Going Offline: Spontaneous Alternation Between "Online" and "Offline" Waking States

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Introduction

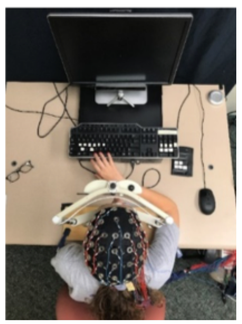
Studies of human memory have typically treated wakefulness as a homogenous state. But to the contrary, moment-to-moment alternation between "online" attention to the current environment and "offline" attention to internally generated thought and imagery may be a fundamental feature of the waking state. ***The objective of this study was to model this temporal microstructure of wakefulness in human subjects, using simultaneous high-density EEG, pupillometry, behavioral, and subjective report measures.*** We expected to find evidence of statistically discriminable online and offline states within wakefulness. Furthermore, we hypothesized that the offline state facilitates the early stages of memory consolidation.

	"Online" State	"Offline" State(s)
EEG	↓ Alpha ↑ Theta	↑ Alpha ↓ Theta
Pupillometry	↑ Pupil diameter reflecting increased NE and ACH neuromodulation	↓ Pupil diameter reflecting decreased NE and ACH neuromodulation
Mental Experience	Focus on present sensory environment	Focus on task-unrelated thought and imagery
Sensory Processing	↓ SART reaction times	↑ SART reaction times
Memory Processes	↑ Encoding ↓ Consolidation	↓ Encoding ↑ Consolidation

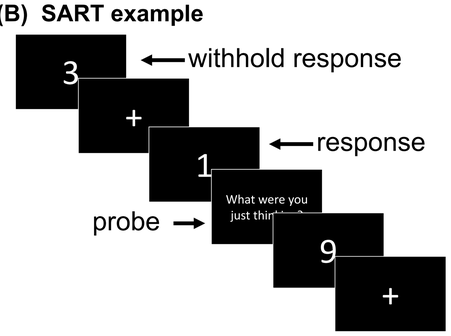
Hypothesized Characteristics of Online and Offline Waking States. We anticipated identifying at least two statistically discriminable states of wakefulness – an "online" state optimized for encoding the present sensory environment, and an "offline" state optimized for consolidation of previously encoded information.

Methods

(A) Study setup



(B) SART example



(B) Probe response categories

	External Focus	Internal Focus
Task Related	Focusing on screen, waiting to respond	This is boring, how much longer do I have?
Task Unrelated	Focusing on sounds coming from hallway	What am I going to do this weekend?

Mind blank
No recollection of previous thought

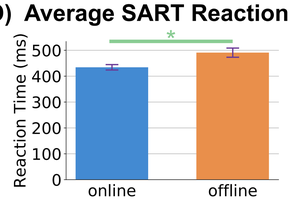
Experimental Setup. Participants encoded a verbal learning task prior to a 30min retention interval. during which EEG and pupil diameter fluctuations were recorded **(A)** while they completed a sustained-attention-to-response task (SART) **(B)**. Meanwhile, subjective experience was intermittently sampled using a forced-choice thought probe. Participants classified their immediate preceding experience according to two dimensions: external/internal focus and task related/task unrelated focus **(C)**.

Analysis & Results

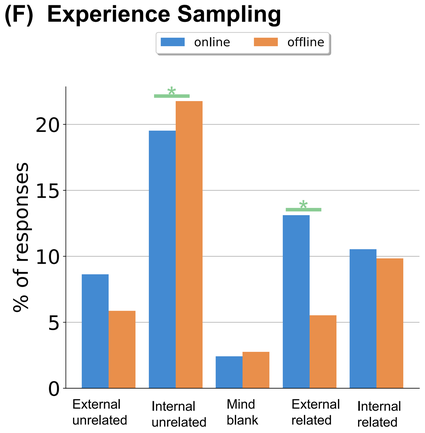
First **we applied estimation maximization (EM) cluster analysis to all experience sampling trials.** Input features included EEG spectral power in 5 frequency bands, reaction time to SART stimuli, pupil diameter, and response to the experience sampling probe. Distance metrics confirmed that optimal cluster separation was obtained with 2 states, which we term the *online* and *offline* states.

Second, **we trained a naïve Bayes classifier to determine cluster assignment (online vs. offline) of each experience sampling trial based on the pupil, EEG, and reaction time data alone.** The classifier was trained on data from 2/3 of participants (n=18), and tested on the remaining 1/3 of participants (n=9), achieving >95% accuracy in determining cluster assignment, without using the subjective report data. We then used this classifier to sort *all* 324 trials per subject into online vs. offline state. This resulted in a time series of state transitions with 5sec temporal resolution. ***Results below illustrate the characteristics of online vs. offline trials, as determined by this classifier:***

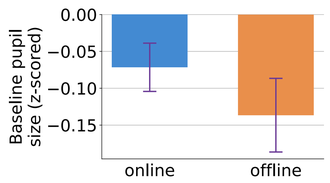
(D) Average SART Reaction Time



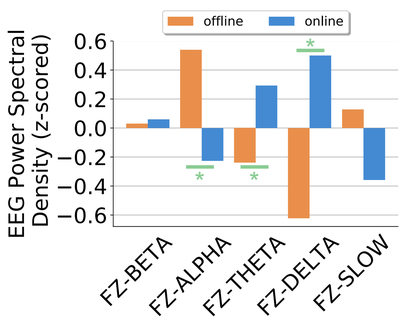
(F) Experience Sampling



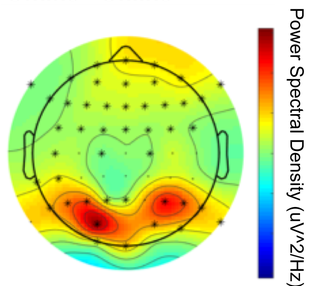
(E) Average Baseline Pupil Size



(G) EEG frequency band power



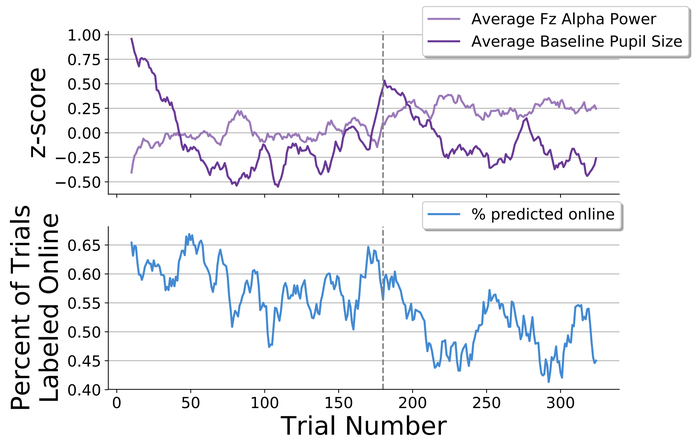
(H) 8-12Hz (Alpha) Power in Offline - Online



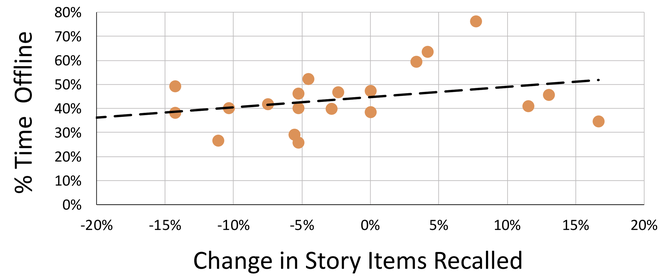
Characteristics of Online vs Offline Trials.
During trials labeled as offline:
- **(D)** Reaction time in the SART was increased.
- **(E)** Pupil size was (nonsignficantly) decreased.
- **(F)** Participants were less likely to report attending to the SART, and more likely to report internally oriented thought and imagery
- **(G)** Alpha power was increased while theta and delta power were decreased.
- **(H)** Topoplot illustrating scalp distribution of the alpha power increase during the offline state.

Error bars represent SEM; * = statistically significant difference (p<0.05) between online and offline

(I) Change in Alpha power, pupil diameter, and proportion of online states over time



(J) Time offline and change in memory



(I) As expected and as described in previous literature, online time decreased with increasing time on task.
(J) There was a trend for time spent offline, as determined by our classifier, to predict subsequent memory for the verbal memory task (r=+0.31, p=0.1).

Conclusion

- These observations are consistent with the presence of discriminable "online" and "offline" attentional states matching the hypothesized characteristics (see table).
- The machine learning methods employed here may prove useful for future research, allowing high temporal resolution assessment of waking state without reliance on self-report measures.
- ***The trend-level association between offline time and memory retention suggests warrants further research exploring a potential memory function of brief periods of spontaneous offline time interspersed throughout the day.***

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