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Characterizing Relationships Between Fluctuating Cognitive
and Neural States During Movie Watching

By

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Abstract

Human experience fluctuates throughout time. The relationship of these subjective experiences to changing brain states has yet to be fully understood. We used an existing MRI dataset in which participants watched movies in the scanner. In an online study, we had participants continuously rate their subjective experiences while watching the same movie clips. We expand on prior research identifying four common latent neural states by looking at the relationship between occurrence of these states and subjective experience. Participant responses of either engagement, arousal, valence, social interaction, focus, curiosity, relatability, importance, surprise, comprehension, or boredom were then compared to the latent state occurrences of either the default mode network (DMN), dorsal attention network (DAN), somatosensory motor (SM), or base states. When the DMN state occurred, participants indicated higher levels of engagement, arousal, external focus, positivity, and sociality. When the DAN state occurred, participants indicated higher levels of surprise, and lower levels of boredom and social interaction. When the SM state occurred, participants indicated low levels of engagement, arousal, curiosity, importance and surprise, as well as negativity, internal focus, and high levels of relatability and boredom. Lastly, when the base state, characterized as a transition hub between states (Song et al., 2022) occurred, participants rated high levels of curiosity and importance and low relatability. Our results show that latent brain state occurrence tracks subjective experience, providing insight into how latent state activity is related to conscious experience.

Key words: latent states, neural dynamics, subjective experience, naturalistic tasks

Characterizing Relationships Between Fluctuating Cognitive and Neural States During Movie Watching

Human experience requires the coordination of a plethora of mechanisms, ranging from unconscious to conscious processes. We are not aware of our neural activations, yet they are necessary for our functioning. Conversely, we are aware of what we are capable of perceiving, via sensory inputs from the environment, and can actively reflect on that accumulated information. Cognitive neuroscientists work to understand both of these systems, often combining neural imaging and behavioral analyses to lend insight into cognitive function. Multidimensional approaches that assess neural, behavioral, physiological and subjective experiences are all important in the pursuit of a holistic understanding of human cognition. Different measurements provide tools for assessing unconscious and conscious experiences. By combining subjective experience ratings and fMRI brain activity we can interpret which brain regions are most indicative of specific subjective cognitive states. Moreover, by looking at the fluctuations in both over time we are able to see how neural activity consistently fluctuates in accordance to the degree of subjective experiences felt. The current study compares eleven subjective experience ratings to neural activity while watching movie clips to characterize neural representations of conscious cognition.

Functional MRI (fMRI) studies have traditionally utilized task-based experimental designs to assess patterns of brain activity associated with different mental processes. In these studies, participants perform psychological tasks, such as sustained-attention tasks, during fMRI data collection which require them to actively participate in an activity (Rosenberg et al., 2013). More recently, there has been a shift toward naturalistic experimental designs, during which stimuli such as audio narratives (Zhao et al., 2018), virtual reality displays (Tromp et al., 2018),

or movies (Lee et al., 2020) are used to elicit naturalistic brain states. These designs do not ask participants to complete tasks, therefore allowing thoughts (and henceforth their associated neural patterns) to wander more freely, replicating more natural experiences that likely take place in daily life (Sonkusare et al., 2019). Using movies as naturalistic stimuli has provided substantial advances in understanding cognition (Jääskeläinen et al., 2021). The use of naturalistic movie-watching during brain imaging, as compared to resting-state in which participants are asked to silently sit in the fMRI machine, has even been found to be better at predicting individual intelligence scores. This suggests that movies elicit neural states more predictive of behavior than resting-state imaging (Gal et al., 2022). Similarly, Finn and Bandettini (2021) found movie-watching fMRI data, compared to resting-state data, better predicts individual differences in behavioral measures related to cognition and emotion. Therefore, naturalistic stimuli can elicit similar neural patterns comparable to daily life, as well as provide more behaviorally relevant neural activity patterns than resting-state fMRIs, which supports the use of movie-watching stimulus materials in the current study.

Our study expands on the findings from Song et al. (2022) to further explore subjective experience in relation to neural activity. They made an interesting and important discovery when they applied a hidden markov model to an fMRI dataset of twenty-seven individuals watching movies. Hidden markov models (HMMs) statistically extract hidden states that are responsible for what is observed (Husmeier et al., 2005). Using an HMM, Song et al. (2022) identified four neural states which they named the default mode network (DMN), dorsal attention network (DAN), somatosensory motor (SM), and base states. These states reflect different patterns of neural activity and functional interactions across brain networks. Participants cycled through these states during the study. For example, at some moments their brain activity and connectivity

pattern indicated that they were in the DMN state template whereas at others indicated that they were in the DAN state. These four latent neural states were further replicated with the Human Connectome Participant (HCP) video watching dataset, which supports that these four latent states are consistent across naturalistic stimuli (HMM-HCP; Van Essen et al., 2013; Song et al., 2022).

Song et al. (2022) also collected behavioral data while participants performed the tasks and watched movies for a second time. Participants completed a sustained attention task (gradCPT; Rosenberg et al., 2013), watched a sitcom movie, and watched a nature documentary during scanning. Attentional state during the gradCPT task was measured with task performance, and the attentional state during movie watching was assessed with a continuous measure of self-reported engagement collected after the scan. They then related the occurrence of each neural state to participants' attentional state. Interestingly, during each of these tasks, the latent brain state that occurred when participants showed evidence of engaged attention (i.e., successful task performance and high self-reported movie engagement) differed. However, low attention, as indicated by lower engagement ratings, consistently correlated with the occurrence of the SM state. Further, the DMN state showed an increase in activity following event boundaries, suggesting it may play a role with comprehension/event cognition (Song et al., 2022). Of important note, Song et al. (2022) found evidence that the base state acts as a "transition hub" between latent state activity, rather than a state where neural activity maintains for a long duration; although it was consistently utilized during high engagement watching a sitcom. This suggests that more comedic content, as seen in the sitcom, requires the utility of numerous cognitive processes related to the other three latent states; the base state may have been more active due to these rapid changes between states. To understand the differences between the four

states, we strive to identify the correlated cognitive experiences during each time point of increased latent state activity.

While this is a sizable goal, we first narrow our focus to cognitive measures most representative of each neural state according to current literature, as well as those that are imperative for conscious experience. One such impactful cognitive experience, surprise, has been linked to affective experience, memories and event segmentation (Anthony et al., 2021). Vogl et al. (2020) further looked at the relationship between surprise, curiosity and confusion and found them to be similar to one another, and positively related to the likelihood of knowledge exploration; critical for learning and cognitive performance. Substantial evidence suggests that the DMN plays a role in processing internal experiences (Ekhtiari et al., 2016; Ma & Zhang, 2021; Manning & Steffens, 2016), and has specifically been linked to measures of surprise (Brandman et al., 2021), emotion (Satpute & Lindquist, 2019) and comprehension (Song, Park, Park, & Shim, 2021; Chang, Lazaridi, Yeshurun, Norman, & Hasson, 2021). More specifically, the ventromedial prefrontal cortex (vmPFC), which is included in the DMN, has been linked to affective experiences (Chang, Jolly, Cheong, Rapuano, Greenstein, Chen, & Manning, 2021). Importantly, in regard to subjective emotion we make a distinction between arousal and valence, which have shown differential brain activity for each (Dolcos et al., 2004). Further, Yeshurun et al. (2021) suggest that the DMN plays a part with integrating prior information and knowledge over time, and other research has found that autobiographical memory is associated with DMN activity (Spreng & Grady, 2010; Philippi et al., 2015). We question whether individuals' classification and categorization of the importance of events contributes to this integration of knowledge. Moreover, we question whether the integration of past information/memories into present contexts is consciously supported by subjective perceptions of personal relatability.

Finally, we assess sociality of stimulus materials as a potential explanation for the variances in latent state occurrences, of which has also been linked to DMN activity (Yeshurun et al., 2021). However, we question whether social content will relate to DAN activity as it may be more demanding of external attention. These findings bring us to hypothesize that the DMN state will occur during moments of a movie that are surprising, emotional, curiosity-evoking, comprehensible, relatable, sociable, and important to the plot of the narrative.

Another key modulator of cognition is attention. Attention can be broken down internally and externally: internal attention being related to mentally derived information and external attention related to perceptual and sensory experiences (Chun et al., 2011). The DAN is typically associated with external processing, specifically when attention is on the external environment (Spreng et al., 2017; Rohr et al., 2017), with some specific findings suggesting that DAN activity is related to selective attention (Rohr et al., 2017; Song, Finn, & Rosenberg, 2021). Conversely, internal focusing of attention has been related to creativity (Benedek, 2018). Internal focus may relate more to DMN activity than DAN activity, as Andrews-Hanna et al. (2010) discuss that the DMN is typically related to analyzing personal significance, internal processing, mind-wandering and passive thinking. Engagement, which may fluctuate between internally and externally focused attention, has recently been related to interactions between DMN and DAN activity (Ohad & Yeshurun, 2023). These findings regarding attention lead us to hypothesize that external focus and engagement will be correlated to increased activity of the DAN state, although engagement may also have similar activity in the DMN state. Furthermore, internal focusing is hypothesized to be correlated to increased activity in the DMN state.

The somatosensory motor (SM) state, as indicated by Song et al. (2022), was most notable during film ‘breaks’, when there was nothing on the screen, between film clips. Within

Song et al.'s (2022) study, the SM state corresponds to some brain regions that are typically responsible for motor and sensory processes (e.g., somatomotor). While Song et al. (2022) infer that the SM state indicates periods of inattention or disengagement, this latent state may purely be related to motor and sensory function, such that high motor movements indicate high SM activity. Looking at the results from Song et al. (2022) it can be intuitively assumed that motor function is naturally reduced during periods of high attention, and during periods of inattention individuals are 'pulled out' of their internal thoughts (DMN) and away from external stimuli (DAN). Therefore, this could lead to an increased awareness of bodily sensations, resulting in a rise in body movement. Research has found that boredom, or mental fatigue, can lead to increased motor function (Jacquet et al., 2021; Ricciardi et al., 2019; Pageaux & Lepers, 2018). For example, Chen et al. (2021) found that children with ADHD have increased somatomotor functional connectivity, which may lead to the difficulty in suppressing excess movements. To delineate whether increased SM activity during periods of low engagement from Song et al. (2022) resulted from inattention, we measured levels of subjective boredom. We hypothesize that the somatosensory motor state will significantly correlate to periods of subjectively high boredom as well as low engagement.

The base state, as identified by Song et al. (2022), was found to act as a transitioning point between the other three states; brain activity would typically enter this state after leaving another, then transition to another rather quickly. While there is no direct literature pertaining to a neural network latent state transition point, to our knowledge, some findings have shown similar evidence for a neural transition structure (Saggar et al., 2022; Passarelli et al., 2021). We therefore question why Song et al. (2022) saw engaged attention during sitcom-viewing associated with high activity in the base state. Comprehensive pursuit of this question requires

further neural investigation, which is outside the scope of the current study. Rather, we propose that sitcoms, which embrace comedic structures, elicit rapid combinations of self-referential processing (related to DMN), external processing (related to DAN), and periods of boredom (related to SM), while engagement remains high. Although we do not have direct hypotheses regarding the subjective experiences felt when activity was most pronounced in the base state, we hope that the subjective measures used in our study may shed light.

These four latent neural states provide insight into the complex activations of the human brain by identifying just a few commonly activated states throughout time. This allows us to start big so we can then work our way down into the smaller individualized cognitive experiences behind neural activity. Solidifying subjective experiences in relation to these states is just the first step, of which the current research acts as a starting point by looking at many conscious experiences. While the majority of the subjective measures used in this study are hypothesized to be related to the DMN state, we aimed to confirm these assumptions as well as provide insight into any overlapping latent state occurrences to understand the dynamic fluctuations that occur throughout time. This project aims to further understand the functional interaction between neural networks and the corresponding conscious experiences during each of the latent states. Subjective experiences are diverse, yet the current study contributes toward advancing neural dynamics and cognition literature through the comparison of eleven cognitive measures to neural activation patterns over time.

Methods

This study aimed to characterize differences between the latent brain states identified by Song et al. (2022) by employing an online behavioral experiment. Online participants watched the same movies that participants in the Human Connectome Project (HCP; Van Essen et al.,

2013; N=184) watched during fMRI while indicating different aspects of their subjective experience. FMRI data have already been collected (Van Essen et al., 2013) and analyzed using the Hidden Markov Model by Song et al. (2022) to separate the four latent states (N=119), of which we utilized in this study (HMM-HCP).

Participants

Data for the current study were collected using the online experiment platform Prolific with the requirements that all participants must be between 18-35 years of age, reside within the United States, speak fluent English, and have normal or corrected-to-normal vision. Participant requirements were closely matched with the inclusion criteria for the HMM-HCP sample. The study was coded with jsPsych and hosted on Cognition.run. For each subjective measure we initially sought to collect 25 subjects each, however final numbers were smaller due to inclusion criteria (see **Table 1**). Inclusion criteria were to make at least one slider movement (indicating a change in subjective experience) per clip, respond to all attention checks correctly, and complete the study. During analysis participant data was excluded on clips where responses were not made at least every two minutes, which allowed us to include subjects who gave meaningful data but did not respond frequently. The total sample after initial exclusion criteria consisted of 226 participants with a mean age of 28.19 ± 4.5 years (range = 18-35 years; Male: 56.19%; Female: 43.81%). The majority of participants identified as White (60.18%; Black: 11.50%; Mixed Race: 10.62%; Asian: 9.73%; Other: 7.96%).

Materials

As the primary goal was to delineate subjective experiences in relation to latent state activations, we utilized eleven different cognitive constructs to provide a first step toward achieving this goal. Therefore, continuous self-reported behavioral measures included

engagement, arousal, valence, social interaction, focus, curiosity, relatability, importance, surprise, comprehension, and boredom. Participants watched the same four movies from the HMM-HCP dataset in randomized orders to account for variability in responses due to fatigue from watching non-cinematic derived clips (an example of a cinematic clip would be ‘Inception’ or ‘Star Wars’, while a non-cinematic clip would be a documentary). The very first clip of each movie started and ended with a 20 second rest period, in which the word “REST” appeared in white lettering with a black background. The following clips in a movie block would only contain the rest period after the video clip was shown to match the presentations of the videos to the HMM-HCP dataset. The slider scale was located underneath the clips and ranged from 0 (typically ‘Not at all’) – 20 (typically ‘Completely’), with 10 being the starting point. Please see Finn and Bandettini (2021) for a detailed description of the video clips utilized in this study.

Measures

In the current study, participants continuously rated one of eleven subjective experiences while watching movie clips. A detailed description of the instructions and definitions of each measure is provided in **Appendix A**.

Engagement. Engagement was rated on a scale ranging from ‘Not at all engaging’ (e.g., “My attention is wandering away from the story”) to ‘Completely engaging’ (e.g., “I am curious and excited to know what’s coming up next”).

Arousal. To measure the intensity of emotion, arousal was measured on a scale ranging from ‘Not aroused at all’ (e.g., “I feel very mentally or physically alert, activated, and/or energized”) to ‘Completely aroused’ (e.g., “I feel very mentally or physically slow, still, and/or de-energized”). While introducing this measure we described arousal followed by “(e.g., energized)” so that the colloquial definition was not immediately primed.

Valence. Valence was measured on a scale ranging from ‘Completely negative’ (e.g., “I feel pleasant, happy, and/or excited”) to ‘Completely positive’ (e.g., “I feel unpleasant, sad, and/or angry”).

Social Interaction. Due to the more objective nature of this measure we decided to provide more context to participants for clarity. This resulted in the scale ranging from ‘Not at all social’ (e.g., “People are not present”) to ‘A little social’ (e.g., “People are present, but not interacting with each other”), to ‘Somewhat social’ (e.g., “People are present and interacting superficially with each other”) to ‘Completely social’ (e.g., “People are present and interacting meaningfully with each other”).

Focus. While our primary interest was how participants’ thoughts shifted while watching the clips, instead of simply whether participants were attending to the videos, our measure of focus was aimed to capture periods of internal or external focus. This scale ranged from ‘Completely directed to my internal thoughts’ (e.g., “I am paying attention to my own thoughts”) to ‘Completely directed to the external environment’ (e.g., “I am paying attention to the video”).

Curiosity. This measure was on a scale ranging from ‘Not at all curious about the video’ (e.g., “I do not care about knowing what will happen next”) to ‘Completely curious about the video’ (e.g., “I want to know what will happen next”).

Relatability. The scale ranged from ‘Not at all personally relatable’ (e.g., “I do not find the events relevant to me personally”) to ‘Completely personally relatable’ (e.g., “I find the events relevant to me personally”).

Importance. Importance was measured on a scale ranging from ‘Not at all important for the story’ (e.g., “What is happening now does not appear to be relevant for the story”) to

‘Completely important for the story’ (e.g., “What is happening in the video now is an important part of the story”).

Surprise. Surprise was rated on a scale ranging from ‘Not at all surprising’ (e.g., “I expected the events in the video”) to ‘Completely surprising’ (e.g., “I did not expect the events to happen in the video”).

Comprehension. To measure participants’ understanding of the videos’ events, the scale ranged from ‘I do not understand the events at all’ (e.g., “The events do not make sense to me”) to ‘I completely understand the events’ (e.g., “The events make sense to me”).

Boredom. Participants’ level of boredom was collected on a scale ranging from ‘Not at all boring’ (e.g., “The events do not seem long and repetitive”) to ‘Completely boring’ (e.g., “The events seem long and repetitive”).

Procedure

At the beginning of the study, participants gave informed consent and completed quality checks to ensure their volume was on and to test using the sliding scale with their keyboard arrow keys. Following this, they were given instructions to continuously respond throughout all clips, including rest periods, by pressing either the ‘left’ or ‘right’ arrow keys on their keyboard and then were given a definition of the measure they would be rating. They then practiced rating a short, unrelated, 30 second video clip of a bird perched in a tree with nature sounds playing in the background (Shae O’R., 2022). They then had the opportunity to repeat the instructions, definition, and practice video prior to starting the experiment.

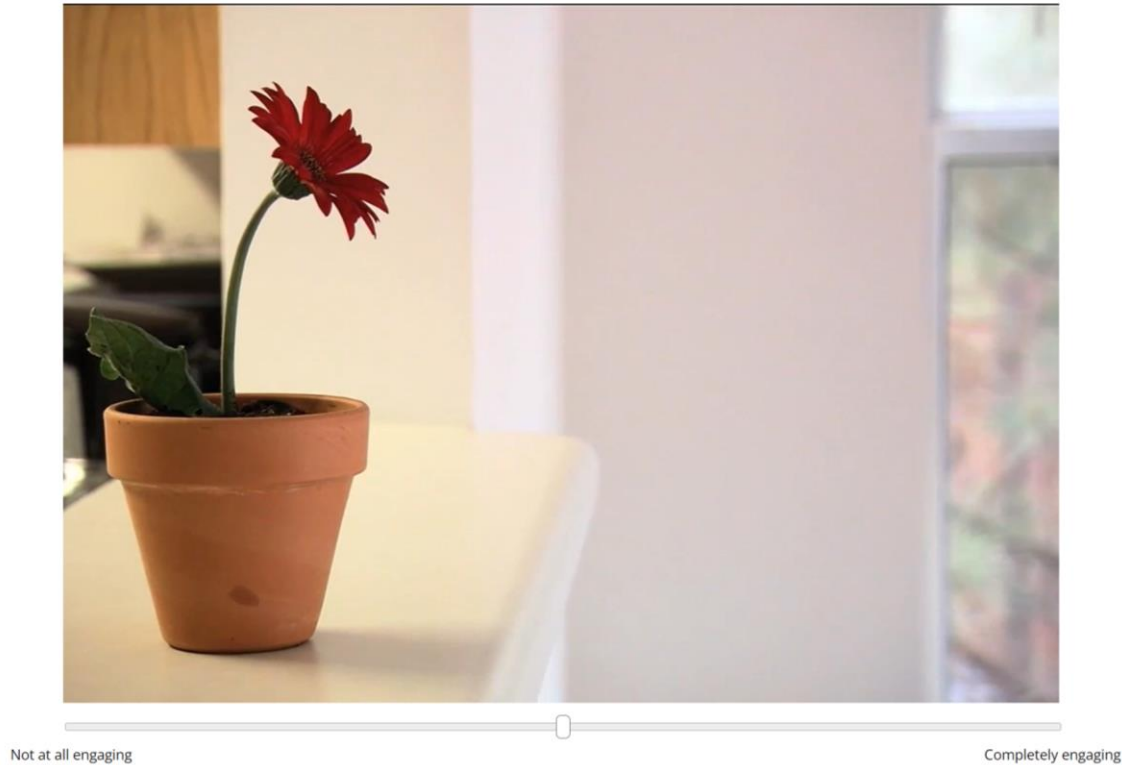


Figure 1. Example screen of continuous rating during movie clips measuring engagement for the clip “Flower”. Video size was automatically formatted for each individuals’ specific monitor size, and mouse capabilities were disabled which required the use of either the “left” or “right” arrow keys.

Next, participants watched the first video clip in a movie block (see **Figure 1**). Each clip was followed by a question asking if they had seen the clip before and then another one asking them to give the clip an overall rating of that measure (e.g., “Overall, how engaging did you find the video?”). This format continued through all of the videos in a movie block. After they watched an entire block, participants were notified that they completed a section and asked to give an overall rating of their measure for the entire movie block. They were then prompted with a multiple-choice question asking them to confirm which activity was presented in one of the clips they have watched (attention check). This continued through all four movie blocks until

they had completed the experiment, in which they were asked to provide any feedback they may have.

Analysis

Assessment of Participant Reliability Within Clips

A primary concern in this study was the reliability in participant responses due to both self-report and the short durations of each clip. Participant response time courses were normalized via z -scoring across time. As some clips were short (e.g., 64 seconds), some subjects continuously maintained their responses around one rating (e.g., keeping the slider at '10'), which resulted in 'nan' values for their z -scored responses. We therefore did not include those responses in our analysis. We calculated the Pearson correlation between all pairs of subjects for each clip prior to applying Fisher- z transformation. We then calculated the mean of the Fisher- z transformed correlation coefficients, then inverted the values for reporting r -values. To statistically test whether the distribution of pairwise r -values for each video clip was significantly greater than that expected by chance (i.e., an r -value of 0), we then bootstrapped (1000 iterations) the mean Fisher- z transformed correlation coefficients and ran one-tailed tests to calculate p -values, with significance at $\alpha < 0.05$.

Correlation of Subjective Ratings

As multiple experience ratings were obtained, we were interested in how similar ratings were related to one another. Within each clip we averaged z -scored ratings across participants and then z -scored once more to maintain normalization. We then calculated Pearson's correlation coefficient values within each clip for each of the subjective measures. To then look at subjective experience across all clips we transformed the r -values using Fisher- z and averaged across all movie clips prior to inverse Fisher- z transformation.

Latent State Occurrence and Subjective Experiences

After assessing reliability in participant responses, we then time matched both self-reported experience and the HMM-transformed neural latent state data (HMM-HCP). To do this, we related the mean time courses for each movie clip whose pairwise r -values were significant to the occurrence of each latent state. We therefore did not analyze the relationship between subjective experience and latent state occurrence for movie clips that were not significantly correlated between participants. Participant z-scored responses per clip were then averaged at each time point, and then z-scored once more to maintain normalization in responding. The average subjective ratings at each time point were matched to each participant of the HMM-HCP dataset. We then averaged across all clips for each measure. One-way repeated-measures analysis of variance (RM-ANOVA) tests were conducted to test whether group mean self-reported ratings significantly differed across the four latent states. From there, we conducted pairwise t-tests to understand how subjective experiences differ across the four different states.

We further conducted RM-ANOVA on each individual clip, which allowed us to look at group differences in latent state activation patterns that may be attributable to the type of movie clip being watched (e.g., popularized film versus nature film). All procedures were similar; however, values were not averaged across clips. Some participants from the HMM-HCP sample did not have neural activity within all four latent states throughout the duration of every clip. Therefore, we only included fMRI samples from participants who had activity in all four states in the timeframe of the clip. While the type of clip may have contributed to differences in activation patterns and subjective experience, it is outside the scope of the current study. We encourage future research to address this question, but have provided the RM-ANOVA results per clip from our findings in **Appendix C**.

Results

Reliability of Participant Responses

Analyses of within-clip reliability in participant responses showed consistency for multiple measures and clips (see **Table 1** and **Figure 2**). For a comprehensive list of the final number of participants, correlation r -values, p -values, and overall clip measures for each clip and measure please reference **Appendix B**.

Table 1. Ratings, Correlations, and Significance for Each Measure

Measure	Clip name	Duration (s)	Included subjects	Mean pairwise r	p -value	Seen clip before	Mean overall clip ratings
curiosity							
	twomen	240	18	0.322	0.001*	0.00%	46.18
	bridgeville	222	18	0.179	0.001*	0.00%	28.06
	pockets	189	19	0.019	0.332	0.00%	44.88
	overcome	64	19	0.433	0.001*	0.00%	66.18
	inception	223	18	0.421	0.001*	26.32%	83.82
	socialnet	259	17	0.154	0.008*	31.58%	62.71
	oceans11	250	18	0.149	0.003*	10.53%	74.41
	testretest	85	19	-0.012	0.565	0.00%	33.82
	flower	176	19	0.107	0.004*	0.00%	47.94
	hotel	186	19	0.36	0.001*	0.00%	69.77
	garden	205	16	0.152	0.007*	0.00%	34.77
	dreary	144	19	0.298	0.001*	0.00%	40.71
	homealone	228	18	0.13	0.002*	63.16%	65.12
	brockovich	231	19	0.012	0.408	15.79%	69.77
	starwars	256	18	0.151	0.003*	57.89%	34.77

Curiosity ratings for each movie clip. The number of participants used in analyses varied per measure based on exclusion criteria. Correlation and significance analyses showed relative consistency in responses across participants. Mean overall clip ratings ranged from 0 - 100.

* p -values were calculated via one-tailed testing with significance at $\alpha=0.05$

For ratings of valence, social interaction, importance, and comprehension almost all, or all but one, of the clips reflect significance ($p < 0.05$). This potentially may have been due to the

inherent objectivity of these measures. The most objective measure we obtained, which we recognized prior to testing, was the perception of social interaction, of which participants' ratings were strongly correlated for each movie clip ($p < 0.01$). Similarly, ratings of importance also showed significance amongst participants ($p < 0.05$). Rating the importance of events to the narrative may have an objective quality which contributed to the consistency in responding across participants. Ratings of valence and comprehension showed similar agreement across clips, showing significance amongst fourteen of the fifteen clips ($p < 0.05$).

Conversely, it is interesting to look at the measures that were not in consistent agreement amongst participants for each clip. Measures of arousal and focus had the least number of clips with significant correlation amongst participants' ratings. This suggests that these measures may be more subject to individual differences. However, many factors could drive differences in participant ratings and differences in ratings between videos, such as the type of clip (e.g., popularized films versus documentaries), so we interpret these null effects with caution.

Of note, for clips and measures that did not show a significant correlation between participant responses we did not perform further analyses. Insignificant correlations in responding between participants hints at individual differences within participants that make a group-average time course challenging to interpret. While it is interesting to hypothesize why certain clips resulted in more differentiation in responses, that does not align with the primary aim of the current study: to identify commonalities in responses between subjective ratings and neural activity within the four latent states identified by Song et al. (2022). By only including clips and measures with high correlation amongst participants we are able to more confidently compare to the neural latent state activation patterns.

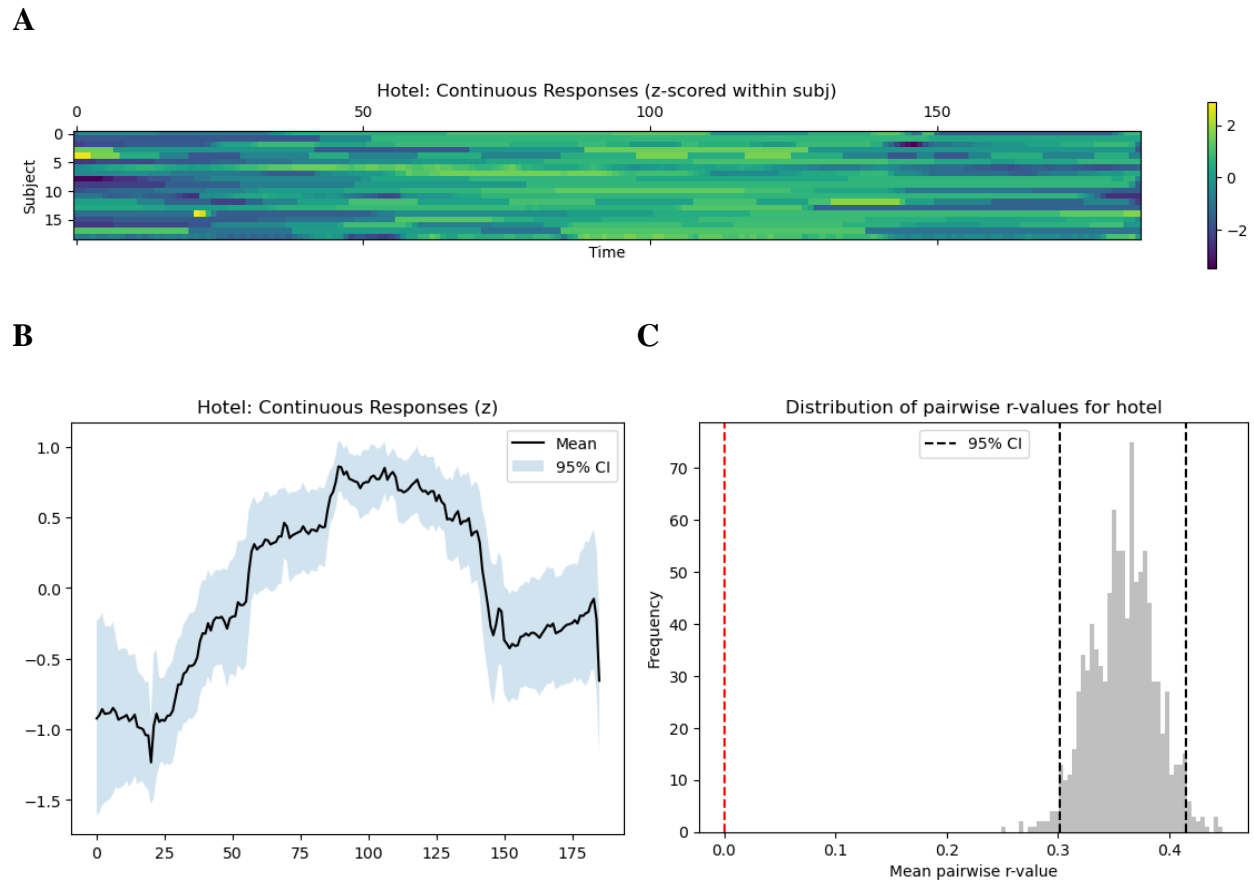


Figure 2. Assessment of reliability.

Reliability assessment of participant ratings of curiosity across time during the clip “Hotel”, (N=19). **(A)** Matrix of participant z-scored responses over time. **(B)** Line plot of averaged z-scored responses with 95% confidence interval overlaid. The x-axis indicates the duration of the clip in seconds, and the y-axis depicts normalized responses. **(C)** Statistically tested if the distribution of pairwise r -values were significantly different than zero. Pearson correlation values were Fisher-z transformed before averaging, and then inverse Fisher-z transformed. Values were then bootstrapped 1000 iterations and one-tailed p -values were calculated to determine significant correlations between participant responses. Black dotted lines depict 95% confidence intervals and the red dotted line indicates zero for visual clarity ($r = 0.36$, $p = 0.001$).

Correlating Subjective Experiences

Correlations between each measure were conducted to visualize the relationship between measures (see **Figure 3**). Engagement has a positive relationship with arousal, external focus, curiosity, importance and surprise. Ratings of engagement also have a negative correlation with boredom, as well as a negative relationship with relatability, indicating that, at least in the clips shown here, when content is engaging it is less relatable. Arousal ratings show strongly positive correlations with engagement ratings. Further, ratings of positive and negative events (valence) showed a positive relationship with comprehension, indicating positively valenced moments also tended to be more understandable. Social interaction ratings were positively correlated with external focus and importance ratings and negatively correlated with relatability and boredom. This suggests that, in these clips, moments when participants were more focused were also rated as less relatable and more boring, however they were also rated as important to the narrative.

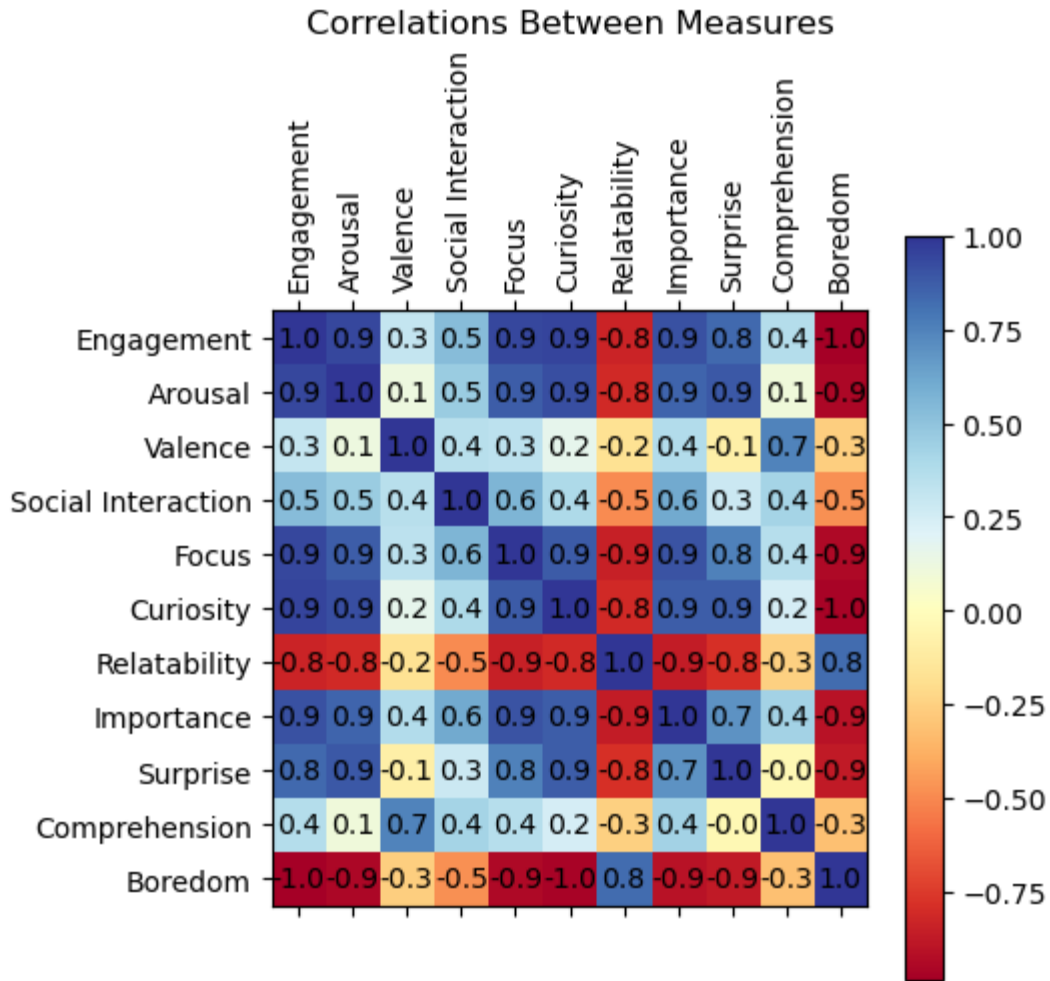


Figure 3. Pearson correlation was conducted between all measures and all movie clips on z-scored responses. Fisher-z transformation was conducted prior to averaging across all clips. Matrix shows the inverted values. Lower (red) correlations indicate a stronger relationship between more negative responses, except for focus which here lower values indicate internal focus, and higher (blue) correlations indicate a stronger relationship between more positive responses, except for focus it indicates external focus. The correlation matrix is symmetric about the diagonal.

Focus had a strongly positive relationship with curiosity, importance, and surprise. This indicates that external focus is related to higher levels of curiosity and surprise, and that the more important the content is to the plot, the more externally focused one is. Interestingly, external focus was strongly negatively correlated with relatability and boredom. This suggests that relatable content and lower levels of boredom are associated with internal focus. Curiosity had a positive correlation with importance and surprise, and a negative correlation with relatability and boredom. This suggests that less relatable content was also more curiosity-inducing and less boring. Relatability was also positively related to boredom, such that the more relatable the videos were the more bored the participants were. Further, relatability had a negative correlation with importance and surprise, such that more relatable content was less important and less surprising. The importance of events to the narrative was further related to increased levels of surprise, and negative related to boredom levels, indicating that, in these clips, important events were surprising and less boring.

Relationships Between Latent Brain State Occurrence and Subjective Experience

RM-ANOVA results between all clips yielded significance for all measures except for comprehension ratings (see **Table 2**). A significant RM-ANOVA result indicates that at least one of the latent states significantly relates to the subjective self-report ratings, while controlling for the other latent states. An insignificant result could suggest that the experience is not related to the four neural states tested, that we have insufficient rating data, and/or that there is too much variability in subjective experience ratings across people, resulting in a noisy group-average time course. Further, insignificance may suggest that although subjective experience is interpreted similarly, neural activity may be differentially timed.

Table 2. All Movie Clips Analyses per Measure

Measure	Original # subjects per clip	Included clips*	Included subjects	RM-ANOVA for All Movies
engagement	23	10	213	$F(3,118) = 101.4431, p < 0.0001^*$
arousal	17	9	150	$F(3,118) = 84.5734, p < 0.0001^*$
valence	21	13	269	$F(3,118) = 36.4599, p < 0.0001^*$
social	19	15	261	$F(3,118) = 210.7376, p < 0.0001^*$
focus	24	9	209	$F(3,118) = 109.8482, p < 0.0001^*$
curiosity	19	12	217	$F(3,118) = 110.5240, p < 0.0001^*$
relatability	21	13	265	$F(3,118) = 50.3544, p < 0.0001^*$
importance	22	15	325	$F(3,118) = 174.8888, p < 0.0001^*$
surprise	20	11	216	$F(3,118) = 37.3616, p < 0.0001^*$
comprehension	20	14	260	$F(3,118) = 1.3595, p = 0.2549$
boredom	21	12	242	$F(3,118) = 134.6384, p < 0.0001^*$

RM-ANOVA results for all movie clips for each measure. There were 15 original numbers of

clips per measure, but some were excluded as they did not have significant inter-subject

correlations ($p < 0.05$). The original number of subjects represents the total number collected per

measure, with some subjects excluded per exclusion criteria.

* p -values are significant at $\alpha=0.05$

Pairwise t-tests conducted for measures that yielded significant RM-ANOVA results revealed significant relationships between subjective experience ratings and latent state occurrence for the majority of the relationships between states (see **Table 3**).

Table 3. Paired T-Test Analyses for All Clips

Measure	$t(118)$					
	DMN / DAN	DMN / SM	DMN / base	DAN / SM	DAN / base	SM / base
engagement	4.427***	11.825***	1.239	9.506***	-3.529**	-11.425***
arousal	2.254*	10.572***	1.218	10.085***	-1.281	-10.473***
valence	5.390***	7.902***	4.469***	4.875***	-2.307*	-6.010***
social	23.087***	16.246***	14.762***	-0.603	-16.185***	-9.752***
focus	5.067***	12.489***	1.668	9.525***	-4.699***	-11.857***
curiosity	1.726	11.051***	-4.322***	10.156***	-5.937***	-13.305***
relatability	2.157*	-6.541***	4.619***	-7.680***	2.338*	9.359***
importance	6.386***	14.730***	-3.126**	11.591***	-10.467***	-15.840***

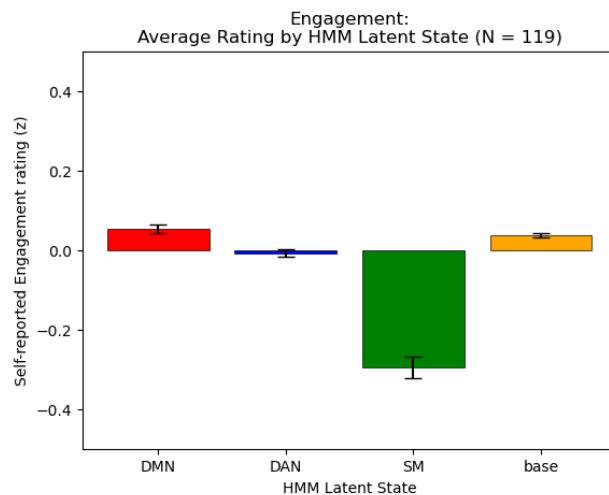
surprise	-4.613***	4.662***	-4.962***	7.340***	0.574	-8.057***
comprehension	-	-	-	-	-	-
boredom	-1.825	-13.058***	-0.831	-12.272***	1.294	13.367***

Paired t-tests were conducted for all measures with significant RM-ANOVA results. Results include all movie clips for each measure with significant inter-subject correlations. Values correspond to *t*-statistics.

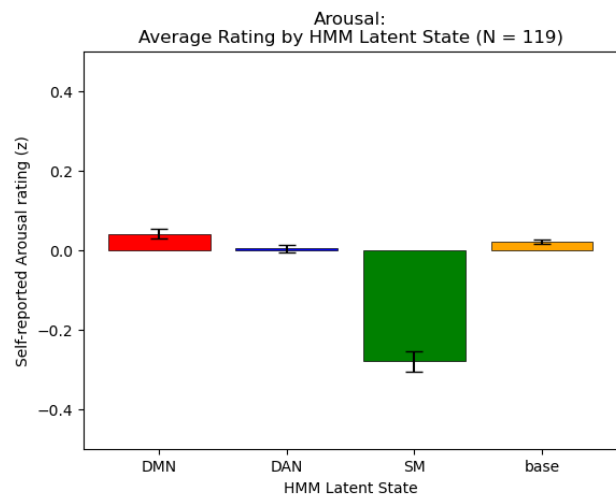
* $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$

To further characterize the relationship between each latent state occurrence and subjective experience we visualized bar graphs (**Figures 4-6**). Six measures showed similar latent state activation patterns: ratings of engagement, arousal, valence, focus, curiosity, and importance (see **Figure 4**).

A



B



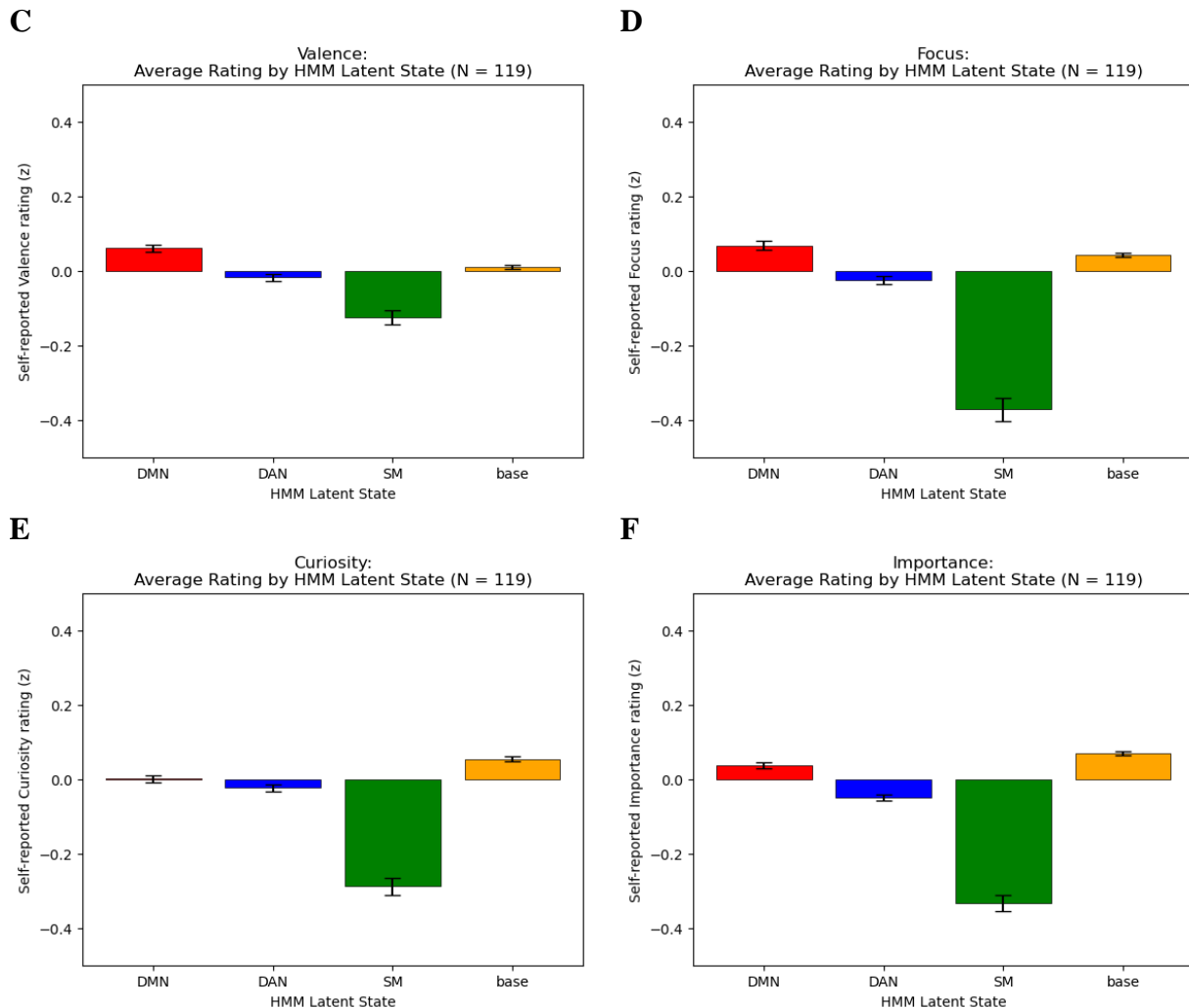


Figure 4. Similarity in degree of subjective ratings at moments of latent state occurrence.

Participant z -scored responses were averaged at each time point, and then z -scored once more to maintain normalization in responding. The average subjective ratings at each time point were matched to each participant of the HMM dataset. The bar graphs indicate the average occurrence of each latent state throughout time, as matched with subjective ratings, for all clips with significant pairwise t-test results. The number of subjects “N” depicts the number of HMM participants. (A-F) Bar graphs depicting similar latent state activation patterns during subjective experiences of (A) engagement, (B) arousal, (C) valence, (D) focus, (E) curiosity, and (F) narrative importance.

When the DMN and base states occurred, these six measures were more positive, and when the SM state occurred, they were more negative (**Figure 4**, see **Table 3** for pairwise t-test results). DMN and base states were not significantly differentiated per pairwise t-testing during increased ratings of engagement, arousal, and focus. DAN and base state activity was not significantly different when arousal was high. Moreover, DMN and DAN activity was not significantly different from each other when ratings of curiosity were high. Valence and importance ratings significantly differed between all pairs of states.

The remaining subjective measures showed different associations with latent state occurrence (**Figure 5**, see **Table 3** for pairwise t-test results). DMN state, followed by slight activity of the base state, occurred when video clips were subjectively more social (**Figure 5A**). DAN and SM occurrences were associated with lower ratings of social interaction. When the SM state occurred, and slight activity of the DMN state, relatability ratings were higher (**Figure 5B**). When the base state occurred, and DAN did not, participants indicated lower relatability. During the DAN and base states, participants rated surprise higher (Figure 5, see Table 3 for pairwise t-test results). When the SM and DMN states occurred, participants indicated lower levels of surprise (**Figure 5C**). Lastly, when the SM state occurred, participants rated boredom higher (**Figure 5D**).

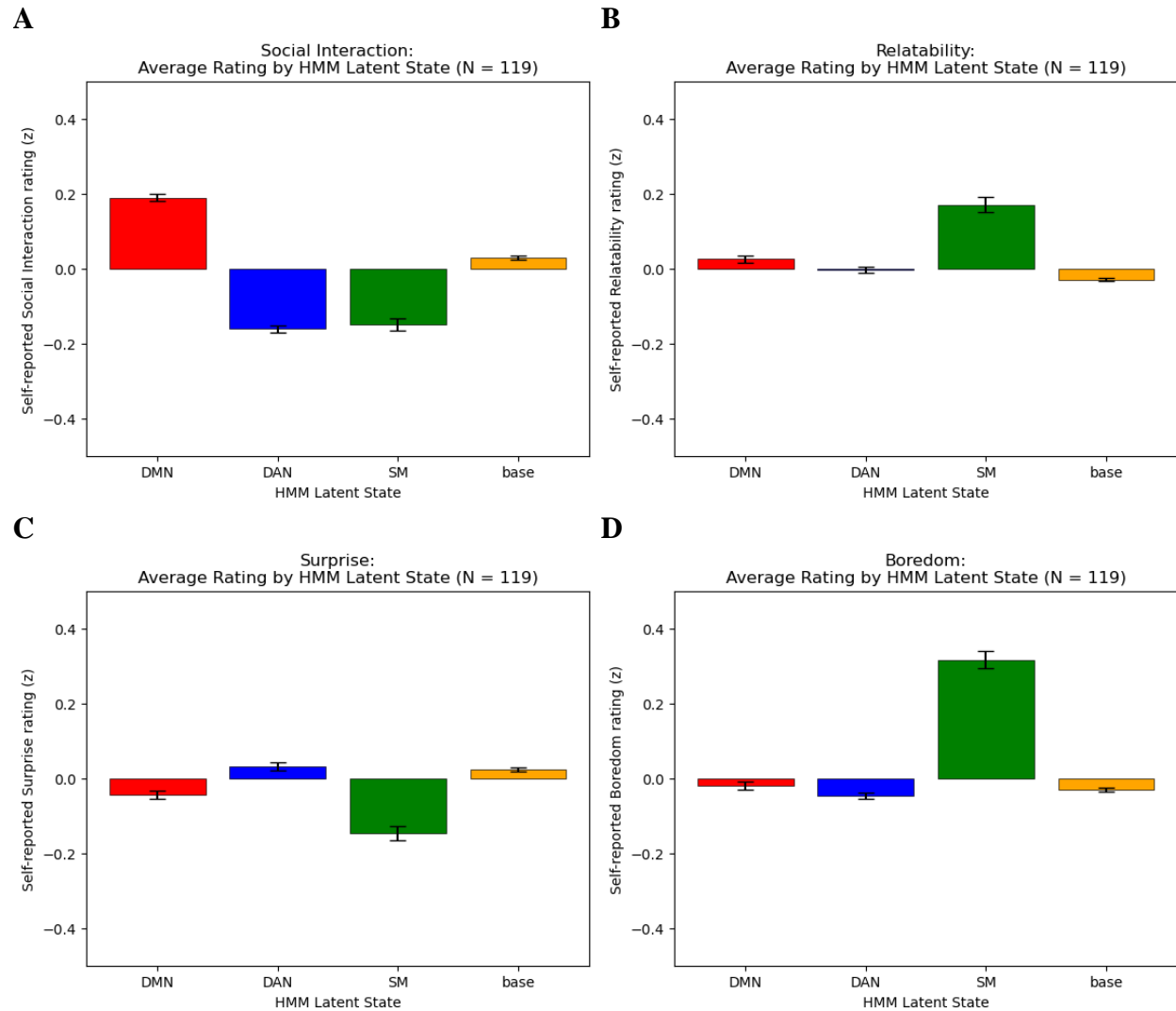


Figure 5. Degree of subjective ratings at moments of latent state occurrence.

Bar graphs were created using the same analyses as described in **Figure 4**. Average latent state occurrence over time as matched with subjective ratings of **(A)** social interaction, **(B)** reliability, **(C)** surprise, and **(D)** boredom.

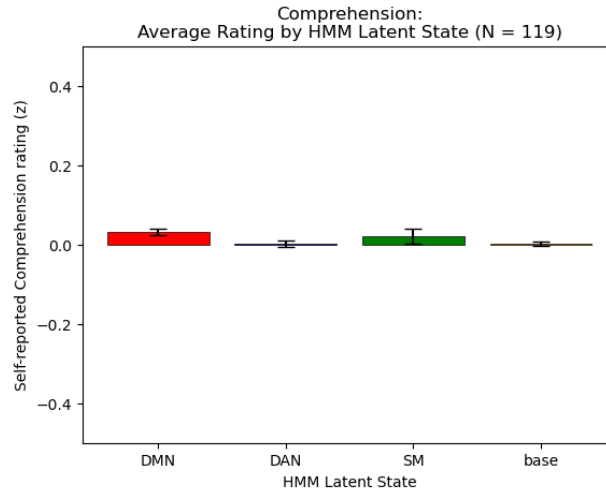


Figure 6. Comprehension: Subjective ratings at moments of latent state occurrence.

Bar graph was created using the same analyses as described in **Figure 4**. Average latent state occurrence over time as matched with subjective ratings of their understanding (comprehension).

Although subjective ratings of comprehension were not significant per RM-ANOVA analyses, **Figure 6** shows a potential trend that may be worth pursuing in future studies. Here, we can see that during the DMN and SM states, participants rated slightly higher levels of comprehension. This may hint at a relationship between DMN and SM while individuals attempt to comprehend events although this result should be interpreted with caution.

Discussion

The current study builds upon Song et al. (2022) by exploring multiple subjective experiences in relation to corresponding neural latent state activations. To do so we looked at the relationships between the occurrence of latent neural states and eleven subjective experiences throughout time as participants watched movie clips. We first found relative consistency amongst participant ratings for each measure, specifically showing that even over short time durations of each clip participants have similar subjective experiences. This allotted confidence in pursuing further analyses for correlating to the latent state activations from the HMM-HCP

dataset. After assessing reliability in participant responses within each movie clip, we compared each subjective rating with one another to see how similarly they were rated (**Figure 3**).

Relatability and boredom were very similarly rated, showing that, at least in these clips, more relatable content was also more boring. Moreover, they were both negatively related with engagement, arousal, focus, curiosity, importance, and surprise, which are all similarly rated, suggesting similarities in subjective interpretations. This relationship between these ratings may suggest that individuals found more ambiguous information more engaging and prescribe similar ratings dependent upon this criterion. However, this speculative interpretation should be addressed in future work. Further, high comprehension was similarly rated as the positiveness of content, which suggests they may have a fluctuating relationship with one another, although this too requires further investigation.

Overall, we found that subjective experiences were largely reliably associated with latent state occurrence. When the DMN state occurred, participants indicated higher levels of engagement, arousal, external focus, positivity, importance, and sociality. When the DAN state occurred, participants indicated higher ratings of surprise and decreased boredom. When the SM state occurred, participants indicated lower engagement, arousal, curiosity, importance and surprise, as well as rated events negatively, internally focused attention, and rated higher levels of relatability and boredom. When the base state, characterized as a “transition hub” by Song et al. (2022), occurred, participants indicated higher levels of curiosity and importance and lower ratings of relatability.

Interpreting Relationships Between Measures and Latent State Occurrence

Although the analysis of continuously rated subjective experiences provides insight into the relationships between conscious experiences, the comparison to neural activity allows us to work toward disentangling commonly rated experiences from one another.

Measures of Attention

Interestingly, measures related more directly to attention were both similarly rated and showed similar latent state occurrences. Engagement, arousal and focus were all rated similarly and had similar latent state activation patterns. We include boredom as a measure of attention as it is highly anticorrelated with these measures, suggesting its role as a measure of inattention. When participants rated boredom, however, latent occurrences were not similar.

Engagement. We hypothesized that engagement would be associated with increased activity of the DAN state with some potential overlap observed with the DMN state. Our results show instead that when the DMN and base states occur engagement is high, and when the SM state occurs engagement is lower. These results may suggest that the degree of engagement is determined by internal states rather than externally driven as we previously suggested.

Arousal. Although we will expand on these findings in the next section, it is important to discuss the similarity between arousal ratings, engagement and focus. Further, it is negatively correlated with boredom. These results indicate that although we utilized arousal as part of the measurement of affect, it has a strong relationship to attentional experiences.

Internal and External Focus. When the DMN and base states occurred, participants indicated their focus was on the external environment. However, when the SM state occurred participants indicated the internal focusing of attention. Therefore, our hypothesis that internal focus would be associated with DMN activity and external focus associated with DAN activity

was not supported. These results may be interpreted such that external focus requires internal processing of the information, whereas internal focusing is similarly rated to boredom (which was found via the correlation between measures). Future work should expand on these findings to see whether the external focusing of attention is truly related to DMN state activity and whether internal focusing of attention is truly associated with SM activity.

Boredom and Low Engagement. As predicted, when the SM state occurred participants reported higher levels of subjective boredom. When the occurrence of the other three states appeared, participants rated lower boredom levels, with occurrences of DMN, DAN, and base states not differentiated from one another. Additionally, the SM state occurred when engagement was low, which further supports our hypothesis. However, there was a differentiation between activation levels between DMN and DAN as well as between DAN and base states when participants rated higher levels of engagement. This suggests that low engagement and boredom are similar but not identical.

Affective Measures

Arousal and Valence. Emotion was assessed via the intensity (arousal), or energy, and the positive or negative qualities (valence) prescribed. We predicted that these measures would both be associated with more activity within the DMN state. Although these were not similarly rated across participants the DMN and base states occurred during higher arousal ratings, similar to engagement. Further, the SM state occurred the most out of the other states during periods of low arousal, which was also similar to engagement ratings.

The DMN state was the most active of the states, with some activity seen in the base state, when participants prescribed valence ratings more positively. When the SM and DAN states occurred, content tended to be rated more negatively. Although nearly all subjective

measures used in this study could be argued as emotional constructs, we focused on arousal and valence based on previous literature (Hanjalic & Xu, 2005; Koelstra et al., 2012; Du et al., 2020). Our results show that although arousal and valence are rated differently, they are similarly associated with occurrence of the latent states: when the DMN state occurred, followed by the base state, ratings of events were more positive and intense, and when the SM state occurred content was rating more negatively and less arousing. Therefore, our hypothesis was supported, although the SM state was consistently associated with decreased rating.

Narrative Understanding

Comprehension. We hypothesized that the understanding of events would be most related to DMN state occurrence. However, RM-ANOVA results were insignificant. This suggests that individual differences in relation to comprehension contribute more heavily to the differences in latent state occurrences. Although DMN activity was numerically most active during periods of high comprehension, we do not try to interpret these results since the RM-ANOVA was insignificant. Nguyen et al. (2019) found that when individuals have similar interpretations of a story, then their neural activity was more similar. Perhaps our results were not significantly related to latent state activity because comprehension employs numerous latent states at different times for each individual, suggesting that although subjective comprehension ratings may be similar, this is represented differently neurally across individuals.

Importance. As discussed prior, ratings of importance had a similar activation pattern as engagement, arousal, valence, focus, and curiosity. The base state was the most active of the states, followed by the DMN state, when participants rated the content as more important for the plot. While Song et al. (2022) categorized the base state as a transition hub where activity fluctuates between the states, here we can see the benefits of this hub as it switches between

states while events are important, with DMN activity suggesting that throughout this process highly important information is reflected upon and internally represented. However, during SM, and to a lesser degree DAN, state occurrence, importance ratings were lower. This suggests that highly important events may engage internal thought processes, and less important events may demand external analysis of the movie clip as importance is being searched for. Increased SM activity may further be related to low engagement when content is not important. Although our hypothesis was not directly supported, these findings also shed light into the subjective experiences occurring when the base state is active.

Surprise. Contrary to our hypotheses, surprise was higher when the DAN and base states occurred. This is interesting because it shows that subjective surprise is driven by the external environment and requires the rapid transitioning between each of the states. Perhaps this suggests that surprising content makes us curious and causes us to rapidly search for an explanation. Further, when the SM and DMN states occurred participants indicated lower levels of surprise. This suggests that less surprising content results in the internal representation of information until it becomes too surprising and we then analyze the external environment as we search for an explanation.

Curiosity. When the base state occurred participants rated curiosity highly, which contradicted our hypothesis that the DMN state would be active. This is interesting because it suggests that subjective curiosity is related to the consistent transitioning between the latent states. These results were unexpected and shed light into the processes of the base state, suggesting that the base state is modulated by subjective curiosity. Further, when the SM state occurred participants indicated decreased curiosity, which suggests that lower levels of curiosity are experienced similarly to low engagement and low arousal.

Measures of the Self and Others

Social Interaction. We questioned whether the sociality of the movies would relate more to DMN or DAN activity. Our results show that when the DMN state occurred, with some activity of the base state, participants rated higher levels of social interaction. What was not expected was that DAN and SM states would show similar levels of activation when participants indicated lower social interaction ratings. These findings suggest that during periods of perceived social interactions, self-referential processes within the DMN state are activated.

Relatability. Interestingly, DMN state occurrence was not most active when participants indicated higher ratings of relatability. Rather, the SM state was the most active, followed by the DMN state, when participants rated movie content as more relatable. This suggests that, at least in the movie clips tested here, relatable content is less engaging and less arousing, but still requires self-referential processing. Of note, the base state was active when participants indicated lower relatability. This too is intriguing because it suggests that less familiar information may engage the transitioning between states for interpretation.

Overall Findings

Through the analysis of eleven self-reported measures, we were able to provide insight into the relationships between the latent states identified by Song et al. (2022) and subjective experience. First, our findings suggest that the SM state is related to periods of inattention, low arousal, negativity, internal focus, diminished curiosity, importance and surprise, and high levels of relatability and boredom. While we approached this study assuming the SM state was strictly related to low engagement and boredom, these results are understandable. These ratings appear to be associated with one another, with the most surprising finding that relatable content was also characterized alongside these cognitive measures. Although we are wary to draw too many

conclusions, this suggests that individuals may be naturally more privy to attend to ambiguous content.

Although occurrence of the DMN state was not most related to the hypothesized measures, our results provide insight into the conscious experiences during DMN state occurrence. With our results, we see that the DMN and base state are similarly related to high engagement, arousal, and external focus. The DMN is the most active of the states during periods when participants rated the content positively and when there were high levels of social interaction. These results suggest that although DAN is often associated with external processing, these subjective experiences of similar constructs are more related to DMN activations. The classification of importance is intuitively understandable why DMN activity would be most prevalent, as importance ratings result from internally thought-out processing of the external information. However, the other measures provide a more nuanced understanding of how the DMN state is consciously experienced. It is interesting to mention that DMN activity was least active during moments of high curiosity. Future studies should expand on these findings to determine whether these results remain constant across subjective interpretations of experience.

Further, the DAN state was most associated with surprise, although similar activity was seen in the base state. DAN state activity did not appear to be the primary state activated during subjective experiences for majority of the measures, although it typically trended in similar directions as the SM state. This may be interpreted as when the DAN processes external information, individuals are more likely to experience cognitive states associated with the SM state (e.g., low curiosity, negative, internally focused). An exception was seen for surprise and boredom ratings, of which DAN activity was associated with increased surprise and decreased

boredom, while SM activity was related to the opposite. Surprising content may encourage the more active, conscious, analysis of the external environment, while this is also the case for decreased levels of boredom. Further, when the base state occurred it showed similar activation levels, although slightly less than the SM state, when participants rated surprise and boredom. This suggests that when content is boring or surprising, individuals rapidly transition between multiple states.

Our findings also lend insight into how the occurrence of the base state corresponds to subjective experiences. The DMN and base states typically trend in the same direction, with similar intensity as one another, except for when rating reliability and surprise. Most interestingly, curiosity and importance ratings were high, and reliability was low when the base state occurred most. With base state activity more often occurring when participants indicated periods of high curiosity and importance, it suggests that multiple states are needed, and that participants modulate this process while searching for importance and reliability. Future work can test whether subjective measures (e.g., curiosity) are more associated with the base state than objective measures (e.g., importance).

Looking at the correlations between subjective responses aids in the interpretations of the latent state occurrences. Of the measures that were rated similarly (i.e., engagement, arousal, focus, curiosity, importance, and surprise), latent state occurrences showed different patterns when participants rated their level of surprise, while valence was instead associated with a more similar pattern, although it was not similarly rated across participants (**Figure 4**). Further, while boredom and reliability were similarly rated, higher ratings of reliability and lower ratings of boredom the DMN state occurred marginally (**Figure 5B & 5D**). It is interesting to look at the relationship between similarly rated experiences and the latent states because although measures

may be rated similarly, there is some fluctuation in state activation patterns. We encourage future researchers to expand on these findings.

While the current study provides advancements for characterizing how subjective experiences are represented neurally, it does not come without limitations. Primary limitations are the number of participants collected for each measure, the online nature of the behavioral study, and the use of a separate neural dataset. Therefore, future studies should aim to collect a larger sample and either conduct it in person, or include more strict online protocols to control for participant interruptions. Such protocols could include disqualifications if participants exit full screen or switch internet tabs or eye tracking software to ensure attention is on the monitor, or close to it, throughout the entire session. Further, future studies should collect these ratings during neural imaging to confirm these findings. Another interesting question is whether the type of video watched could influence the occurrence of latent states per subjective experience. Future studies should compare ratings during popularized films and documentary-stylized films.

Another open question is whether SM state occurrence is related to head motion, which often accompanies low attentional states. Future work can test this by controlling for mean frame-to-frame head motion in analyses relating subjective experience measures to latent state occurrence. The current project provides just a stepping stone. To advance these findings, future studies could additionally measure physiological responses such as heart rate, skin conductance, or pupil dilation to understand the potential unconscious components contributing to subjective experience. Lastly, future studies should investigate the subjective experiences associated with the latent states with more scrutiny, perhaps utilizing different task procedures and definitions while controlling for adverse variables and collecting neural data from the same participant dataset.

Conclusion

The current study had participants watch movie clips while continuously rating their experience. Responses were compared to one another to ensure consistency in ratings between participants, and then time-matched to fMRI data that was segmented out using hidden markov modeling to identify four common latent neural states. We found that although the DMN state was typically associated with self-referential processing in the literature, engagement, arousal, external focus, positivity, importance, sociality was relatively high when the DMN state occurred and when curiosity was high DMN occurrence was relatively low. DAN latent state activity, which has been associated with externally-driven attention, was associated with subjective experiences of surprise and low levels of boredom. Further, when the DAN state occurred the least, arousal levels were high and relatability was low. These results shed a more nuanced view of what conscious experiences participants have during DMN and DAN latent state occurrence. The SM state occurred most frequently when participants highly rated boredom and relatability, as well as during periods of low engagement, arousal, curiosity, importance, and surprise. The SM state additionally occurred in relation to the negativity of content and internal focus. Lastly, the base state was most active when participants highly rated curiosity and importance and indicated lower relatability. Overall, we show that latent state occurrences are related to specific subjective experiences, providing some insight into how neural activation patterns are experienced consciously. The analysis of latent state activation patterns, therefore, provides a useful mechanism for untangling and interpreting self-reported experiences over time.

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Appendix A

General Instructions
<p>We are interested in how [measure] you find the videos changes over time.</p> <p>Every time how [measure] you find the video changes - even just a little bit - please change the scale bar to match.</p> <p>Your compensation will in part depend on continuously indicating how [measure] you find the videos.</p> <p>As you rate the following videos, make sure you record whenever there is a noticeable increase or decrease in how [measure] you find the video.</p>
Measure Definitions
Engagement
<p>I find the video engaging when...</p> <ul style="list-style-type: none"> - I am curious and excited to know what is coming up next - I am immersed in the story - My attention is focused on the story - The events are interesting <p>I find the video not engaging when...</p> <ul style="list-style-type: none"> - I am bored - Other things pop into my mind, like my daily concerns or personal events - My attention is wandering away from the story - I can feel myself dozing off - The events are not interesting
Arousal
<p>I find myself aroused by the video when...</p> <ul style="list-style-type: none"> - I feel very mentally or physically alert, activated, and/or energized <p>I find myself not aroused by the video when...</p> <ul style="list-style-type: none"> - I feel very mentally or physically slow, still, and/or de-energized
Valence
<p>The video makes me feel positive when...</p> <ul style="list-style-type: none"> - I feel pleasant, happy, and/or excited <p>The video makes me feel negative when...</p> <ul style="list-style-type: none"> - I feel unpleasant, sad, and/or angry
Social Interaction
<p>I find the video completely social when:</p> <ul style="list-style-type: none"> - People are present and interacting meaningfully with each other - The events strongly imply meaningful social interactions, even if no people are present or

<p>only one person is present</p> <p>I find the video somewhat social when:</p> <ul style="list-style-type: none"> - People are present and interacting superficially with each other - The events imply some social interactions, even if no people are present or only one person is present <p>I find the video a little bit social when:</p> <ul style="list-style-type: none"> - People are present, but not interacting with each other - The events imply very little social interaction, even if no people are present or only one person is present <p>I find the video not social at all when</p> <ul style="list-style-type: none"> - People are not present - I do not perceive interactions between people
Focus
<p>My thoughts are directed to the external environment when...</p> <ul style="list-style-type: none"> - I am paying attention to the video - I am paying attention to sights or sounds around me <p>My thoughts are directed internally when...</p> <ul style="list-style-type: none"> - I am paying attention to my own thoughts - I am thinking about the past or future rather than what is happening around me at the present moment - I am not actively paying attention to the video or sights and sounds around me
Curiosity
<p>I feel curious about the video when...</p> <ul style="list-style-type: none"> - I want to know what will happen next - I am interested in figuring out the video's plot - I am eager to know more about what is happening in the video - I am interested in learning more about the characters, objects, places, and/or events <p>I do not feel curious about the video when...</p> <ul style="list-style-type: none"> - I do not care about knowing what will happen next - I am not interested in figuring out the video's plot - I am not eager to know more about what is happening in the video - I am not interested in the characters, objects, places, and/or events
Relatability
<p>The events are personally relatable to me when...</p> <ul style="list-style-type: none"> - I find the events relevant to me personally - I understand the story because it is similar to my own experience - Events in the story remind me of my own experience <p>The events are not personally relatable to me when...</p> <ul style="list-style-type: none"> - I do not find the events relevant to me personally

<ul style="list-style-type: none"> - The events do not remind me of my own experience - I do not feel personally connected to the events
Importance
<p>I find the events important for developing the narrative of the video when...</p> <ul style="list-style-type: none"> - What is happening in the video now is an important part of the story - What is happening now helps me understand the story - What is happening now is critical to the rest of the story - What is happening now affects other events in the story - What is happening now has important causal relationships with other events in the story <p>I find the events not important for developing the narrative of the video when...</p> <ul style="list-style-type: none"> - What is happening now does not appear to be relevant for the story - What is happening now does not help me understand the story - What is happening now is not important in the context of the story
Surprise
<p>I find the video surprising when...</p> <ul style="list-style-type: none"> - I did not expect the events to happen in the video - I did not predict or anticipate the events <p>I find the video not surprising when...</p> <ul style="list-style-type: none"> - I expected the events in the video - I predicted what is happening now based on what I saw in the video
Comprehension
<p>I understand the events when...</p> <ul style="list-style-type: none"> - The events make sense to me - I am not confused by what is happening in the video - I know the significance and/or meaning of the events <p>I do not understand the events at all when...</p> <ul style="list-style-type: none"> - The events do not make sense to me - I am confused by what is happening in the video - I do not know the significance and/or meaning of the events
Boredom
<p>I find the video boring when...</p> <ul style="list-style-type: none"> - The events seem long and repetitive - I am losing interest in the story <p>I find the video not boring when...</p> <ul style="list-style-type: none"> - The events do not seem long and repetitive - I am interested in the story

Instructions and definitions used in the online study. Grammar and measure names were updated as needed for the instructions. Definitions were presented prior to rating the video stimuli.

Appendix B

Clip Comparisons: Ratings, Correlations, and Significance for Each Measure.

Measure	Clip name	Included subjects	Mean pairwise r	p -value	Seen clip before	Mean overall clip ratings
engagement						
	twomen	22	0.329	0.001*	0.00%	55.91
	bridgeville	22	0.028	0.251	0.00%	30.33
	pockets	22	0.057	0.089	0.00%	47.29
	overcome	23	0.476	0.001*	0.00%	64.33
	inception	18	0.575	0.001*	52.17%	87.14
	socialnet	21	0.306	0.001*	43.48%	64.81
	oceans11	20	0.433	0.001*	30.43%	77.52
	testretest	23	-0.032	0.742	0.00%	40.43
	flower	23	0.121	0.007*	0.00%	46.52
	hotel	23	0.202	0.001*	0.00%	48.71
	garden	22	0.028	0.27	0.00%	49.76
	dreary	23	0.231	0.001*	0.00%	42.19
	homealone	21	0.418	0.001*	95.65%	80.71
	brockovich	20	0.007	0.444	21.74%	48.71
	starwars	19	0.124	0.003*	73.91%	49.76
arousal						
	twomen	17	0.424	0.001*	0.00%	42.07
	bridgeville	16	0.109	0.027*	0.00%	34.40
	pockets	17	0.126	0.005*	0.00%	36.73
	overcome	17	0.674	0.001*	0.00%	68.67
	inception	15	0.627	0.001*	70.59%	76.07
	socialnet	16	-0.041	0.771	52.94%	40.20
	oceans11	17	0.02	0.352	35.29%	45.53
	testretest	17	0.019	0.377	0.00%	41.47
	flower	17	0.2	0.001*	0.00%	56.40
	hotel	17	0.245	0.001*	0.00%	57.93
	garden	17	-0.028	0.653	0.00%	45.07
	dreary	17	0.084	0.067	0.00%	39.87
	homealone	17	0.513	0.001*	70.59%	69.93
	brockovich	16	0.035	0.249	23.53%	57.93
	starwars	17	0.302	0.001*	76.47%	45.07
valence						
	twomen	21	0.075	0.022*	0.00%	54.84
	bridgeville	21	0.191	0.001*	0.00%	71.84
	pockets	21	0.132	0.001*	0.00%	57.26

	overcome	20	0.285	0.001*	0.00%	64.84
	inception	19	0.144	0.003*	57.14%	77.32
	socialnet	20	-0.012	0.618	33.33%	60.68
	oceans11	21	0.308	0.001*	28.57%	74.58
	testretest	21	0.073	0.034*	0.00%	53.74
	flower	21	0.209	0.001*	0.00%	65.37
	hotel	21	0.108	0.002*	0.00%	58.26
	garden	21	0.343	0.001*	0.00%	82.68
	dreary	21	0.324	0.001*	0.00%	30.00
	homealone	21	0.134	0.002*	76.19%	72.53
	brockovich	20	0.17	0.001*	19.05%	58.26
	starwars	20	0.257	0.001*	52.38%	82.68
social						
	twomen	18	0.558	0.001*	0.00%	42.53
	bridgeville	17	0.353	0.001*	0.00%	72.53
	pockets	18	0.222	0.001*	0.00%	52.24
	overcome	18	0.588	0.001*	0.00%	40.12
	inception	15	0.44	0.001*	52.63%	82.00
	socialnet	14	0.516	0.001*	21.05%	87.35
	oceans11	15	0.224	0.001*	26.32%	87.18
	testretest	19	0.678	0.001*	0.00%	63.77
	flower	18	0.436	0.001*	5.26%	19.12
	hotel	19	0.562	0.001*	5.26%	44.12
	garden	19	0.383	0.001*	5.26%	67.35
	dreary	18	0.579	0.001*	0.00%	1.94
	homealone	18	0.641	0.001*	89.47%	37.35
	brockovich	15	0.715	0.001*	0.00%	44.12
	starwars	18	0.774	0.001*	52.63%	67.35
focus						
	twomen	24	0.184	0.001*	0.00%	69.23
	bridgeville	24	0.002	0.486	0.00%	50.82
	pockets	23	0.019	0.271	0.00%	61.05
	overcome	23	0.506	0.001*	0.00%	73.18
	inception	23	0.052	0.016*	45.83%	82.50
	socialnet	23	0.115	0.001*	29.17%	65.50
	oceans11	23	0.172	0.001*	29.17%	74.55
	testretest	24	0.011	0.338	0.00%	56.82
	flower	24	0.148	0.002*	0.00%	63.46
	hotel	24	0.091	0.005*	0.00%	69.46
	garden	23	0.026	0.111	0.00%	31.18
	dreary	23	-0.016	0.699	0.00%	49.41
	homealone	24	0.014	0.289	91.67%	69.23
	brockovich	20	0.302	0.001*	29.17%	69.46

	starwars	24	0.102	0.001*	62.50%	61.18
curiosity						
	twomen	18	0.322	0.001*	0.00%	46.18
	bridgeville	18	0.179	0.001*	0.00%	28.06
	pockets	19	0.019	0.332	0.00%	44.88
	overcome	19	0.433	0.001*	0.00%	66.18
	inception	18	0.421	0.001*	26.32%	83.82
	socialnet	17	0.154	0.008*	31.58%	62.71
	oceans11	18	0.149	0.003*	10.53%	74.41
	testretest	19	-0.012	0.565	0.00%	33.82
	flower	19	0.107	0.004*	0.00%	47.94
	hotel	19	0.36	0.001*	0.00%	69.77
	garden	16	0.152	0.007*	0.00%	34.77
	dreary	19	0.298	0.001*	0.00%	40.71
	homealone	18	0.13	0.002*	63.16%	65.12
	brockovich	19	0.012	0.408	15.79%	69.77
	starwars	18	0.151	0.003*	57.89%	34.77
reliability						
	twomen	20	0.064	0.014*	0.00%	49.53
	bridgeville	21	0.1	0.001*	0.00%	53.32
	pockets	21	0.168	0.001*	0.00%	46.16
	overcome	21	0.237	0.001*	0.00%	41.21
	inception	19	0.053	0.041*	57.14%	29.00
	socialnet	20	0.154	0.001*	28.57%	35.53
	oceans11	20	0.267	0.001*	19.05%	18.37
	testretest	21	0.08	0.002*	0.00%	49.68
	flower	20	0.128	0.001*	0.00%	45.11
	hotel	21	0.04	0.115	0.00%	38.32
	garden	21	0.025	0.162	0.00%	50.47
	dreary	21	0.231	0.001*	0.00%	30.84
	homealone	21	0.147	0.001*	76.19%	61.16
	brockovich	21	0.08	0.002*	14.29%	38.32
	starwars	19	0.096	0.003*	57.14%	50.47
importance						
	twomen	22	0.336	0.001*	0.00%	70.75
	bridgeville	22	0.166	0.001*	0.00%	61.15
	pockets	22	0.175	0.001*	0.00%	59.55
	overcome	22	0.611	0.001*	0.00%	60.80
	inception	21	0.238	0.001*	63.34%	87.10
	socialnet	22	0.281	0.001*	31.82%	68.10
	oceans11	21	0.361	0.001*	36.37%	78.25
	testretest	22	0.063	0.017*	0.00%	15.95
	flower	22	0.633	0.001*	0.00%	62.90

	hotel	22	0.21	0.001*	0.00%	44.25
	garden	22	0.199	0.001*	0.00%	77.70
	dreary	22	0.17	0.001*	0.00%	15.70
	homealone	20	0.282	0.001*	72.73%	76.65
	brockovich	21	0.286	0.001*	9.09%	44.25
	starwars	22	0.217	0.001*	72.73%	77.70
surprise						
	twomen	19	0.234	0.001*	0.00%	55.39
	bridgeville	20	0.237	0.001*	0.00%	19.44
	pockets	19	0.071	0.006*	0.00%	50.17
	overcome	20	0.636	0.001*	0.00%	74.06
	inception	20	0.499	0.001*	55.00%	76.89
	socialnet	20	0.019	0.282	60.00%	36.33
	oceans11	16	0.046	0.131	40.00%	46.17
	testretest	20	0.186	0.001*	0.00%	60.89
	flower	20	0.213	0.001*	0.00%	53.89
	hotel	20	0.256	0.001*	0.00%	57.33
	garden	19	0.105	0.012*	0.00%	30.89
	dreary	19	0.129	0.001*	0.00%	34.94
	homealone	20	0.011	0.42	75.00%	39.28
	brockovich	20	0.023	0.198	20.00%	57.33
	starwars	19	0.44	0.001*	35.00%	30.89
comprehension						
	twomen	18	0.142	0.011*	0.00%	53.78
	bridgeville	18	0.529	0.001*	0.00%	84.78
	pockets	19	0.53	0.001*	0.00%	79.17
	overcome	20	0.153	0.001*	0.00%	67.50
	inception	16	0.053	0.192	40.00%	65.78
	socialnet	18	0.341	0.001*	30.00%	78.33
	oceans11	19	0.636	0.001*	40.00%	88.39
	testretest	19	0.284	0.001*	0.00%	22.67
	flower	17	0.364	0.001*	0.00%	61.89
	hotel	20	0.075	0.049*	0.00%	39.17
	garden	17	0.679	0.001*	0.00%	96.89
	dreary	20	0.265	0.001*	0.00%	20.44
	homealone	17	0.218	0.001*	75.00%	91.17
	brockovich	19	0.231	0.001*	20.00%	39.17
	starwars	16	0.381	0.001*	50.00%	96.89
boredom						
	twomen	18	0.272	0.001*	0.00%	51.00
	bridgeville	20	0.073	0.029*	0.00%	64.21
	pockets	20	0.107	0.009*	0.00%	45.37
	overcome	21	0.686	0.001*	0.00%	31.53

	inception	20	0.406	0.001*	61.90%	10.90
	socialnet	21	0.073	0.066	38.10%	46.11
	oceans11	19	0.04	0.153	23.81%	32.95
	testretest	21	-0.048	0.828	0.00%	52.37
	flower	20	0.09	0.022*	0.00%	47.21
	hotel	20	0.257	0.001*	0.00%	38.42
	garden	21	-0.037	0.825	0.00%	53.26
	dreary	20	0.116	0.002*	0.00%	56.26
	homealone	20	0.285	0.001*	80.95%	22.53
	brockovich	21	0.239	0.001*	19.05%	38.42
	starwars	20	0.137	0.001*	61.90%	53.26

Comprehensive outline of the number of subjects used for analyses, correlation and significance ratings, and overall clip ratings for each measure between subjects for each measure across all video clips. The percentage of subjects who have seen the video clip reflects all collected subjects. Mean overall clip ratings ranged from 0 - 100.

* p -values were calculated via one-tailed testing with significance at $\alpha=0.05$

Appendix C

Movie 1				
	twomen	bridgeville	pockets	overcome
engagement	F(3,114) = 2.1643, $p = 0.0920$			F(3,81) = 11.3812, $p < 0.0001^*$
arousal	F(3,114) = 2.5550, $p = 0.0553$	F(3,117) = 4.2886, $p = 0.0054^*$	F(3,116) = 25.0899, $p < 0.0001^*$	F(3,81) = 13.7056, $p < 0.0001^*$
valence	F(3,114) = 5.5609, $p = 0.0010^*$	F(3,117) = 0.2413, $p = 0.8675$	F(3,116) = 2.2508, $p = 0.0822$	F(3,81) = 4.1009, $p = 0.0073^*$
social	F(3,114) = 16.6850, $p < 0.0001^*$	F(3,117) = 29.6582, $p < 0.0001^*$	F(3,116) = 20.7324, $p < 0.0001^*$	F(3,81) = 8.5294, $p < 0.0001^*$
focus	F(3,114) = 2.8066, $p = 0.0397^*$			F(3,81) = 12.6402, $p < 0.0001^*$
curiosity	F(3,114) = 8.5859, $p < 0.0001^*$	F(3,117) = 12.4933, $p < 0.0001^*$		F(3,81) = 12.6274, $p < 0.0001^*$
reliability	F(3,114) = 1.6914, $p = 0.1686$	F(3,117) = 20.3122, $p < 0.0001^*$	F(3,116) = 1.9172, $p = 0.1265$	F(3,81) = 10.0235, $p < 0.0001^*$
importance	F(3,114) = 3.6768, $p = 0.0124$	F(3,117) = 40.5175, $p < 0.0001^*$	F(3,116) = 35.7935, $p < 0.0001^*$	F(3,81) = 12.0203, $p < 0.0001^*$
surprise	F(3,114) = 6.8143, $p = 0.0002^*$	F(3,117) = 3.7294, $p = 0.0116^*$	F(3,116) = 8.6351, $p < 0.0001^*$	F(3,81) = 14.2125, $p < 0.0001^*$
comprehension	F(3,114) = 32.5268, $p < 0.0001^*$	F(3,117) = 0.2565, $p = 0.8567$	F(3,116) = 0.4275, $p = 0.7334$	F(3,81) = 1.4177, $p = 0.2382$
boredom	F(3,114) = 4.3597, $p = 0.0050^*$	F(3,117) = 14.6096, $p < 0.0001^*$	F(3,116) = 25.8407, $p < 0.0001^*$	F(3,81) = 12.4448, $p < 0.0001^*$
Movie 2				
	inception	socialnet	oceans11	testretest
engagement	F(3,109) = 27.9569, $p < 0.0001^*$	F(3,115) = 27.1625, $p < 0.0001^*$	F(3,118) = 58.7496, $p < 0.0001^*$	
arousal	F(3,109) = 30.4730, $p < 0.0001^*$			
valence	F(3,109) = 57.5704, $p < 0.0001^*$		F(3,118) = 46.5080, $p < 0.0001^*$	F(3,98) = 12.3022, $p < 0.0001^*$
social	F(3,109) = 122.6955, $p <$ 0.0001*	F(3,115) = 35.4492, $p < 0.0001^*$	F(3,118) = 41.6863, $p < 0.0001^*$	F(3,98) = 10.2500, $p < 0.0001^*$
focus	F(3,109) = 36.7788, $p < 0.0001^*$	F(3,115) = 26.3644, $p < 0.0001^*$	F(3,118) = 50.9969, $p < 0.0001^*$	
curiosity	F(3,109) = 36.9268, $p < 0.0001^*$	F(3,115) = 11.4908, $p < 0.0001^*$	F(3,118) = 62.0340, $p < 0.0001^*$	
reliability	F(3,109) = 59.5005, $p < 0.0001^*$	F(3,115) = 34.7028, $p < 0.0001^*$	F(3,118) = 57.5747, $p < 0.0001^*$	F(3,98) = 9.3904, $p < 0.0001^*$
importance	F(3,109) = 30.6131, $p < 0.0001^*$	F(3,115) = 29.5693, $p < 0.0001^*$	F(3,118) = 67.4481, $p < 0.0001^*$	F(3,98) = 0.9644, $p = 0.4099$
surprise	F(3,109) = 40.6420,			F(3,98) = 2.8971,

	$p < 0.0001^*$			$p = 0.0354^*$
comprehension		$F(3,115) = 15.8958,$ $p < 0.0001^*$	$F(3,118) = 45.1834,$ $p < 0.0001^*$	$F(3,98) = 16.0884,$ $p < 0.0001^*$
boredom	$F(3,109) = 47.7955,$ $p < 0.0001^*$			
Movie 3				
	flower	hotel	garden	dreary
engagement	$F(3,109) = 16.1999,$ $p < 0.0001^*$	$F(3,114) = 35.7622,$ $p < 0.0001^*$		$F(3,114) = 10.8735,$ $p < 0.0001^*$
arousal	$F(3,109) = 17.1298,$ $p < 0.0001^*$	$F(3,114) = 37.4644,$ $p < 0.0001^*$		
valence	$F(3,109) = 35.6488,$ $p < 0.0001^*$	$F(3,114) = 12.9855,$ $p < 0.0001^*$	$F(3,117) = 19.4629,$ $p < 0.0001^*$	$F(3,114) = 2.0145,$ $p = 0.1116$
social	$F(3,109) = 41.0066,$ $p < 0.0001^*$	$F(3,114) = 42.1387,$ $p < 0.0001^*$	$F(3,117) = 31.2978,$ $p < 0.0001^*$	$F(3,114) = 0.7275,$ $p = 0.5362$
focus	$F(3,109) = 33.1165,$ $p < 0.0001^*$	$F(3,114) = 49.0170,$ $p < 0.0001^*$		
curiosity	$F(3,109) = 16.4159,$ $p < 0.0001^*$	$F(3,114) = 93.4643,$ $p < 0.0001^*$	$F(3,117) = 39.9569,$ $p < 0.0001^*$	$F(3,114) = 8.5725,$ $p < 0.0001^*$
relatability	$F(3,109) = 18.1386,$ $p < 0.0001^*$			$F(3,114) = 1.7636,$ $p = 0.1539$
importance	$F(3,109) = 15.5046,$ $p < 0.0001^*$	$F(3,114) = 70.7456,$ $p < 0.0001^*$	$F(3,117) = 48.2043,$ $p < 0.0001^*$	$F(3,114) = 5.3177,$ $p = 0.0014^*$
surprise	$F(3,109) = 8.1937,$ $p < 0.0001^*$	$F(3,114) = 60.8179,$ $p < 0.0001^*$	$F(3,117) = 49.9805,$ $p < 0.0001^*$	$F(3,114) = 5.4259,$ $p = 0.0012^*$
comprehension	$F(3,109) = 11.1843,$ $p < 0.0001^*$	$F(3,114) = 89.2236,$ $p < 0.0001^*$	$F(3,117) = 21.9152,$ $p < 0.0001^*$	$F(3,114) = 0.9710,$ $p = 0.4065$
boredom	$F(3,109) = 29.4195,$ $p < 0.0001^*$	$F(3,114) = 35.6558,$ $p < 0.0001^*$		$F(3,114) = 11.3052,$ $p < 0.0001^*$
Movie 4				
	homealone	brockovich	starwars	
engagement	$F(3,116) = 30.7166,$ $p < 0.0001^*$		$F(3,117) = 5.0066,$ $p = 0.0021^*$	
arousal	$F(3,116) = 28.3827,$ $p < 0.0001^*$		$F(3,117) = 15.8043,$ $p < 0.0001^*$	
valence	$F(3,116) = 11.3171,$ $p < 0.0001^*$	$F(3,115) = 19.2769,$ $p < 0.0001^*$	$F(3,117) = 5.6236,$ $p = 0.0009^*$	
social	$F(3,116) = 35.5224,$ $p < 0.0001^*$	$F(3,115) = 5.3229,$ $p = 0.0013^*$	$F(3,117) = 22.8435,$ $p < 0.0001^*$	
focus		$F(3,115) = 6.6350,$ $p = 0.0002^*$	$F(3,117) = 3.1319,$ $p = 0.0257^*$	
curiosity	$F(3,116) = 25.3879,$ $p < 0.0001^*$		$F(3,117) = 25.2120,$ $p < 0.0001^*$	
relatability	$F(3,116) = 22.3346,$	$F(3,115) = 5.6374,$	$F(3,117) = 8.7689,$	

	$p < 0.0001^*$	$p = 0.0009^*$	$p < 0.0001^*$	
importance	F(3,116) = 13.7355, $p < 0.0001^*$	F(3,115) = 0.2034, $p = 0.8940$	F(3,117) = 2.4749, $p = 0.0613$	
surprise			F(3,117) = 31.5901, $p < 0.0001^*$	
comprehension	F(3,116) = 24.2563, $p < 0.0001^*$	F(3,115) = 11.5695, $p < 0.0001^*$	F(3,117) = 7.8537, $p < 0.0001^*$	
boredom	F(3,116) = 32.1942, $p < 0.0001^*$	F(3,115) = 13.7633, $p < 0.0001^*$	F(3,117) = 10.3854, $p < 0.0001^*$	

Repeated-measures one-way ANOVA results between the four latent states from all individual clips with significant inter-clip participant ratings. Split between the four movie blocks as shown to the HMM sample. The number of subjects varied as some HMM participants did not have activity in all four latent states and were therefore not included in this analysis.

* p -values are significant at $\alpha=0.05$