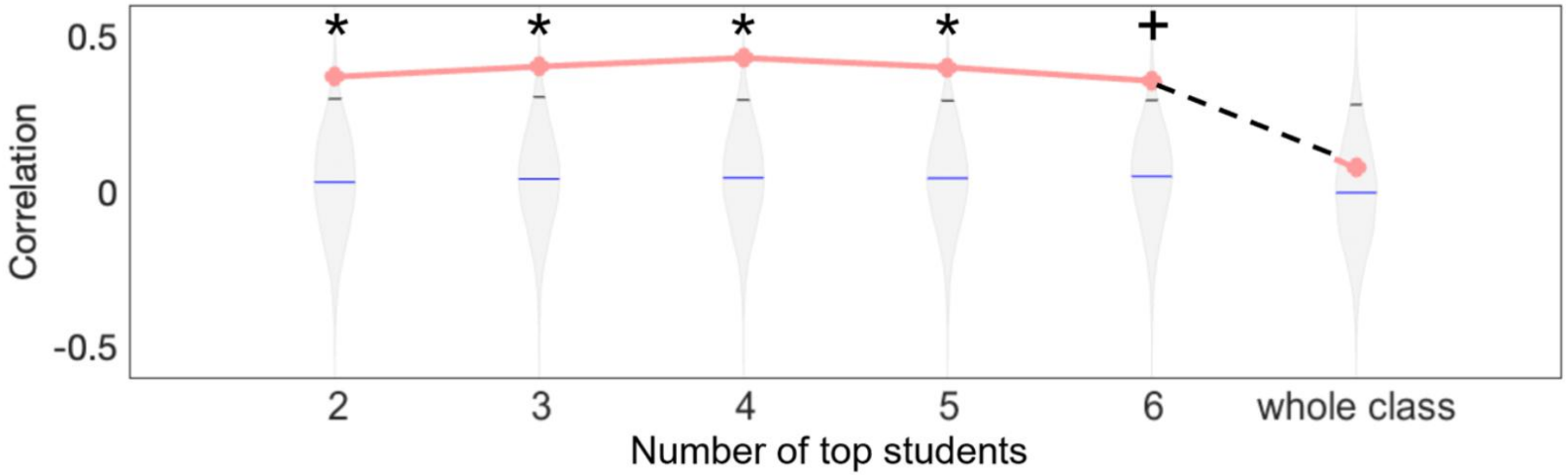
Study 2

Alpha-band student-top coupling correlates with Chinese performance

Chinese, alpha-band



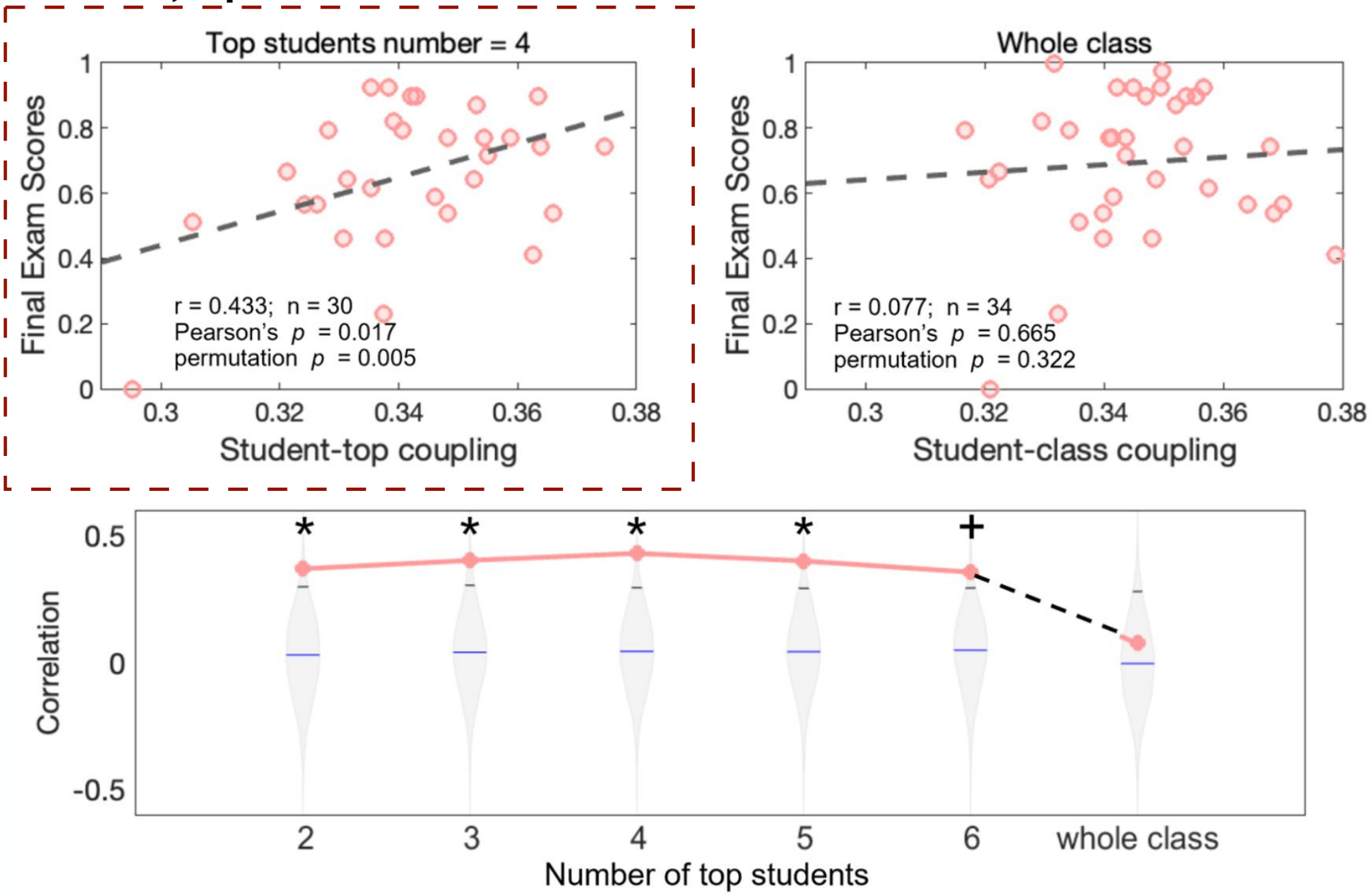




Study 2

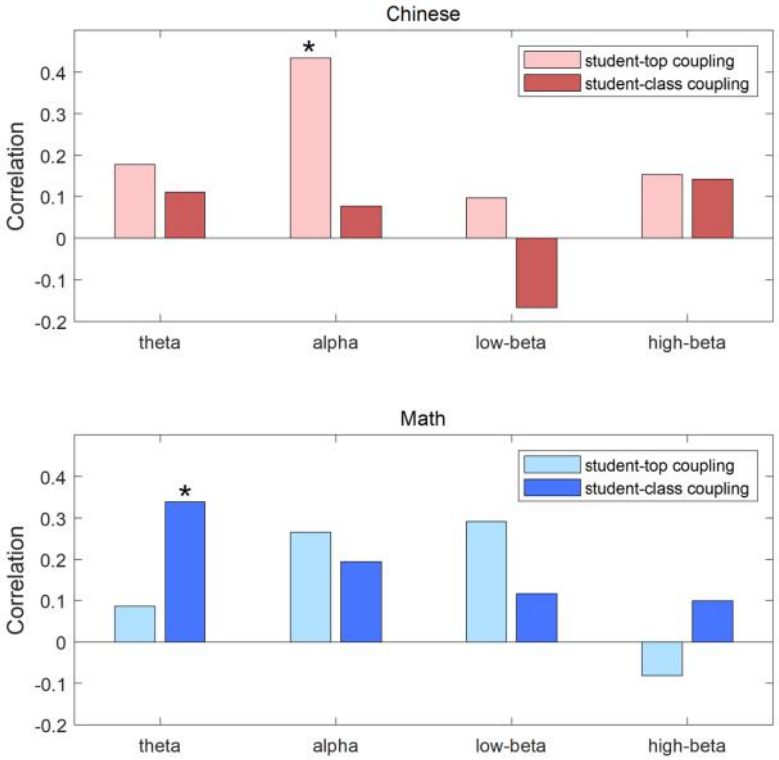
Alpha-band student-top coupling correlates with Chinese performance

Chinese, alpha-band



Study 2

Discipline specificity of the inter-brain couplings



Study 2

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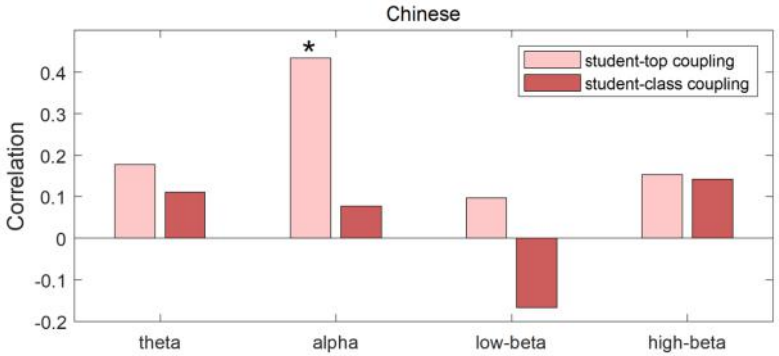

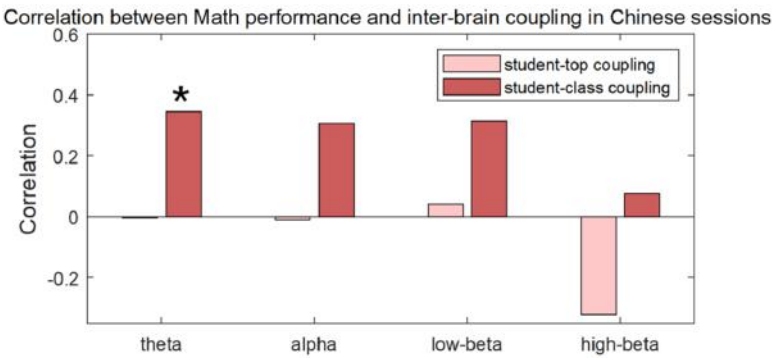

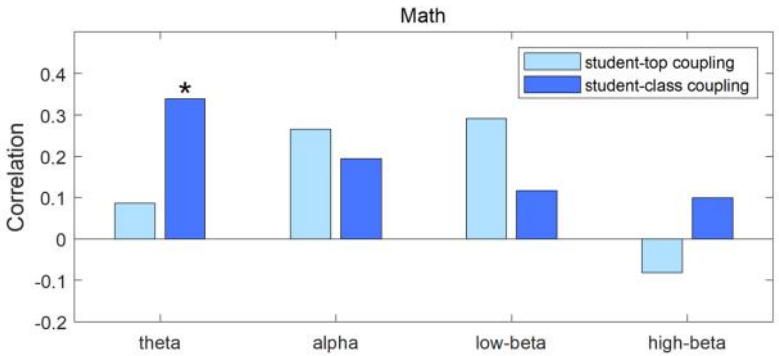

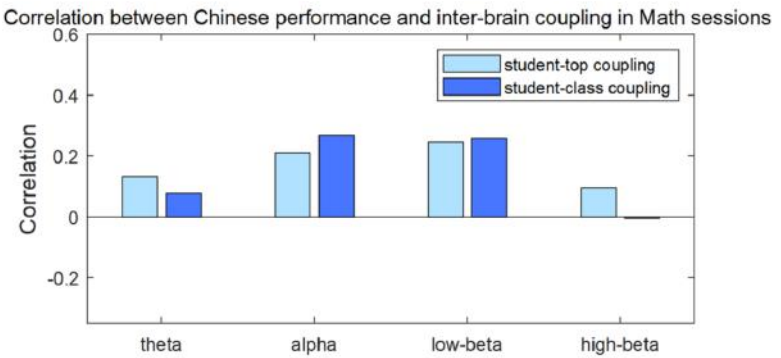

Study 2

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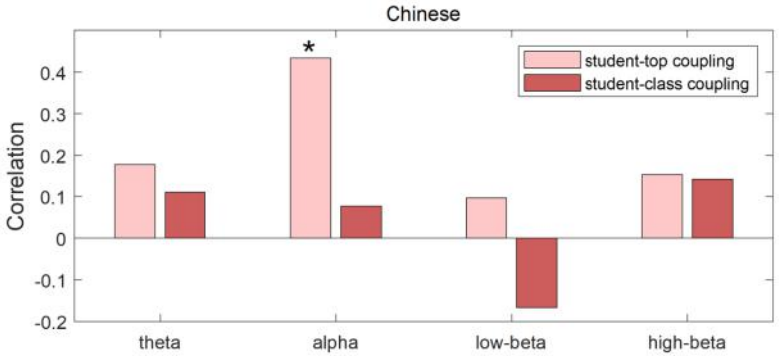
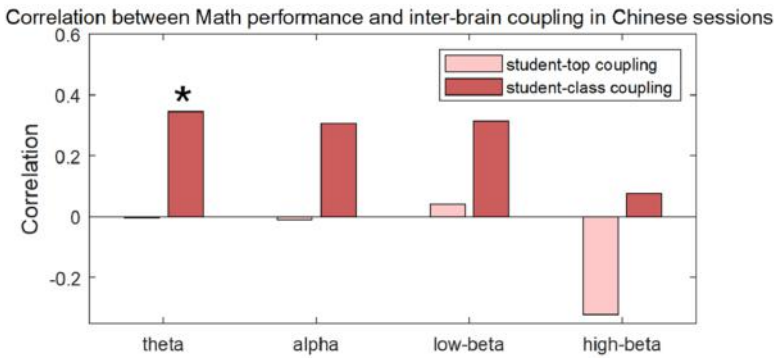
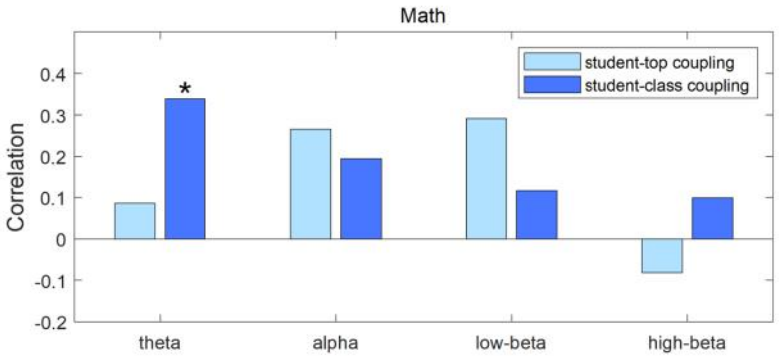
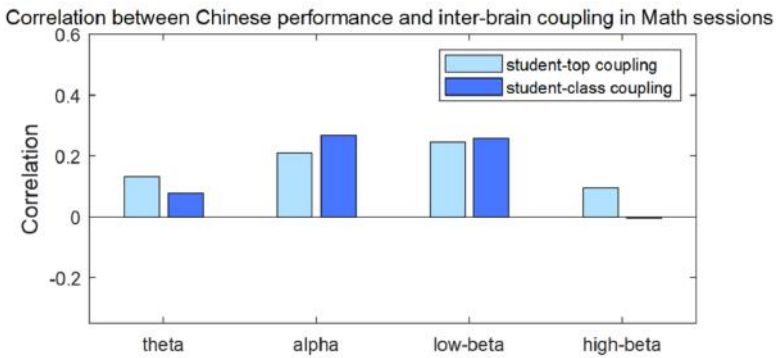








Frontal theta-band couplings

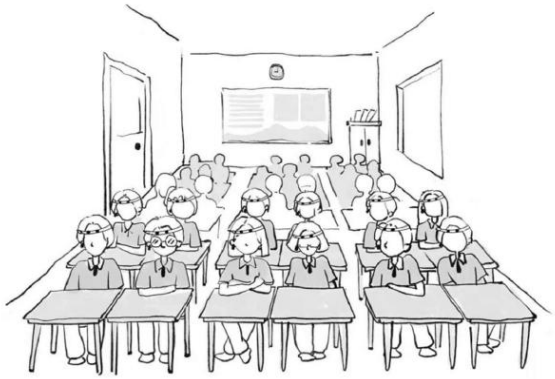
Students' continuous engagement with the course content, supporting both Math learning and discipline-general learning.

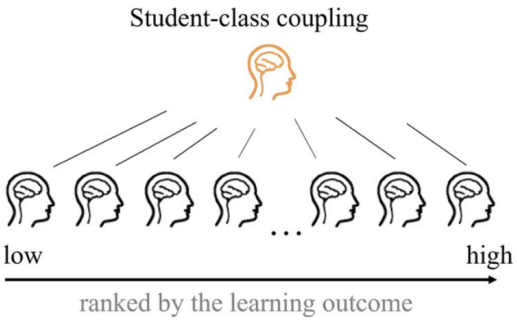
Frontal alpha-band couplings

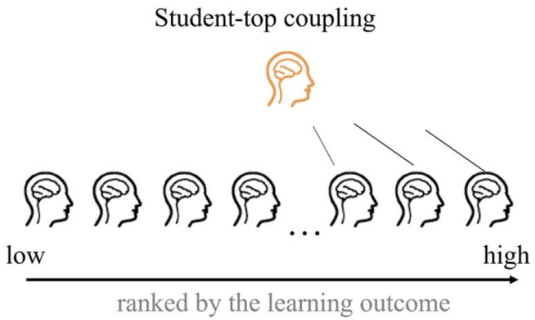
High internal processing with inhibition of stimulus-driven attention, esp. during Chinese sessions

Study 2

Interim Summary







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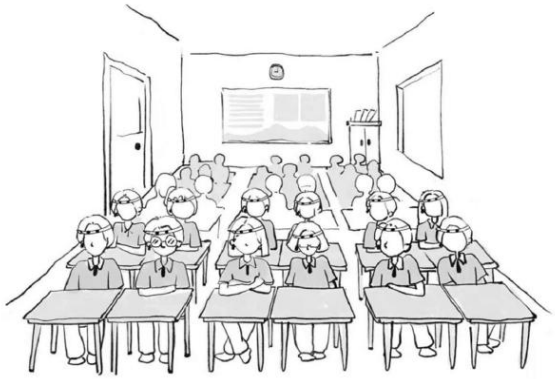
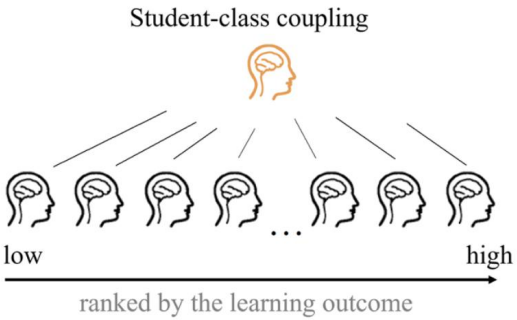
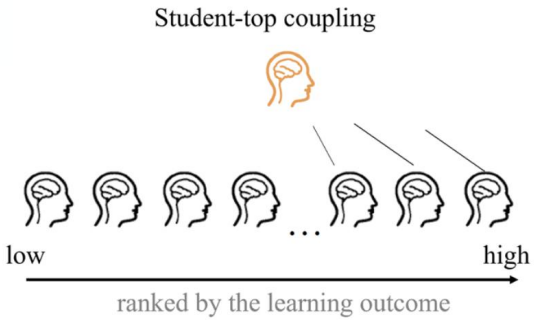
Study 2

Interim Summary



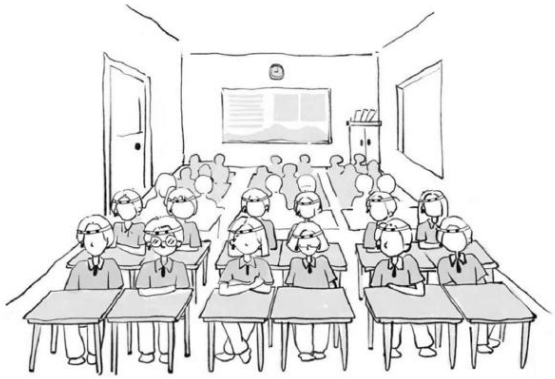


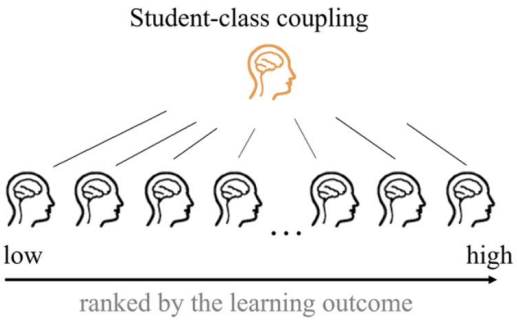


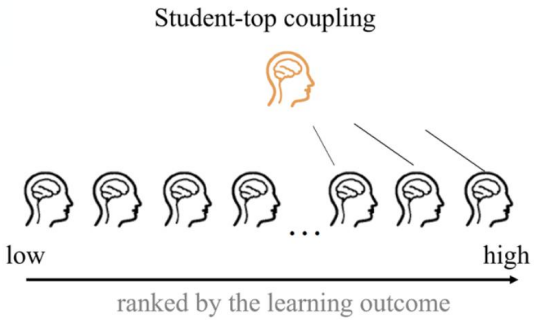
Different disciplines have difference reference for effective learning

Study 2

Interim Summary







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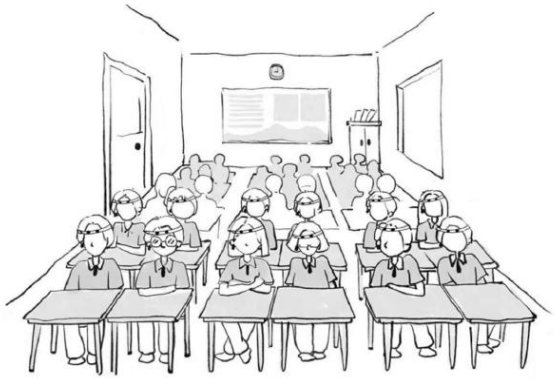

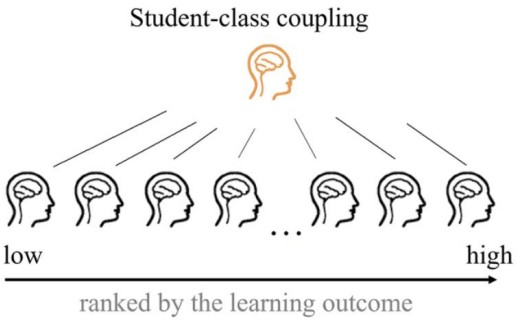

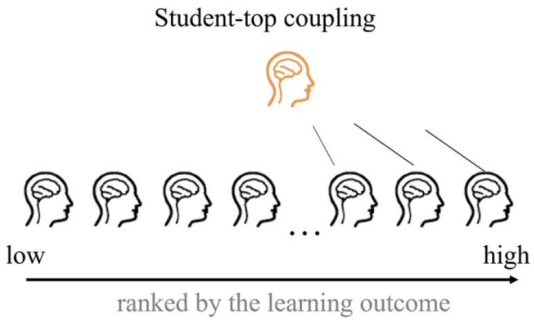

Different disciplines have difference reference for effective learning

Math (hard discipline): class-average as a good reference of effective learning

Study 2

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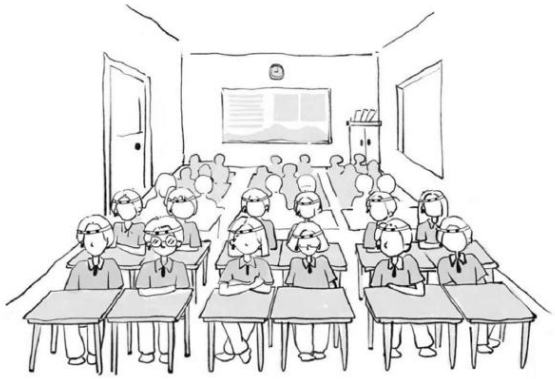

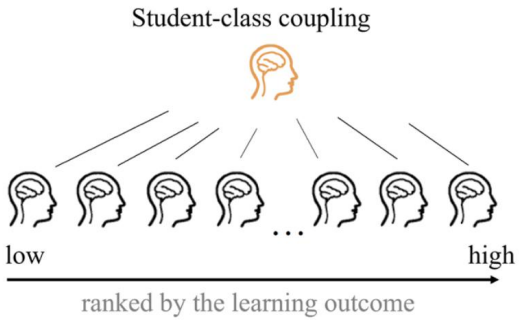

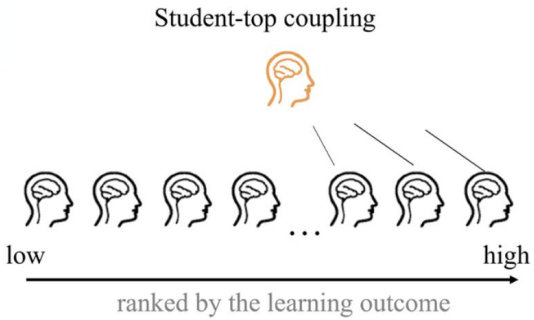

Different disciplines have difference reference for effective learning

Math (hard discipline): class-average as a good reference of effective learning

The higher the frontal theta inter-brain coupling to the class average, the better the academic performance

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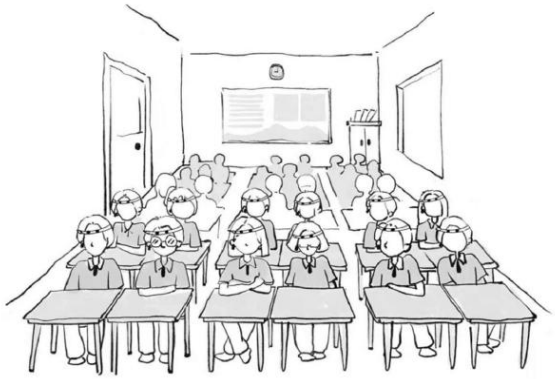
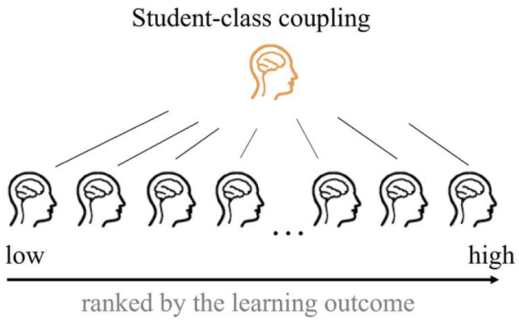
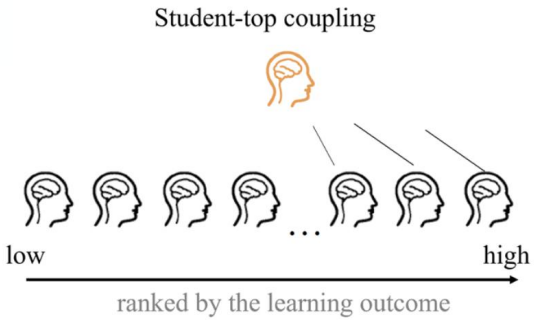
Study 2

Interim Summary







Different disciplines have difference reference for effective learning

Math (hard discipline): class-average as a good reference of effective learning

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Chinese (soft discipline): top students as a good reference of effective learning

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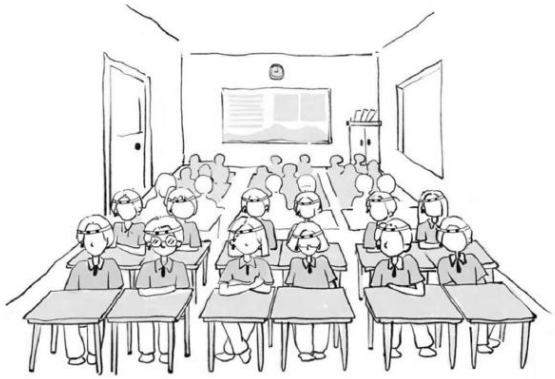
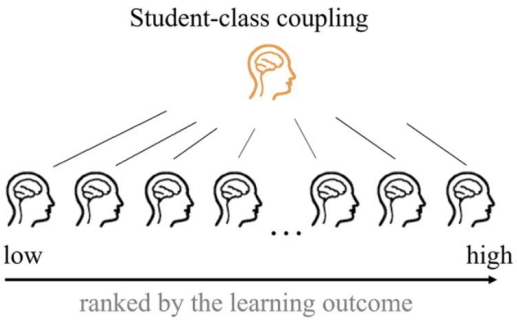
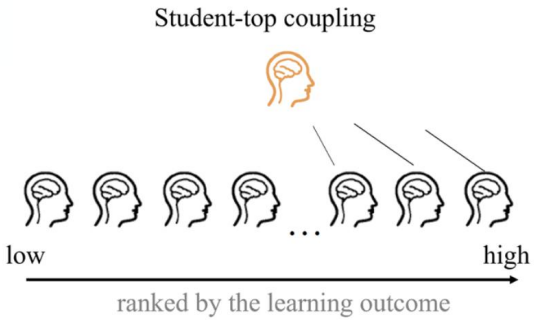
Study 2

Interim Summary







Different disciplines have difference reference for effective learning

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The higher the frontal theta inter-brain coupling to the class average, the better the academic performance

Chinese (soft discipline): top students as a good reference of effective learning

The higher the frontal alpha inter-brain coupling to the top students, the better the academic performance

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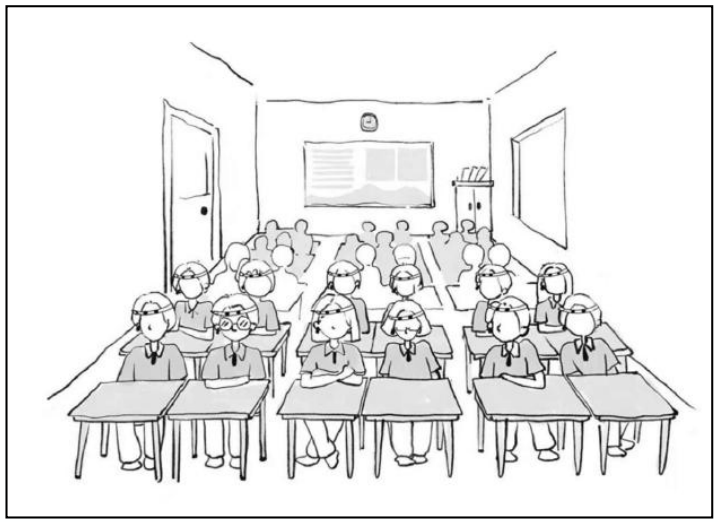
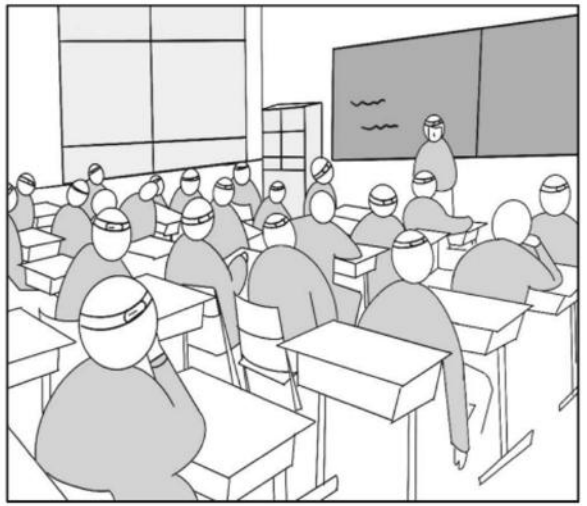
Study 3

Student-teacher coupling for academic performance



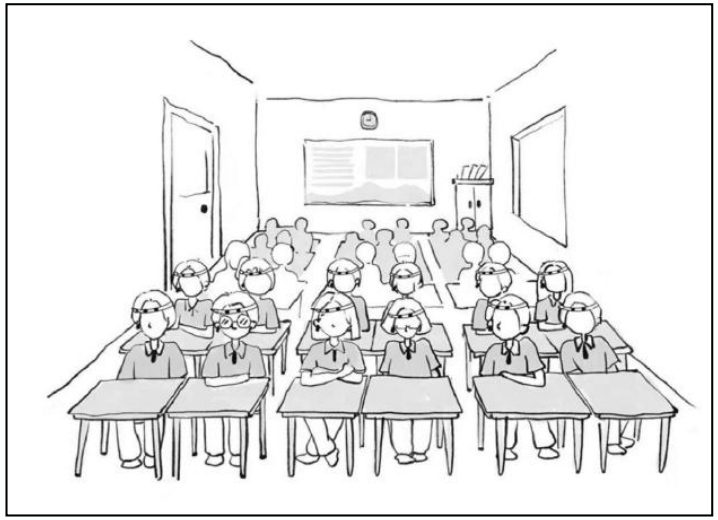
With the teachers recorded



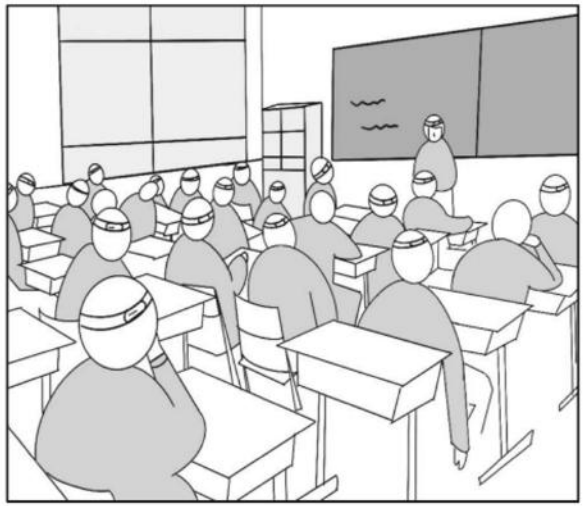
Xu et al. preprint online, doi: 10.1101/2024.05.08.593270 (Ours)

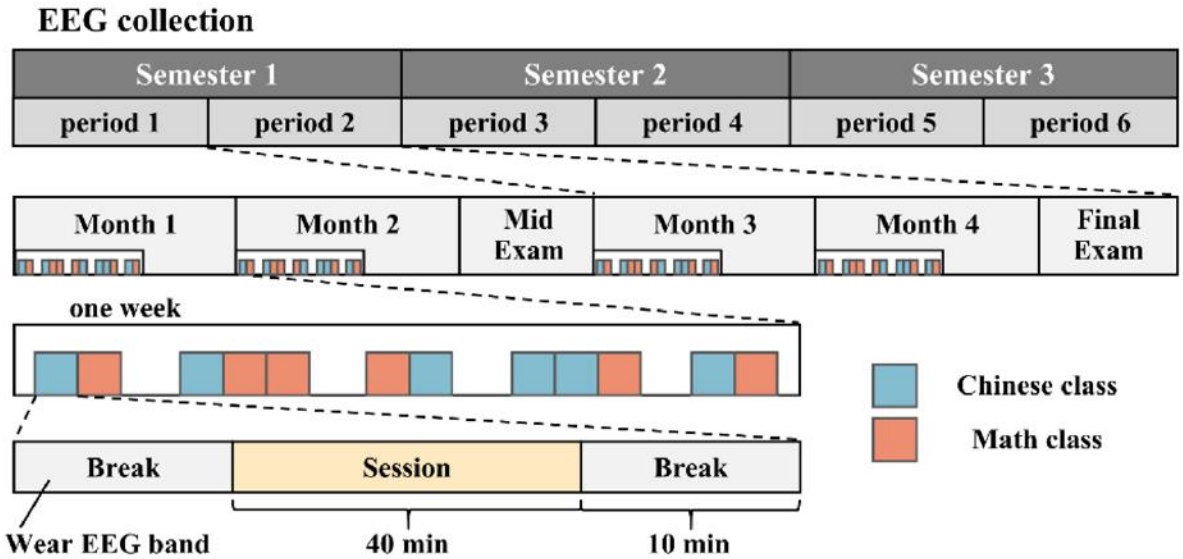
Study 3

Student-teacher coupling for academic performance



With the teachers recorded

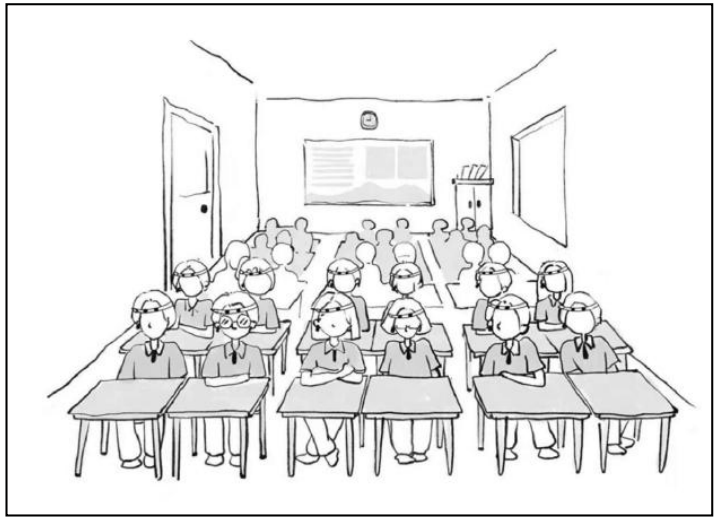




Xu et al. preprint online, doi: 10.1101/2024.05.08.593270 (Ours)

Study 3

Student-teacher coupling for academic performance



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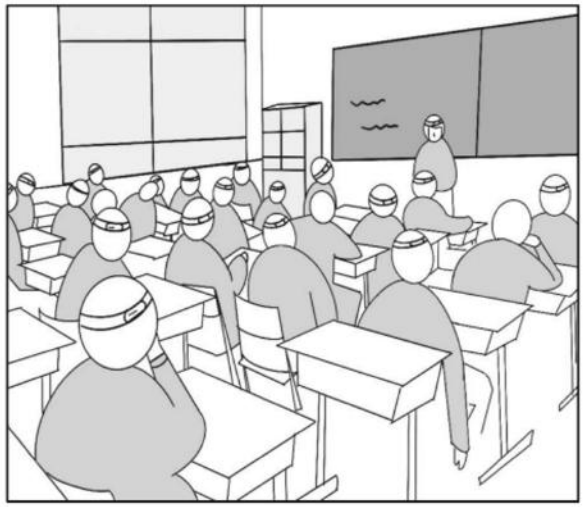

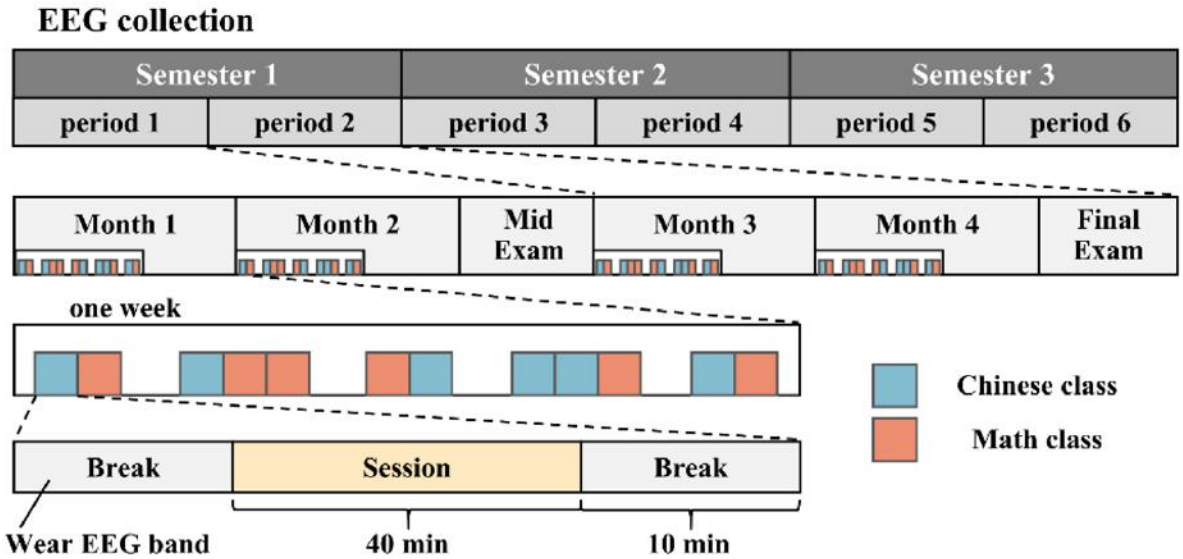

RQ: How will student-teacher coupling reflect students' academic performance?

Recording of multiple semesters: 4,175 longitudinal EEG recordings from 107 junior and senior students across 393 regular Chinese and math classes

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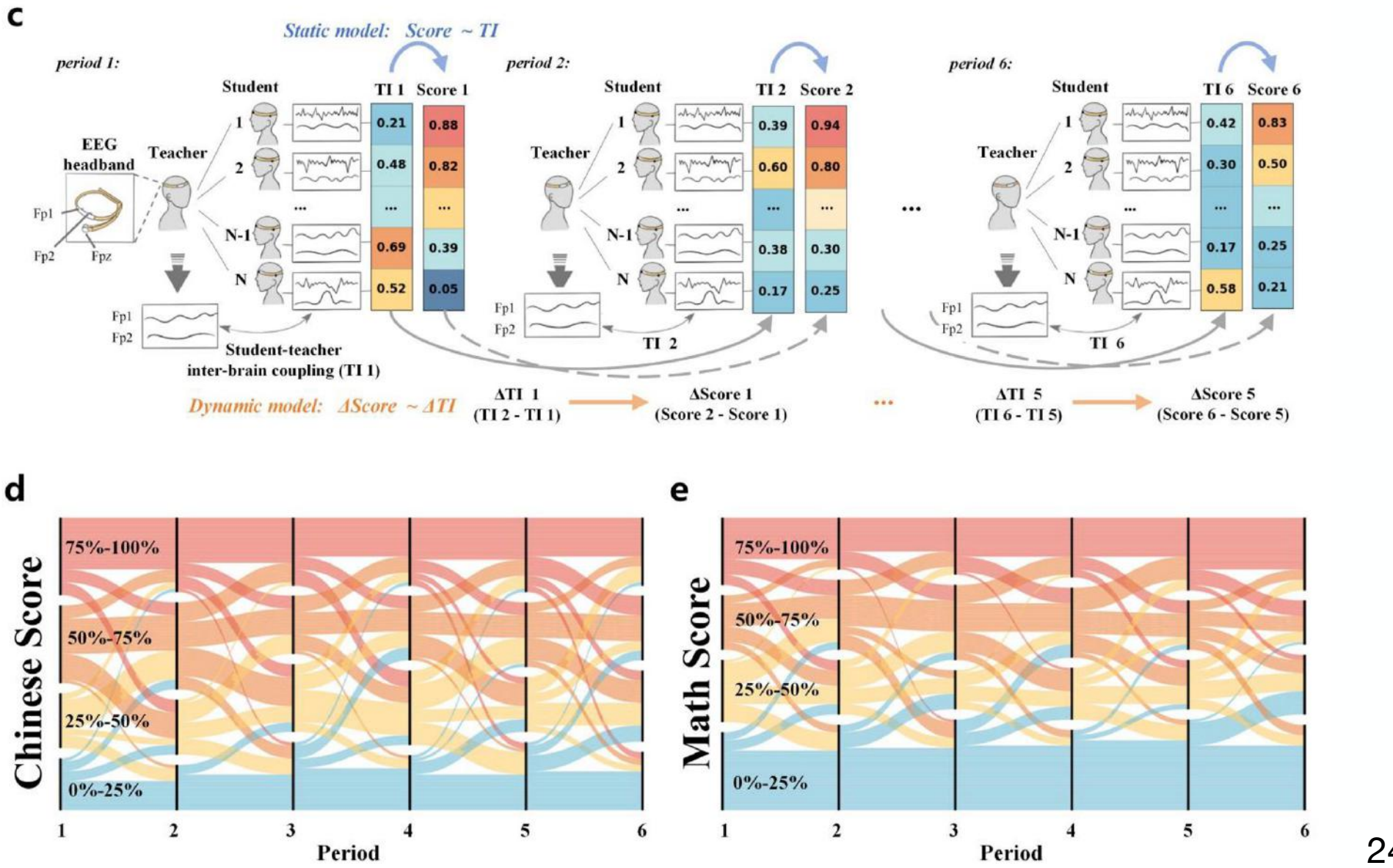

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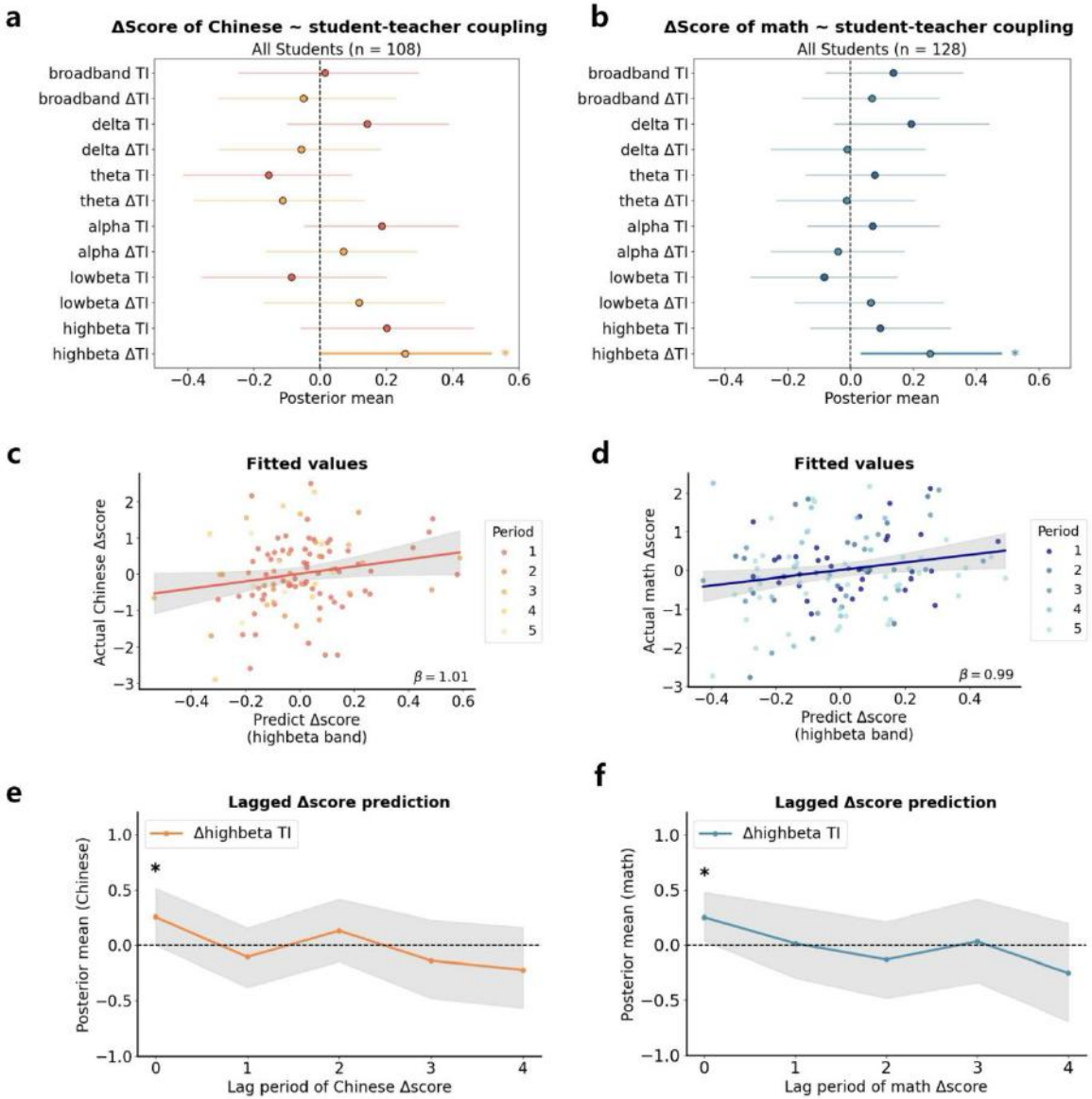

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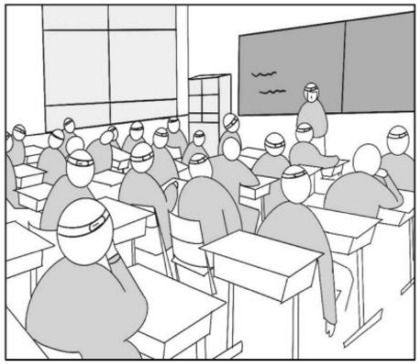

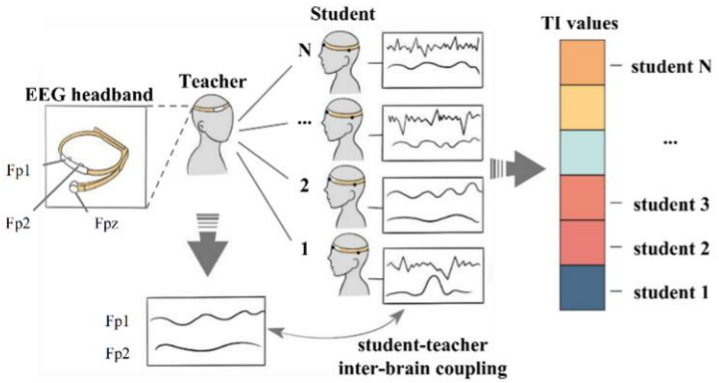

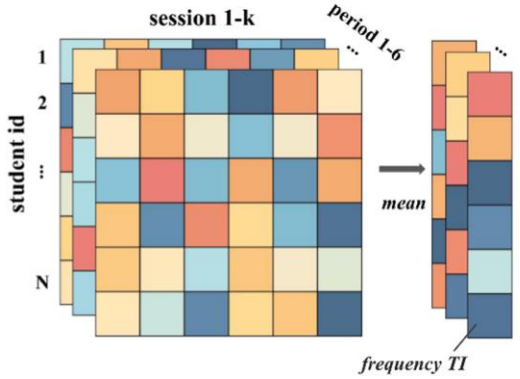

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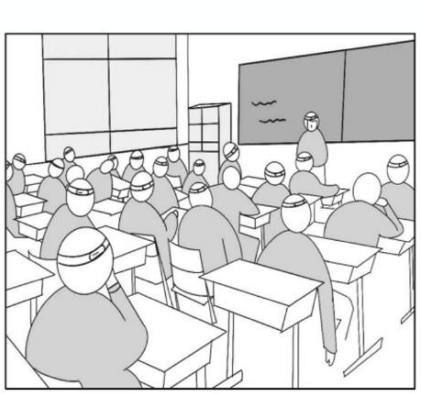

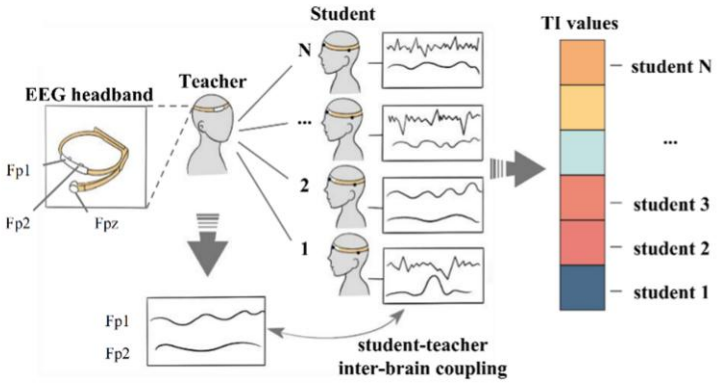

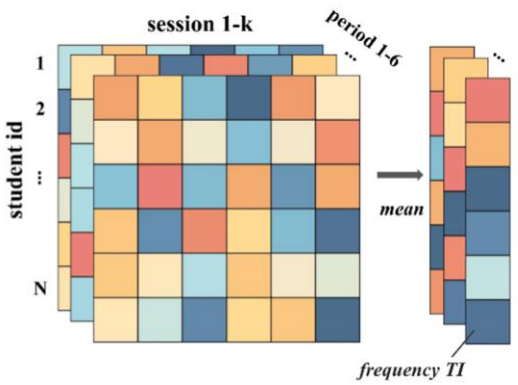

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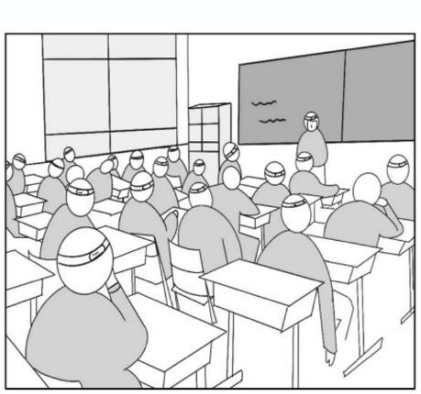

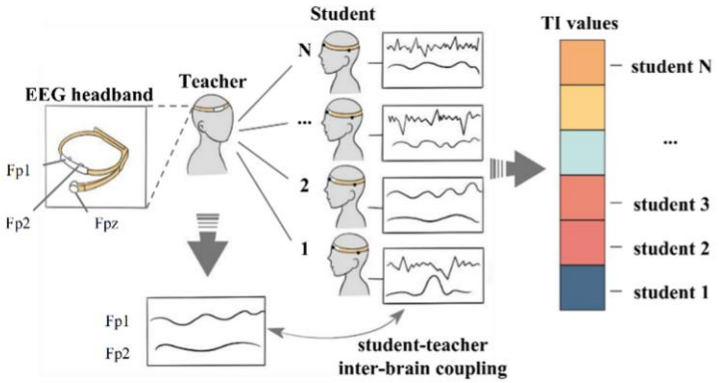

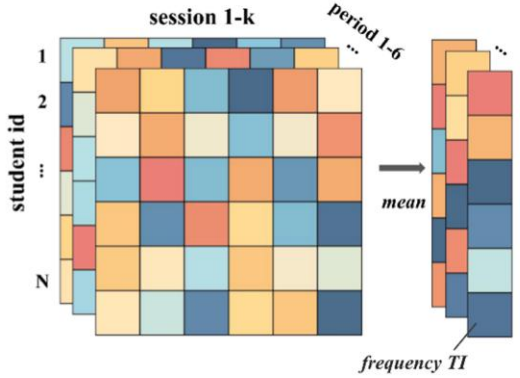

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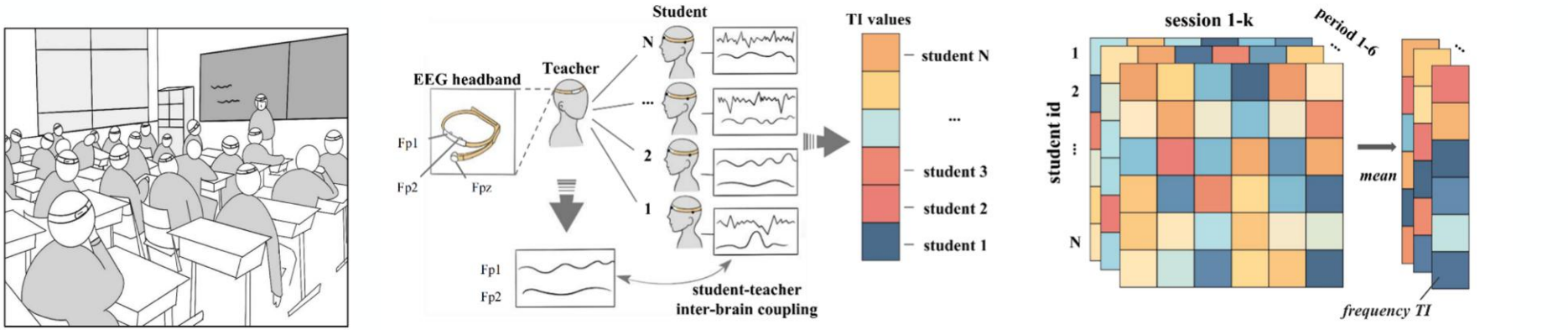

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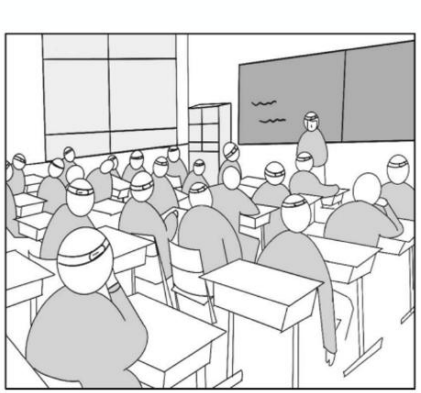

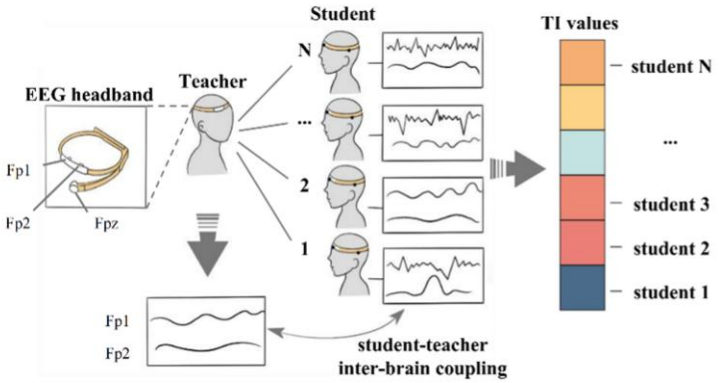

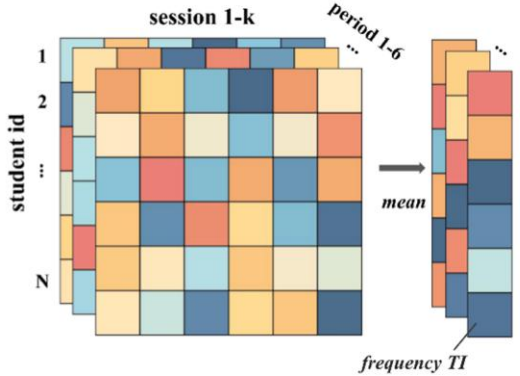

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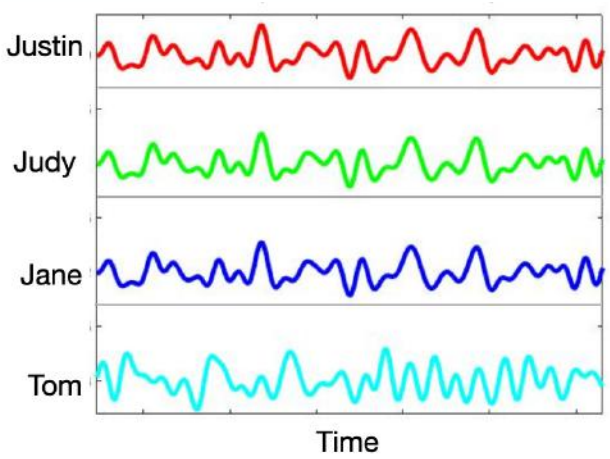
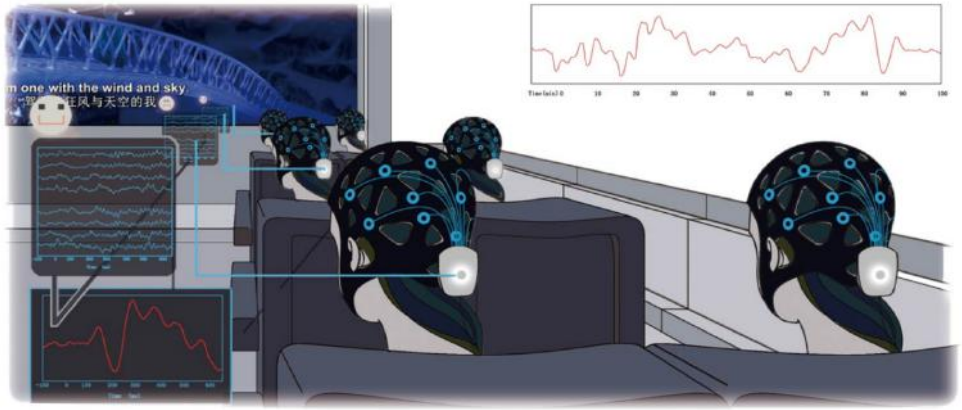
Summary & Future directions





陈菁菁等. 教育领域中的脑-机接口应用：动向与挑战，科技导报，2022, 40(12): 90-101.（Ours)

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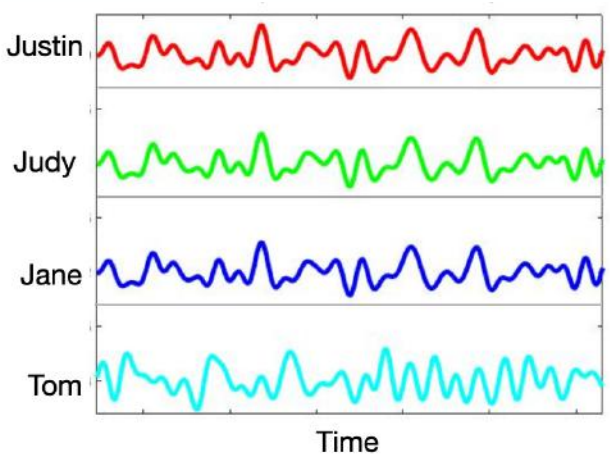

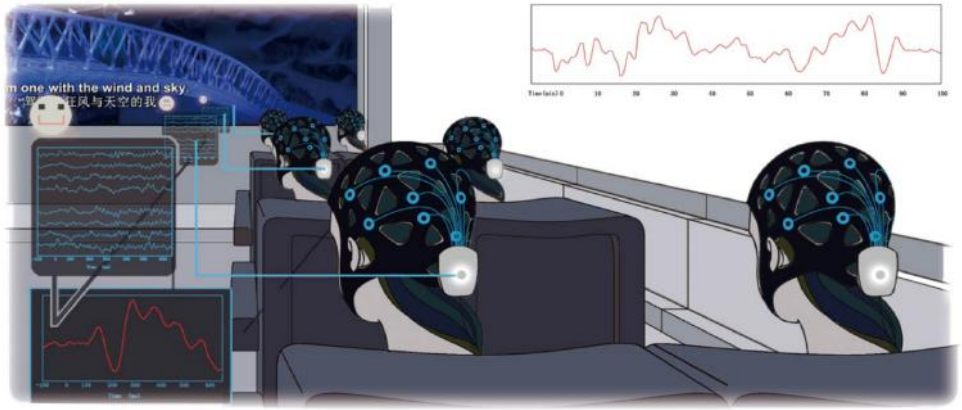

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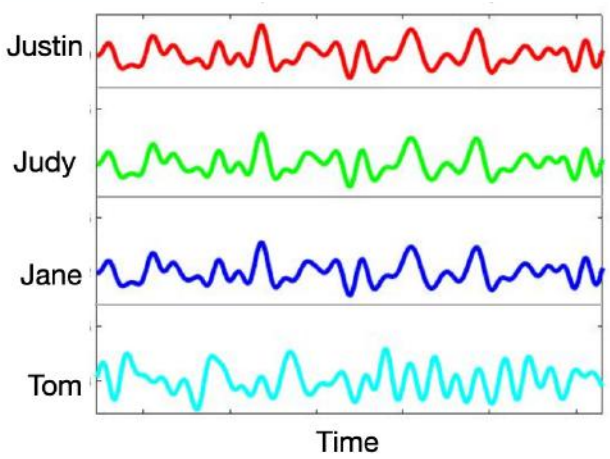

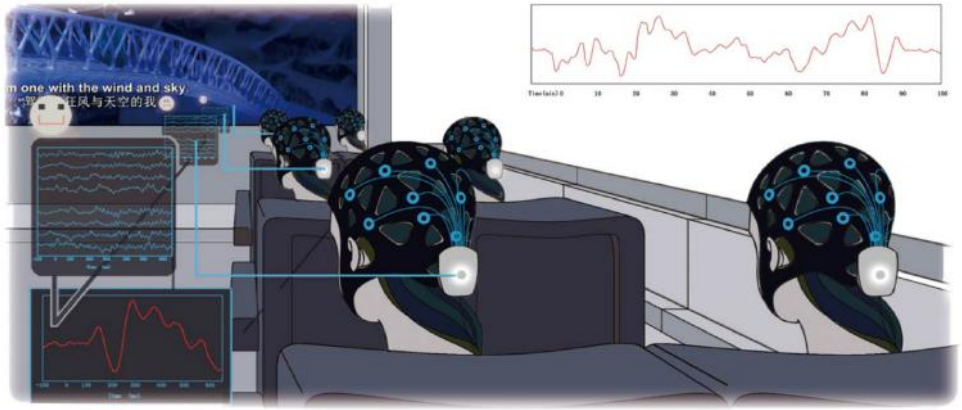

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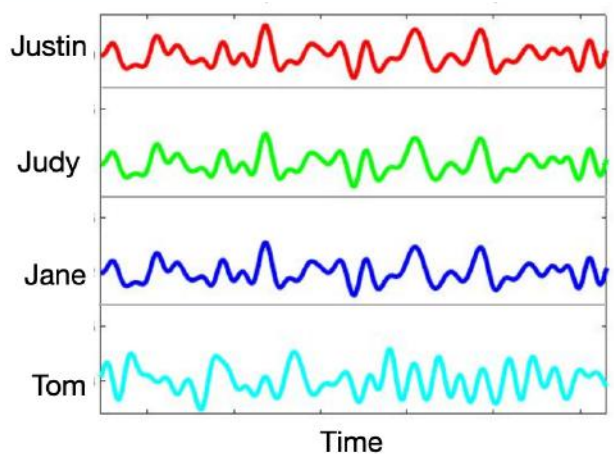

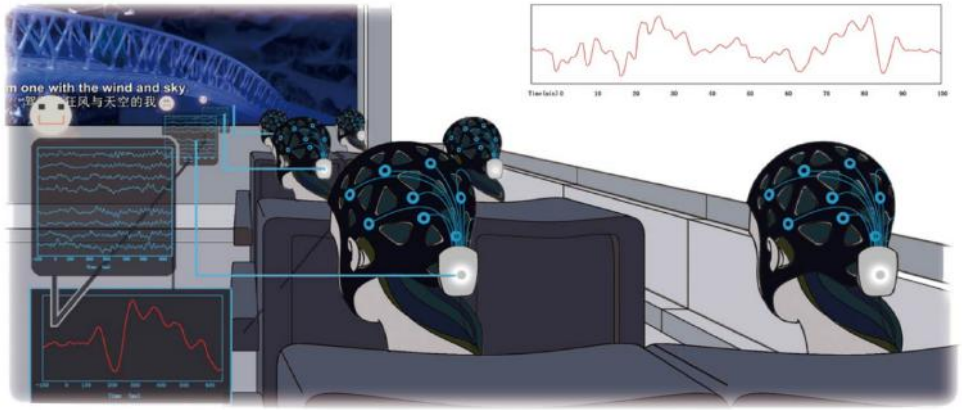

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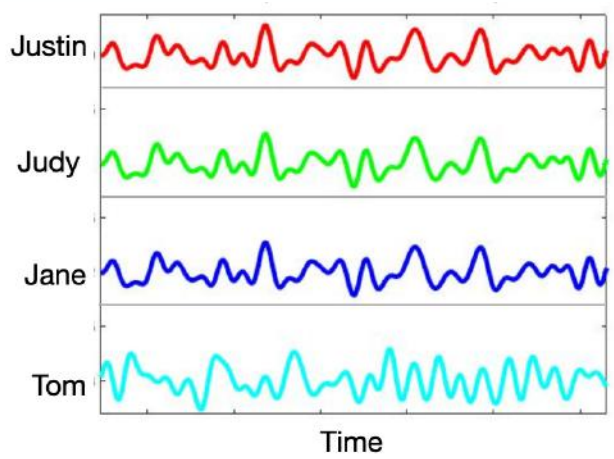

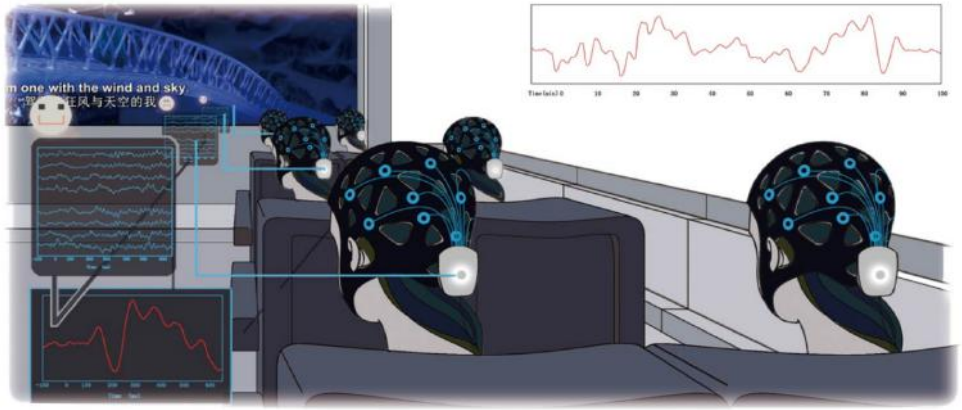

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- Portable EEG and real classroom data could be used for **brain-computer interfaces** to evaluate individual student's learning performance in real-time, hereby supporting individualized optimization in teaching and learning

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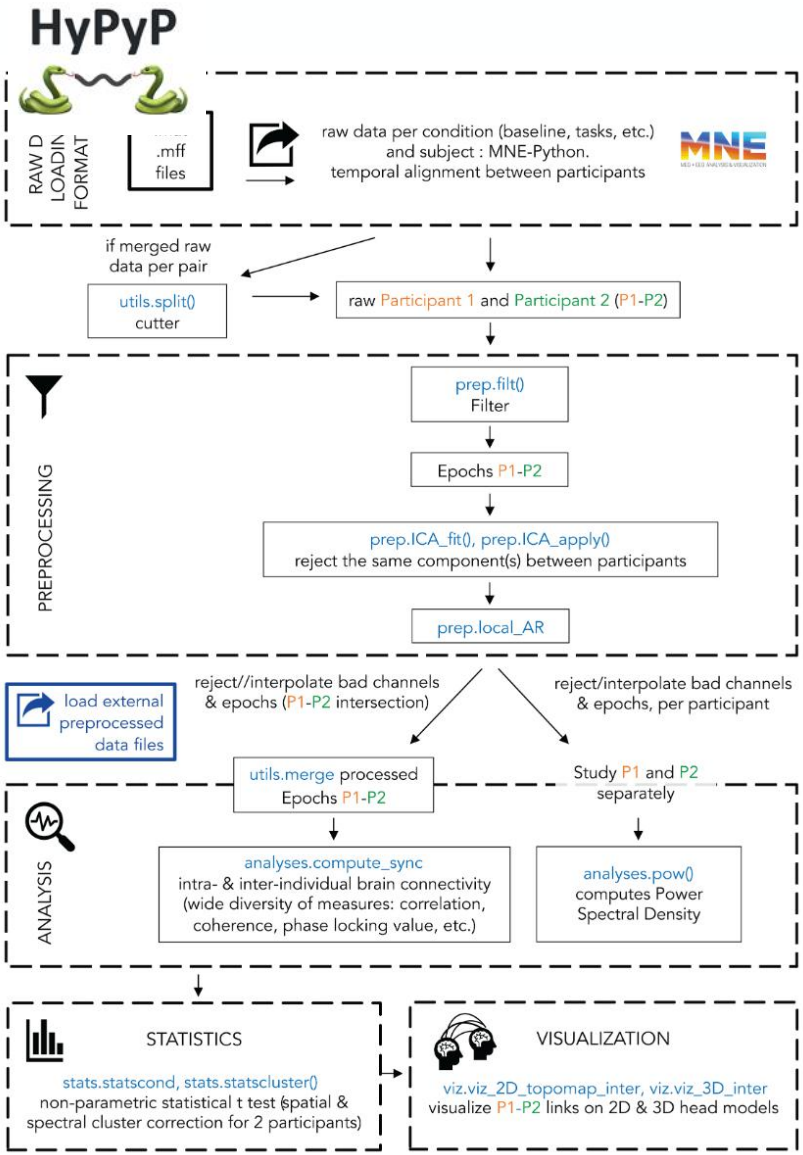
One more thing: inter-brain coupling analysis tools



Ayrolles et al. SCAN 2021

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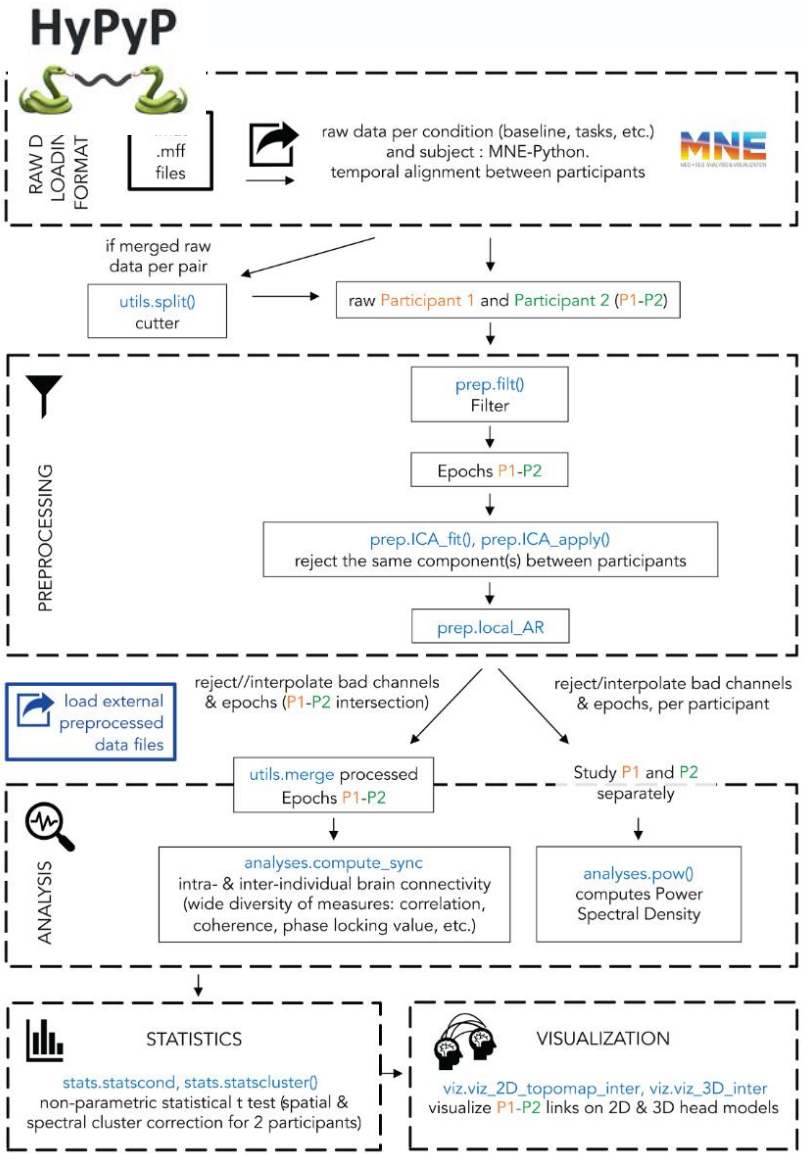

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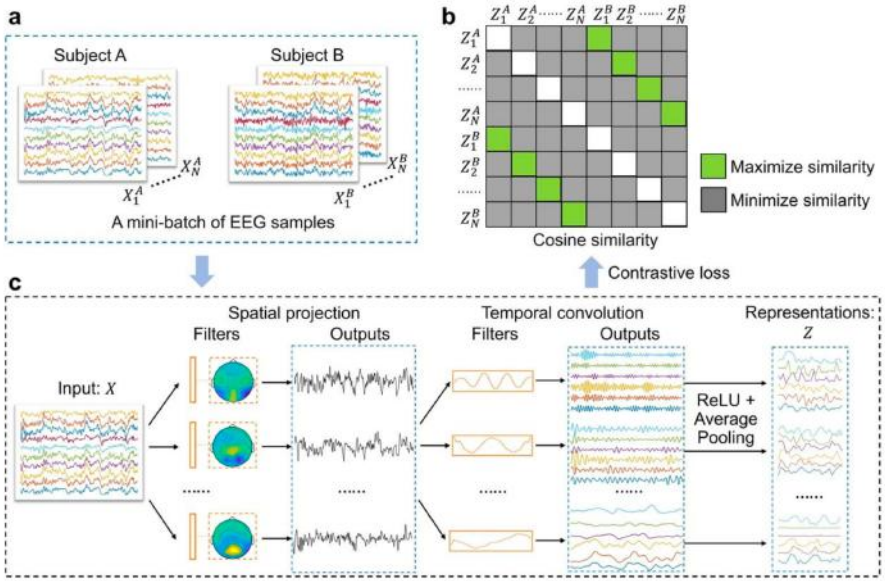
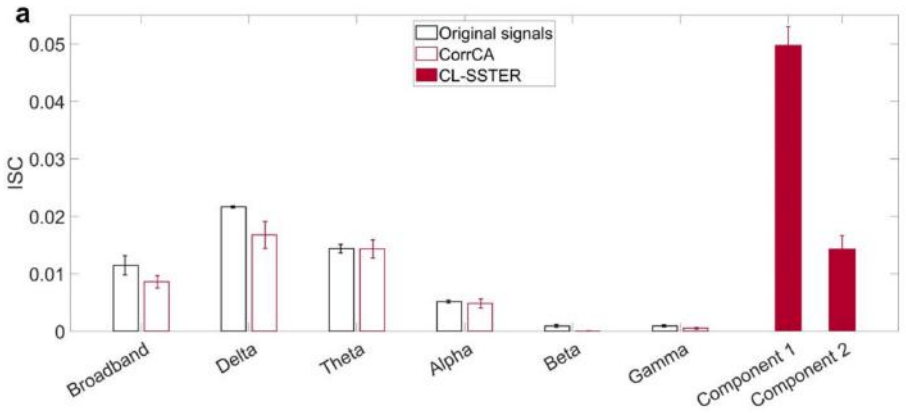
CL-SSTER https://github.com/kekehia123/cl_sster





Shen et al. NeuroImage 2024 (Ours)

Collaborators

Prof. Yu Zhang (张羽), School of Education, Tsinghua University
Dr. Jingjing Chen (陈菁菁), School of Education, Tsinghua University
Ms. Xiaomeng Xu (徐晓萌), School of Education, Tsinghua University

Thank you!

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