# Decoding subjective emotional arousal from EEG during an immersive Virtual Reality experience

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# Hypothesis

The present study tested the hypothesis of a *negative association* between **parieto-occipital alpha power** and **subjective emotional arousal** under **dynamic and interactive stimulation**

…this study aimed to

1. induce variance in emotional arousal in a *naturalistic setting* and
2. capture the temporally evolving and *subjective nature of emotional arousal* via continuous ratings in order to
3. assess their link to *oscillations of brain activity in the alpha frequency range*



# Outlook

1. Dynamic naturalistic experience
2. Subjective emotional arousal
3. …alpha-power
    a. CSP + LDA
    b. LSTM
    c. SPoC
4. Parieto-occipital…
5. Conclusion
6. Discussion & Limitations
    a. Low Accuracy
    b. Naturalstic VR Chanllenges
    c. LSTM
7. Materials & Details

# Dynamic naturalistic experience

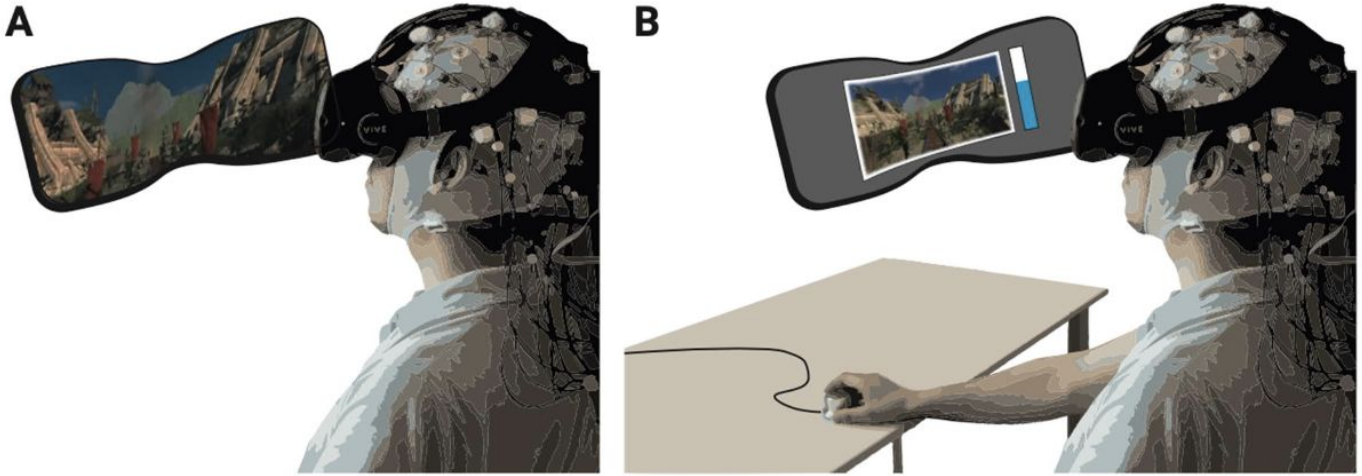
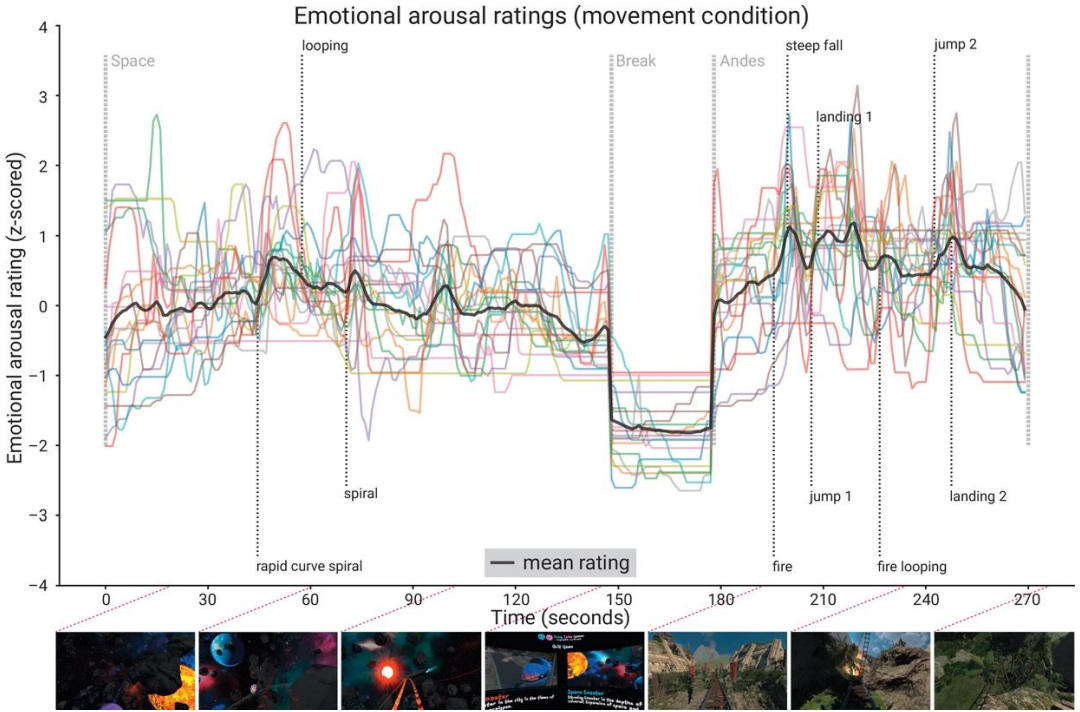


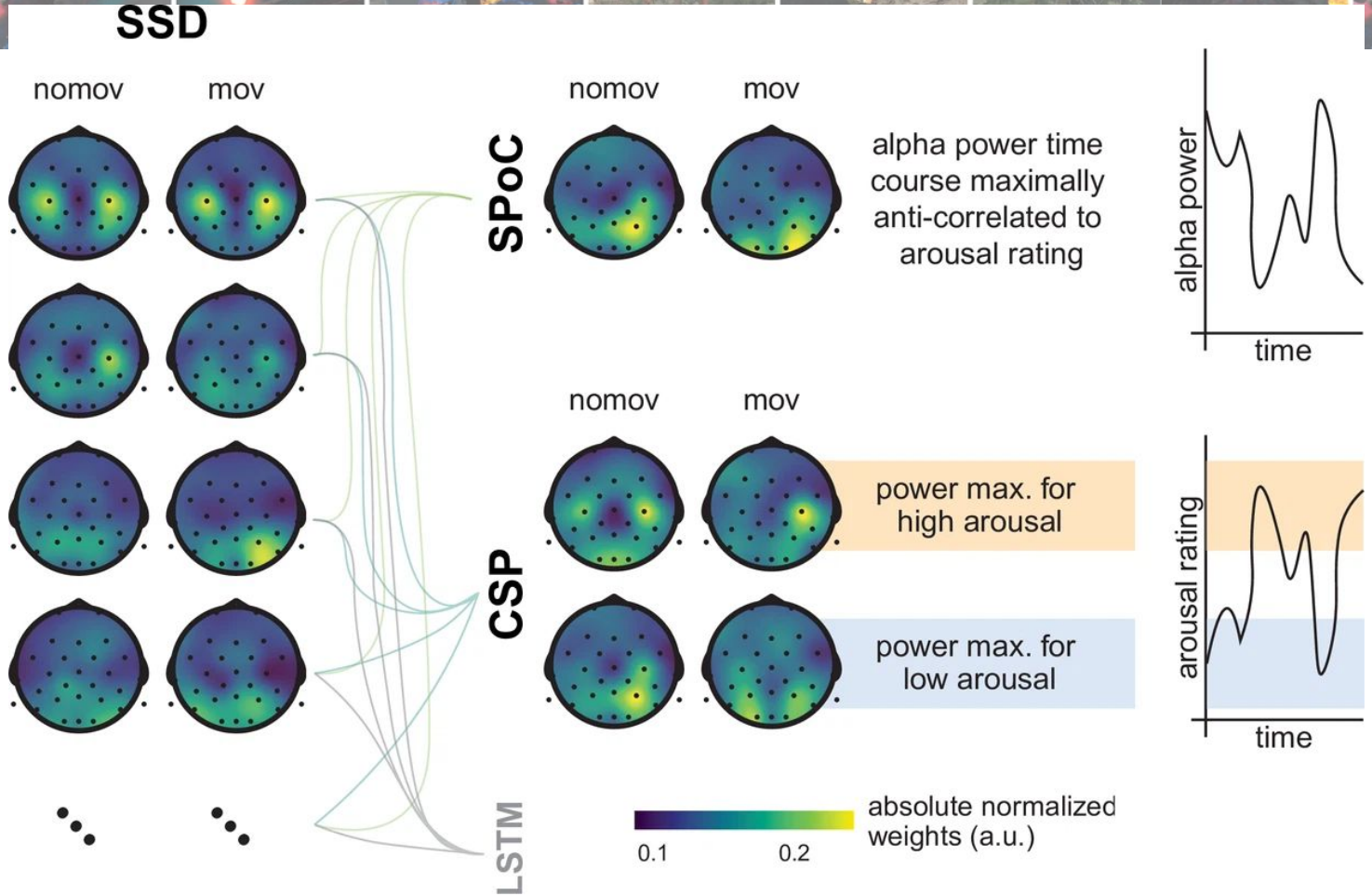

**Figure 7:** Schematic of experimental setup. (A) The participants underwent the experience (two rollercoasters separated by a break) in immersive VR, while EEG was recorded. (B) They then continuously rated the level of emotional arousal with a dial viewing a replay of their experience. The procedure was completed twice, without and with head movements.

Source: Figure 7. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835

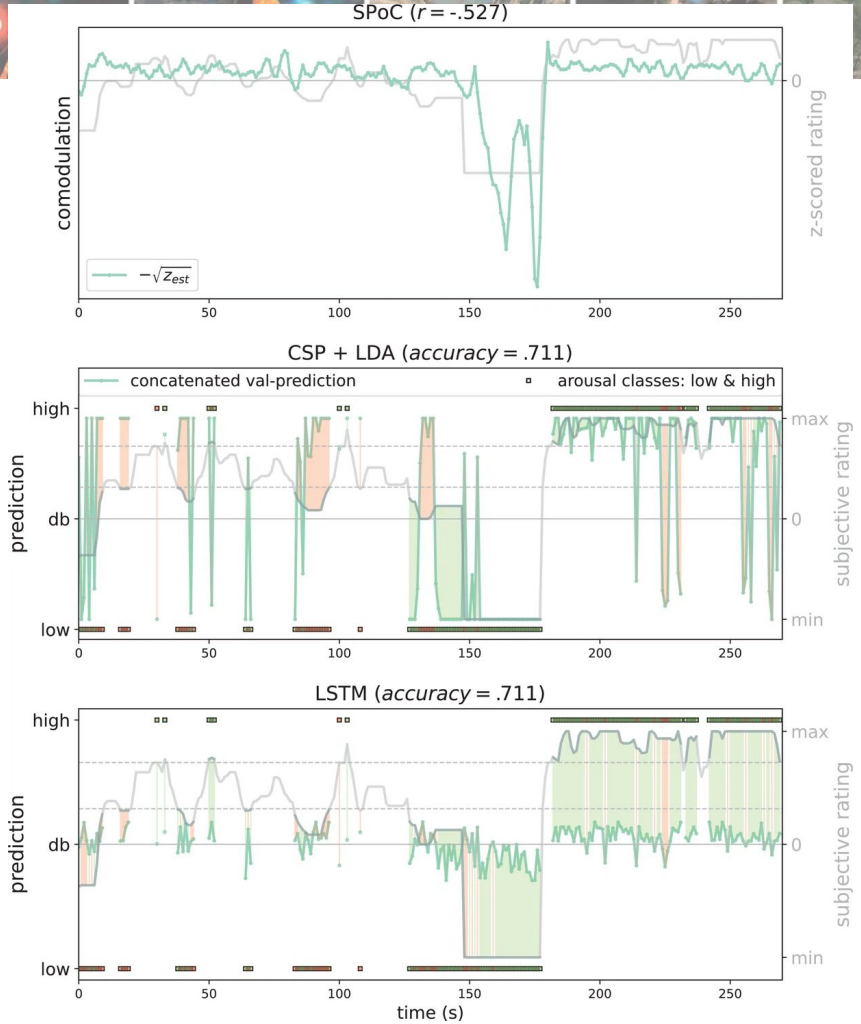
# Subjective emotional arousal




Source: Figure 1. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835

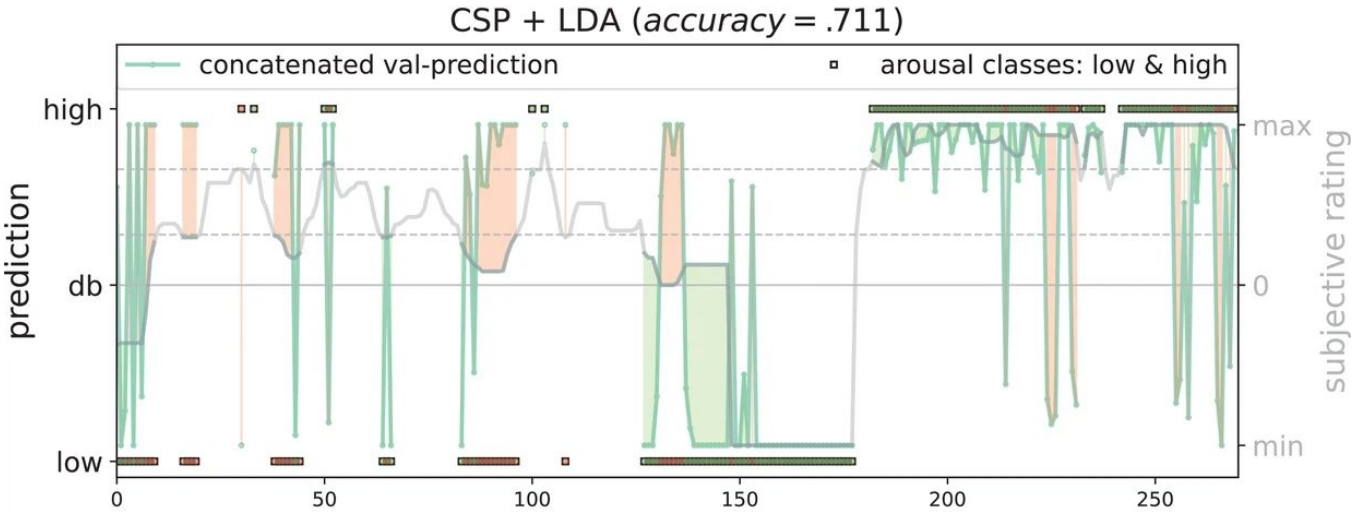



Source: Figure 4. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835




Source: Figure 2. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835






Mean classification accuracies, averaged across subjects

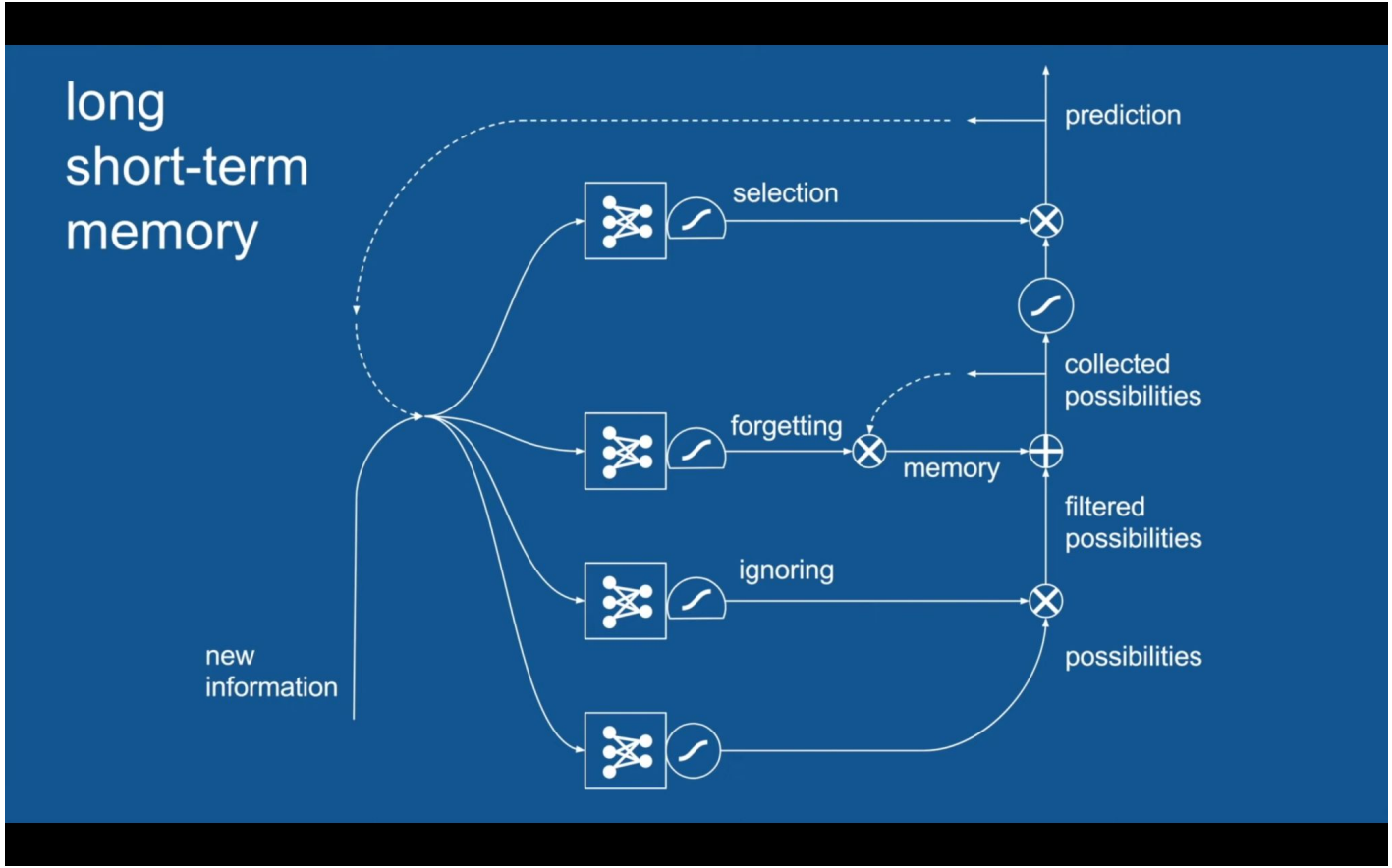
- 60.83% (M±SD; range: 47.22 - 77.78 %) - mov
- 60.76±6.58 % (M±SD) - nomov

Both were significantly above chance level

- tnomov(25) = 7.47, pnomov < .001
- tmov(18) = 7.12, pmov < .001

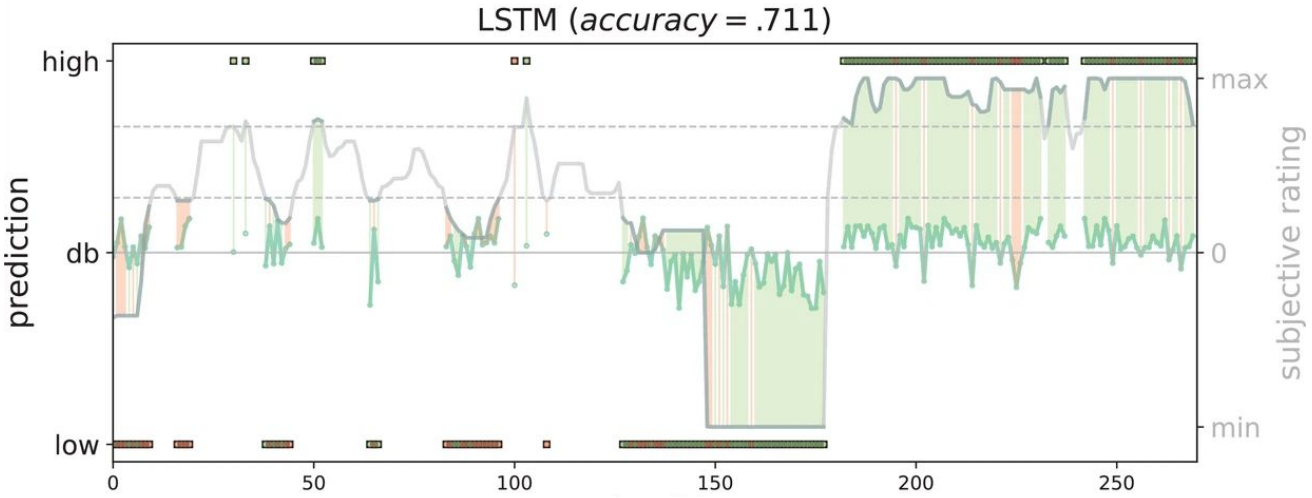
Source: Figure 2. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835






Source: *Recurrent Neural Networks (RNN) and Long Short-Term Memory (LSTM)*, https://www.youtube.com/watch?v=WCUNPb-5EYI






The mean classification accuracy was

- 59.42 ± 4.57 % (M±SD; range: 52.22 % - 68.33 %) - nomov
- 61.29 ± 4.5 % (M±SD; range: 53.89 % - 71.11 %) - mov

Both were significantly above chance level

- tnomov(25) = 10.82, pnomov < .001
- tmov(16) = 10.51, pmov < .001

Source: Figure 2. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835

# SPoC - Source-Power Comodulation

Allows to extract spatial filters and patterns by using *a target (continuous) variable* in the decomposition process in order to *give preference to components whose power correlates with the target variable*.

Can be seen as an **extension of the CSP driven by a continuous variable rather than a discrete variable**

Typical applications include extraction of motor patterns using EMG power or audio patterns using sound envelope.

Source: https://mne.tools/dev/generated/mne.decoding.SPoC.html

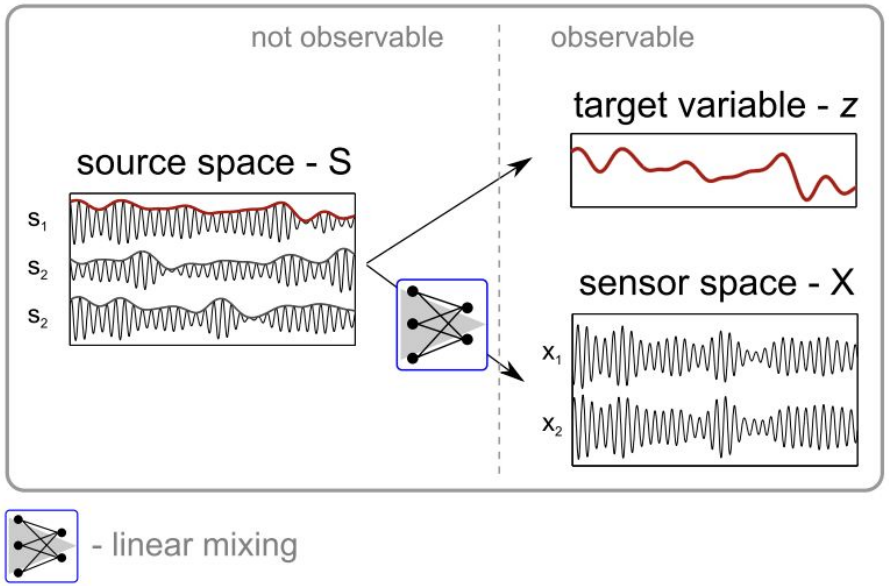



**Fig. 1.** Illustration of the problem setting. The unobservable source space signals (e.g. oscillatory brain sources) are mixed to constitute the sensor space signals (e.g. EEG/MEG). The time course of the observed target variable $z$ (e.g. stimulus intensity, reaction times) corresponds to the power (or envelope) modulation of one of the sources.

Source: Dähne, S., Meinecke, F.C., Haufe, S., Höhne, J., Tangermann, M., Müller, K., & Nikulin, V.V. (2014). SPoC: A novel framework for relating the amplitude of neuronal oscillations to behaviorally relevant parameters. NeuroImage, 86, 111-122.

# SPoC

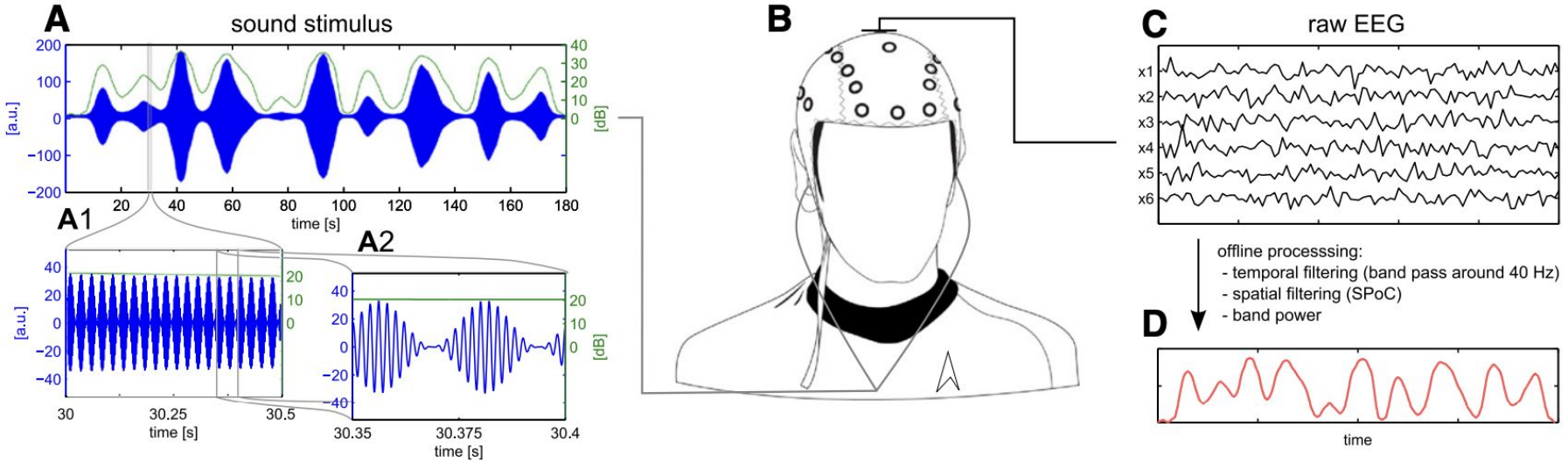
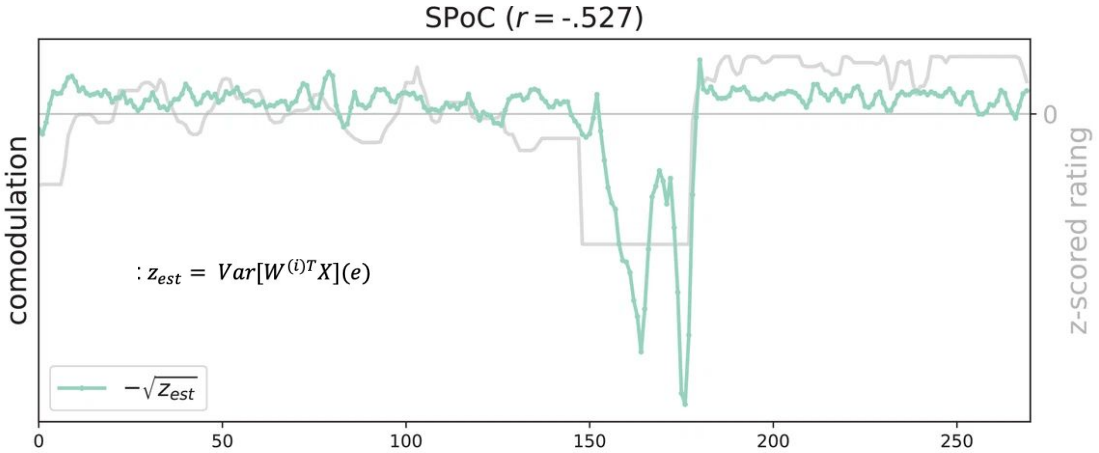



**Fig. 3.** Auditory stimulus and experimental setup. (A) Three minute excerpt of the intensity modulated steady state stimulus. A 500 Hz sinusoid was multiplied with a 40 Hz raised cosine (see the 0.5 s and 0.05 s excerpts in A1 and A2, respectively). The slowly varying intensity modulation (green line in A, A1, and A2) was applied to the full length steady state stimulus. (B) Participants received the sound stimulus via in-ear headphones and EEG was measured concurrently. (C) The raw EEG was analyzed offline to extract an estimate of the intensity modulation (D).

Source: Dähne, S., Meinecke, F.C., Haufe, S., Höhne, J., Tangermann, M., Müller, K., & Nikulin, V.V. (2014). SPoC: A novel framework for relating the amplitude of neuronal oscillations to behaviorally relevant parameters. NeuroImage, 86, 111-122.

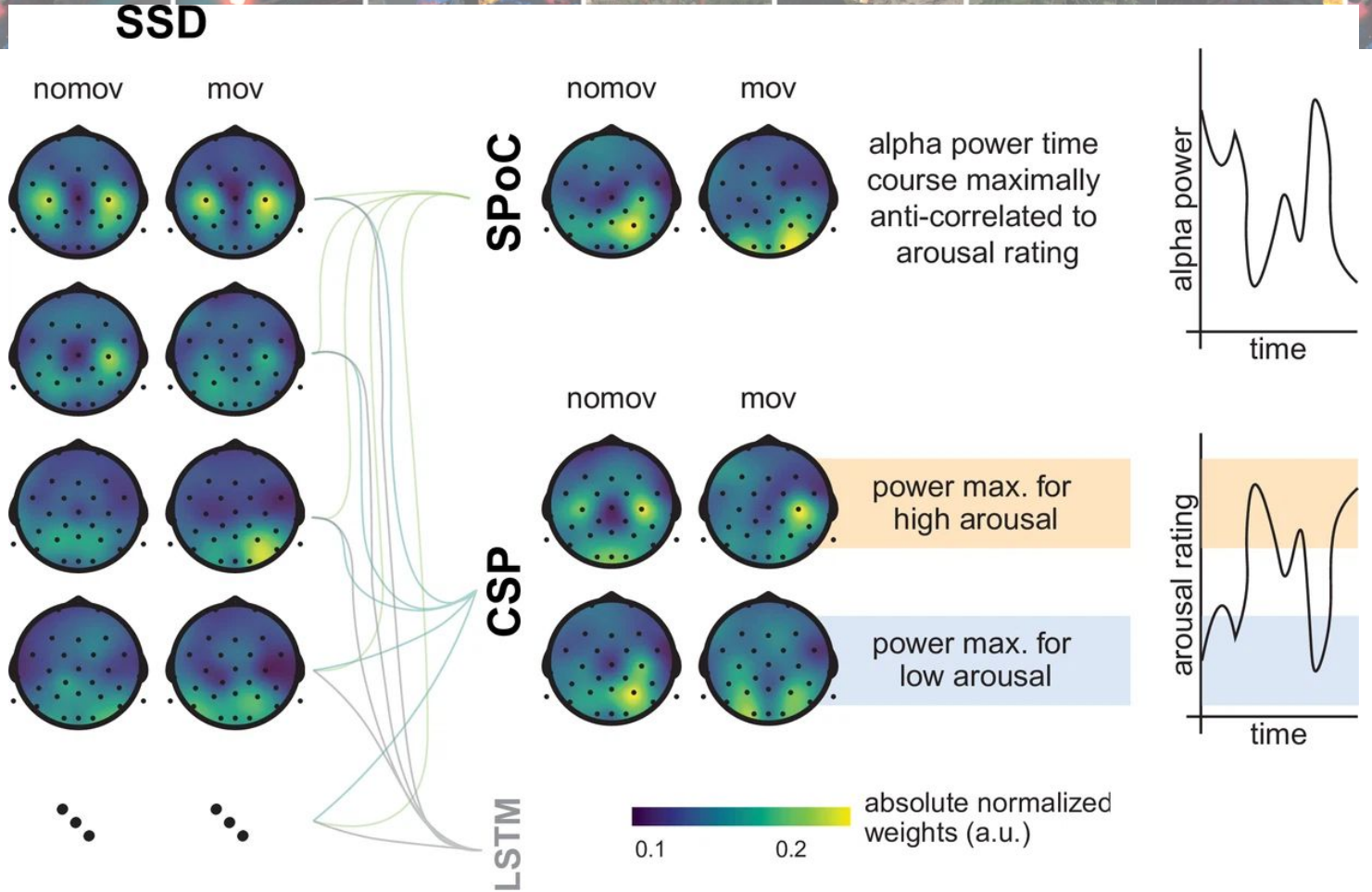





The mean Spearman correlation value between the target variable z (subjective ratings) and zest (estimated target variable) was significantly different from zero for both

- nomov - (M±SD: -.20±.10 ; range: -.36 - +.12; tnomov(25) = -9.84; p < .001)
- mov - (M±SD:-.20±.11; range: -.40 - +.007; tmov(18) = -8.16; p < .001)

Source: Figure 2. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835




Source: Figure 4. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835

# … Parieto-occipital

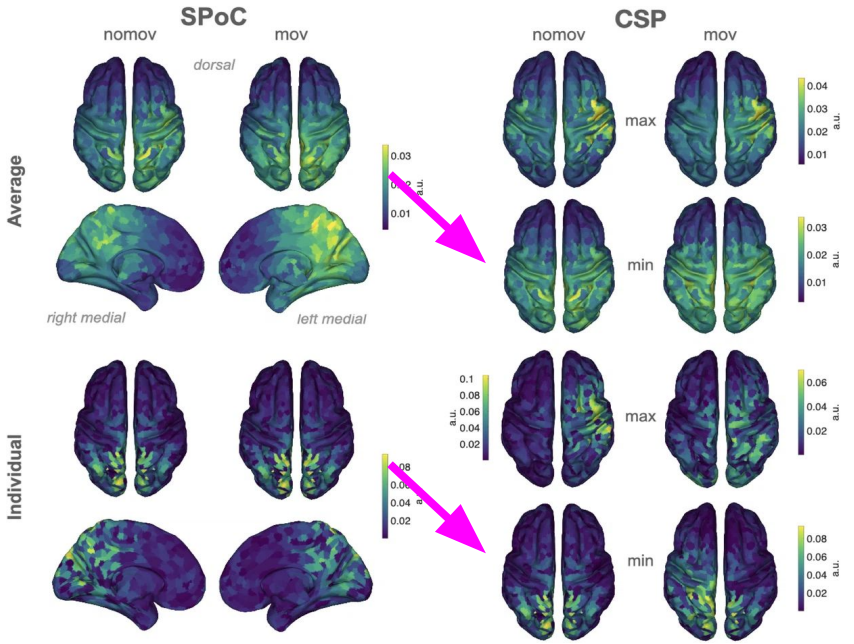
But, training data was not identical

1. CSP - only the upper and lower extreme of the arousal ratings were included (i.e. ⅔ of the data), while epochs with medium arousal ratings (i.e., ⅓ of the data) were excluded
2. SPoC - full continuous datastream

***Why are spatial patterns similar?***

Two potential explanations

1. the most relevant information was encoded in the most extreme parts of the experience
2. there is a truly linear relationship between alpha power and emotional arousal that can be queried on all parts of this spectrum ranging from low to high emotional arousal.




Source: Figure 5. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835



# Conclusion

The hypothesized link between

1. EEG alpha power and
2. self-reported emotional arousal

could be *confirmed*

1. by relating alpha power components to continuous retrospective ratings of emotional arousal (SPoC)
2. by decoding states of higher and lower emotional arousal from them (CSP, LSTMs)

particularly in parieto-occipital regions

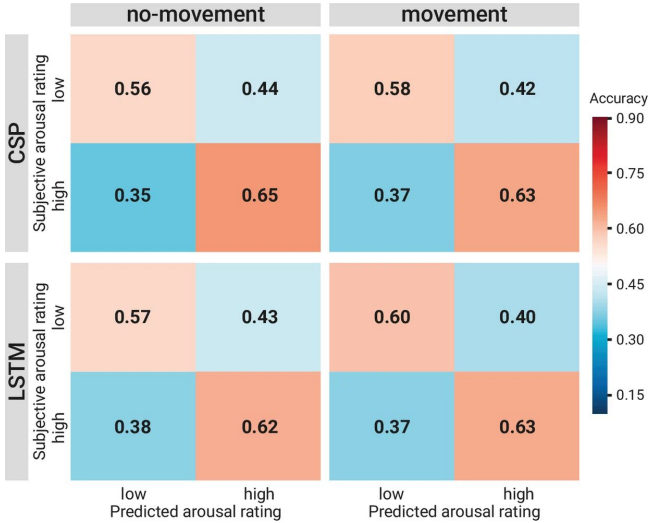
| | nomov | / mov |
|---|---|---|
| CSP | 60.83% | / 60.76% |
| LSTM | 59.42% | / 61.29% |
| SPoC (corr) | -20% | / -20% |

means across all participants
all results statistically significant

# Discussion and Limitations - Low Accuracy

Possible reasons:

1. the fast changing events in the VR experience (particularly the rollercoasters)
2. participants retrieved their emotional states from memory (asynchronicity of the two data streams)
3. the generally high interindividual variability in the interpretability of subjective self-reports (Blascovich, 1990)
4. the “single-trial” study design and its relatively short time series
5. only alpha frequencies considered
    a. higher frequencies could carry additional information about the phenomenon leading to better model predictions. However, higher frequency bands also include non-neural (e.g., muscle activity-related) signals, limiting the interpretability of those results.




Source: Figure 3. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835



# Discussion and Limitations - Naturalistic VR Challenges

**VR for naturalistic research designs**

- the creation of high-quality VR content
- more complex technical setups
- discomfort caused by the immersion into the virtual environment (cybersickness)
- habituation to the stimulus

**Emotional arousal**

- multi-faceted mind-brain-body phenomenon that involves the situated organism and its interaction with the environment

**EEG with VR**

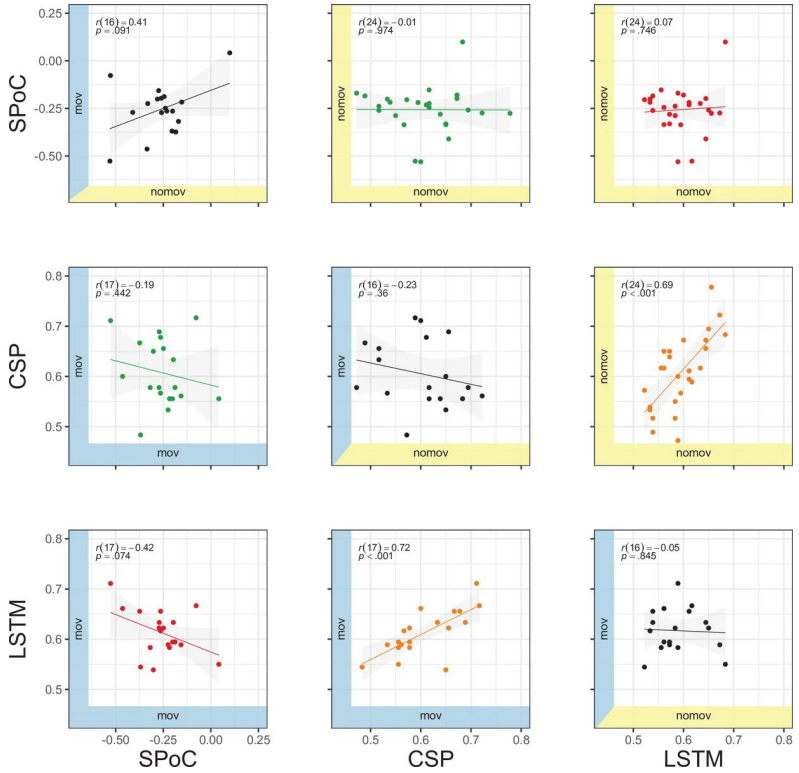
- mechanical interference of the VR headset with the EEG cap
- movement artifacts when the participant interacts with the virtual environment (e.g., head rotations).

***Solution: include other modalities as features***

- peripheral physiological (e.g., HR, GSR)
- environmental (e.g., optical flow) features
- sensorimotor interaction (beyond head movements) in immersive VR
- mobile EEG studies in real-world environments

# Discussion and Limitations - LSTM

- LSTM
  - can extract features from neural input components that reflect changes in subjective emotional arousal
  - the accuracy matched closely that of CSP
- Noteworthy, the inputs to the models were:
  - CSP + LDA - narrowly defined spectral features of the signal
  - LSTM - signal in the time-domain and the feature selection process was part of the model fitting
- Strong correlation (mov: 69%, nomov: 72%, see right) -> LSTM extracts similar information as the CSP to make its prediction
- (similar to spatial filters from SPoC and CSP)




Source: Figure 6. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835



# Materials & Details

**Participants**

45 healthy young participants (22 men, M±SD: 24.6±3.1, range: 20-32 years) completed the experiment.

Data from 8 participants needed to be discarded due to

- technical problems (n = 5) or
- electrode malfunctioning (n = 1);
- one participant discontinued the experiment and an- other participant reported having taken psychoactive medication.

The data from 37 participants entered the analysis (17 men, age: M±SD: 25.1±3.1, range: 20-31 years).

After quality assurance during the EEG preprocessing, data from

- 26 participants in the nomov and
- 19 in the mov condition entered the statistical analyses that included EEG data.

**Neurophysiology / EEG**

1. 30 channels of EEG activity were recorded in accordance with the international
2. 10/20-system (Sharbrough et al., 1991) using a
3. mobile amplifier (LiveAmp32) and
4. active electrodes (actiCap; both by BrainProducts, Gilching, Germany).
5. Two additional electrooculogram (EOG) electrodes were placed below and next to the right eye to track eye movements.
6. Data were sampled at
    a. 500 Hz with
    b. a hardware-based low-pass filter at 131 Hz



# Materials & Details

**Virtual Reality (VR) head-mounted display (HMD)**

1. HTC Vive HMD (HTC, New Taipei, Taiwan)
2. headphones (AIAIAI Tracks, ApS, Copenhagen, Denmark)
3. placed on top of the EEG cap using small, custom-made cushions to avoid pressure artifacts and increase comfort.
4. head position is tracked using infrared light, accelerometry, and gyroscopy.

**Immersive VR experience / stimulation**

“Russian VR Coasters” by Funny Twins Games, Ekaterinburg, Russia, on Steam

1. “Space” - a 153-s ride through planets, asteroids, and spaceships
2. 30-s break (during which participants kept their eyes open and looked straight)
3. “Andes” - a 97-s ride through a mountain scenery

# Materials & Details

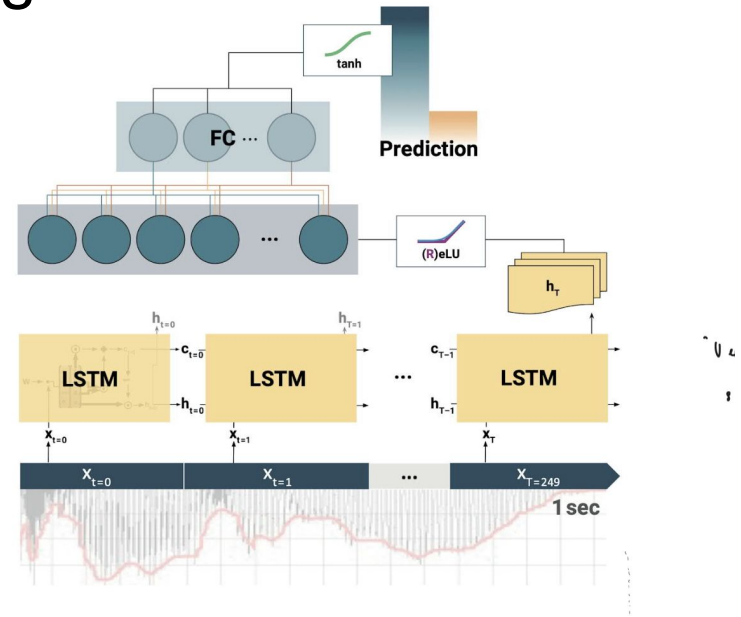



**Figure 9:** Schematic of the Long Short-Term Memory (LSTM) recurrent neural network (RNN). At each training step, the LSTM cells successively slide over 250 data-arrays of neural components ($x_{t=0}$, $x_{t=1}$, ... , $x_{T=249}$) corresponding to 1-s of the EEG recording. At each step $t$, the LSTM cell computes its hidden state $h_t$. Only the final LSTM output ($h_T$) at time-step $T$=249 is then fed into the following fully connected (FC) layer. The outputs of all (LSTMs, FCs) but the final layer are normalised by Rectified linear units (ReLU) or exponential linear units (ELU). Finally, the model prediction is extracted from the last FC layer via a tangens hyperbolicus (tanh). Note: depending on model architecture, there were 1-2 LSTM layers, and 1-2 FC layers.

Source: Figure 9. Hofmann SM, Klotzsche F, Mariola A, Nikulin V, Villringer A, Gaebler M. Decoding subjective emotional arousal from EEG during an immersive virtual reality experience. Elife. 2021 Oct 28;10:e64812. doi: 10.7554/eLife.64812. PMID: 34708689; PMCID: PMC8673835



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Thanks