March Madness: Behavioral, physiological, and neural effects of continuously updated surprise and suspense

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Agents use sophisticated event models to predict characteristics of their environments[1]. As events unfold over time, agents implicitly and rapidly adjust their **predictions** based on these models, which can produce feelings of surprise and suspense[2].

Surprise, or unsigned prediction error, tracks the difference between previous and current predictions[2-5]. According to Event Segmentation Theory **(EST)**, surprise can drive the segmentation of ongoing experience into distinct events[6-7]. Surprise can also trigger learning that updates subsequent predictions about the structure of the world[3,8], and it can benefit memory for immediately preceding events[4].

Suspense occurs when the agent anticipates that an upcoming event will strongly influence their predictions.

We used sports games to understand how surprise and suspense influence memory, physiology, and neural activation patterns in humans.

Operationalizations:

Predictions: "win probability" metrics from an expert basketball analyst (https://kenpom.com/) updated after each change in possession

Surprise: absolute value of the derivative of the win probability time course. We also compute "signed" prediction error if the subject prefers which team wins.

Suspense: 1) find instances in a large set of games with a particular game state (amount of time remaining and difference in win probability between the teams) and 2) calculate, for each state, the variability in the belief change produced by the following state.

Viewing

Basketball fans (subjects) watch the last 5:00 of 9 games from the men's 2012 NCAA tournament

Which team were you cheering for?

Creighton
No Pref
Alabama

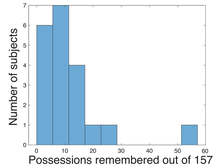
How enjoyable did you find this game?

1 (Not enjoyable) — 7 (Very enjoyable)

Recall

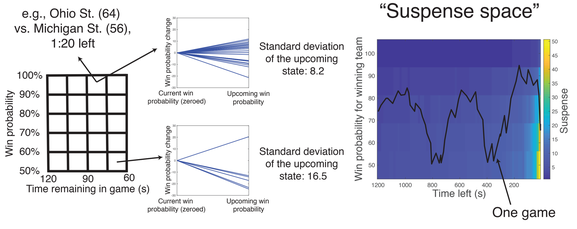
(8) Creighton vs.
(9) Alabama

Recall this game in as much detail as possible.



Suspense calculation

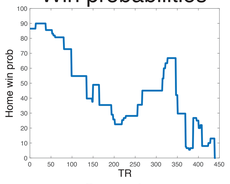
e.g., Ohio St. (64) vs. Michigan St. (56), 1:20 left



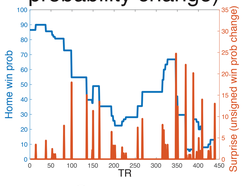
"Suspense space"

Game metrics

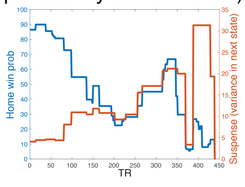
Win probabilities



Surprise (unsigned win probability change)



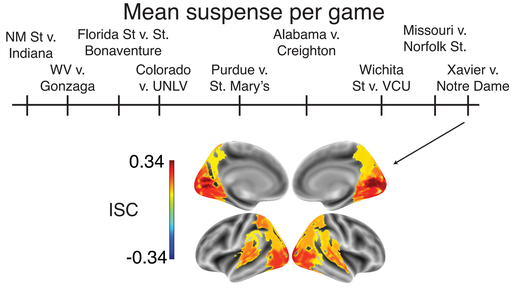
Suspense (variance in win probability of next state)



Intersubject correlations (ISCs) increase with suspense

Whole brain (96 cortical parcels)

Mean suspense per game

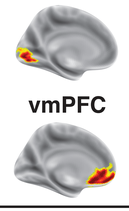


Neural interactions with team preferences

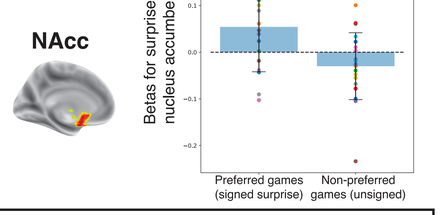
V1 ISCs increase with suspense, while ventromedial prefrontal cortex (vmPFC) ISCs increase when subjects prefer who wins

Mixed effects models:
ISC in V1:
Suspense* (p=0.02)
Preference (p=0.14)

ISC in vmPFC:
Suspense (p=0.44)
Preference* (p=0.01)



Univariate: Nucleus accumbens activity increases with positive prediction error to preferred team



Take-home messages

Surprise and suspense derived from real-world sports games map onto behavioral, physiological, and neural measures.

Suspense predicts ISCs across primary sensory and higher-level cortical regions.

Surprise predicts pupil area changes. Surprise and pupil area changes predict memory.

Results confirm predictions of EST: Games with more surprise => more HMM-identified states; possession changes with greater surprise => greater probability of HMM-identified state transition[1,4,9]. vmPFC transitions predict memory.

References

[1]DuBrow, S., Rouhani, N., Niv, Y., & Norman, K. A. (2017). Does mental context drift or shift? Current Opinion in Behavioral Sciences, 17, 141–6.
[2]Ely, J., Frankel, A., & Kamenica, E. (2015). Suspense and surprise. Journal of Political Economy, 123, 215–260.
[3]O'Reilly, J. X., Schüffelgen, U., Cuell, S. F., Behrens, T. E. J., Mars, R. B., & Rushworth, M. F. S. (2013). Dissociable effects of surprise and model update in parietal and anterior cingulate cortex. Proceedings of the National Academy of Sciences, 110(38), E3660-9.
[4]Rouhani, N., Norman, K. A., Niv, Y., & Bornstein, A. M. (2019). Reward prediction errors create event boundaries in memory. bioRxiv.
[5]Kutas, M., & Hillyard, S. A. (1984). Brain potentials during reading reflect word expectancy and semantic association. Nature, 307, 161–163.
[6]Franklin, N. T., Norman, K. A., Ranganath, C., Zacks, J. M., & Gershman, S. J. (2019). Structured event memory: a neuro-symbolic model of event cognition. bioRxiv.
[7]Zacks, J. M., Braver, T. S., Sheridan, M. A., Donaldson, D. I., Snyder, A. Z., Ollinger, J. M., … Raichle, M. E. (2001). Human brain activity time-locked to perceptual event boundaries. Nature Neuroscience, 4(6), 651–655.
[8]Sutton, R. S., & Barto, A. G. (1998). Introduction to reinforcement learning. (Vol 2, No. 4). Cambridge: MIT press.
[9]Baldassano, C., Chen, J., Zadbood, A., Pillow, J. W., Hasson, U., & Norman, K. A. (2017). Discovering event structure in continuous narrative perception and memory. Neuron, 95(3), 709-721.e5.
[10]Chang, L. J., Jolly, E., Cheong, J. H., Rapuano, K., Greenstein, N., Chen, P.-H. A., & Manning, J. R. (2018). Endogenous variation in ventromedial prefrontal cortex state dynamics during naturalistic viewing reflects affective experience. bioRxiv.

Acknowledgements

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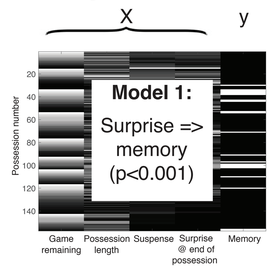
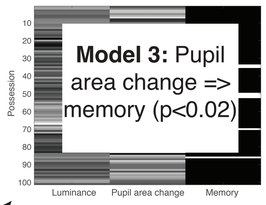
Surprise improves memory

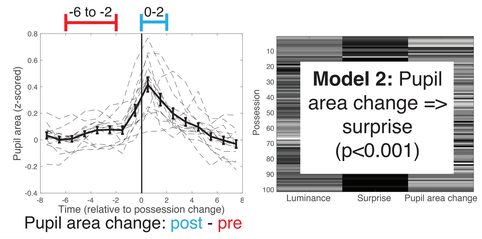
Sample recall of specific possession: "Then Alabama had one last chance to win the game with 4 seconds left ... but they missed the 3-pointer as the clock hit zero."



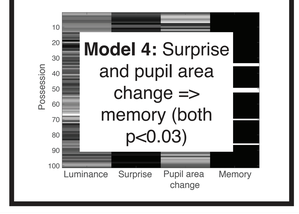
Pupil dilation at boundaries predicts memory



Surprise increases pupil dilation at boundaries



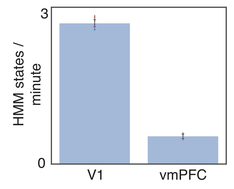
Combined model



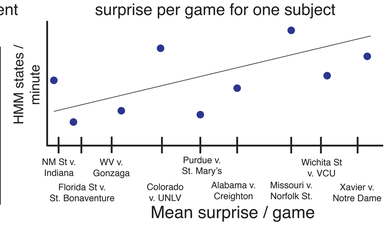
Surprise is associated with changes in Hidden Markov Model (HMM) states

According to event segmentation theory (EST)[7], surprise triggers segmentation[9]. HMMs provide a data-driven way of finding segments by identifying moments when neural patterns shift. We predict surprise will lead to state changes in V1 and vmPFC, but vmPFC will transition more selectively[10].

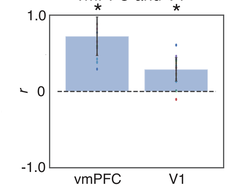
Difference between V1 and vmPFC: V1 shows more frequent state changes than vmPFC



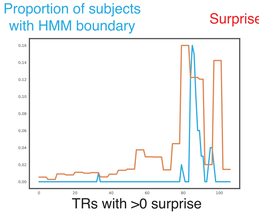
vmPFC HMM states / minute vs. mean surprise per game for one subject



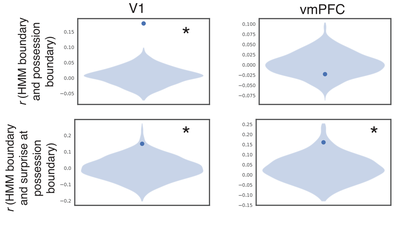
Games with more surprise have more states in vmPFC and V1



vmPFC HMM boundary agreement vs. surprise at boundaries, one game



V1 tracks all possession boundaries and surprise. vmPFC tracks surprise only.



vmPFC transitions predict memory

Mixed effects models:
Memory for possessions:
HMM transition in V1 (p=0.89)
HMM transition in vmPFC (p=0.02)