Resilience-driven neural synchrony during naturalistic movie watching: an ultra-high field fMRI study

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Abstract

Sharing others' emotional states may facilitate the understanding of their well-being characteristics, such as resilience. Here, we showed that a variety of brain networks in participants who viewed emotional movies are synchronized among those with higher resilience scores. Brain activity was measured in healthy young adults while they naturally watched two movies, one with negative and one with neutral emotional valence, in the 7T MRI scanner. Inter-subject correlation and inter-subject representational similarity analyses were used to investigate the association between resilience and brain-to-brain synchrony while watching movies. The modulation effect of intolerance of uncertainty (IU), a personality trait that shapes biased perception and cognition, on the association between resilience and neural synchrony, was also explored. Resilience-driven neural synchrony was found in a wider set of brain regions including the default mode network, control network, and dorsal attentional network, in response to the negative movie compared to the neutral movie. High-resilience individuals had similar neural activities to their peers, while low-resilience individuals showed more variable neural activities. Additionally, IU modulated resilience-driven neural synchrony differently depending on the emotional stimuli. We propose that similar neural responses in resilient individuals signify their aligned adaptive emotion processing, which facilitates social understanding and connections among them. Conversely, the variability in neural responses indicates vulnerability to adverse psychological outcomes, potentially associated with maladaptive emotional responses and regulation. These findings provide insights into the mechanisms of resilience — by maintaining similar selective attention, inhibitory control, and social cognitive functioning, to ultimately foster a shared understanding of negative events.

Introduction

Traumatic and highly stressful events, which occur with frequency in today's world, pose a significant threat to individuals' psychological well-being. These events can profoundly impact mental health, leading to distress, anxiety, and various psychological challenges[1,2]. Psychological resilience, the ability to cope effectively with adversities, plays a crucial role in determining individuals' overall well-being[3]. It empowers people to maintain a positive outlook, regulate emotions, and engage in effective problem-solving when faced with adversity, thus providing protection against negative consequences[4–6].

Individual differences in resilience are closely linked to how individuals perceive and process external stimuli[7,8]. For instance, individuals with higher resilience tend to report more positive emotional experiences[9], demonstrate quicker disengagement from emotional stimuli[10], and employ adaptive emotional regulation strategies more effectively[11]. Accumulating evidence from imaging studies has suggested that these inter-individual differences in resilience may arise from functional variations in brain regions involved in salience detection, emotion regulation, and cognitive control[12,13]. The activity in key regions like the prefrontal cortex, amygdala, and insula, which play crucial roles in emotional processing and salience detection, has consistently been identified as neural markers of resilience[14,15].

Previous studies investigating resilience and its neural correlates have primarily relied on resting-state[16,17] or highly controlled tasks[18–20]. While these approaches offer valuable insights into underlying neural mechanisms, their replicability and ecological validity are limited[21]. In contrast to these traditional paradigms, naturalistic design, such as movie functional Magnetic Resonance Imaging (fMRI), can capture the complexity and dynamics of real-world experiences, providing a unique opportunity to investigate how the human brain processes stimuli in an unconstrained manner while overcoming the limitations of resting-state and task fMRI designs[22,23]. When viewing movies, synchronized brain activities, measurable through inter-subject correlation (ISC), occur among audiences[24], indicating similarity in neural responses to the naturalistic stimuli and ultimately producing similar interpretations of the content[25]. Movie fMRI holds promise in capturing the dynamic process and characterizing resilience along with its neural correlates, as movies provide a real-life setting with multi-modal stimuli that could reveal individual differences in resilience more robustly than resting state or highly controlled tasks.

Individuals with high resilience may share similar ways of perceiving and processing external stimuli[9,11]. Such similarities may be reflected in their neural responses. However, no study to date has explored whether the behavioral similarities observed in resilient individuals can be reflected in their brain activity in naturalistic settings. Previous research involving movie-fMRI in the context of psychiatric disorders has shown a decrease in the similarity of neural responses among patients with attention deficits and hyperactivity disorder[26], schizophrenia[27],and depression[28]. Furthermore, recent investigations have suggested individuals who are socially well-connected tend to exhibit similar brain activity patterns while watching movies[29,30], highlighting that social connections are highly associated with resilience[31,32]. Drawing from these findings, it is reasonable to infer that convergent or similar neural activities may serve as indicators of good mental states and psychological well-being (i.e., high resilience). Conversely, divergence or dissimilarity in neural responses may signal vulnerability to negative psychological consequences (i.e., low resilience). This pattern is in line with the Anna Karenina (AnnaK) model[33]. The AnnaK model draws inspiration from the opening line of Leo Tolstoy's *Anna Karenina* novel, stating all happy families are alike; but each unhappy family is unhappy in its own way. In the context of the current study, we predict that individuals with high scores on a certain measure (i.e., high- resilience individuals) are similar in their responses, while individuals with low scores (i.e., low-resilience individuals) differ from each other in their own responses to naturalistic movies[34].

Multiple psychosocial factors have been proposed to underlie the extent to which individuals are affected by environmental events[35,36], one of which the is the ability to tolerate uncertainty[37]. Intolerance of uncertainty (IU) is a dispositional characteristic indicating a tendency to avoid uncertainty and harbor negative beliefs about ambiguous or uncertain situations[38]. Mounting evidence have documented that IU plays a vital role in shaping emotional perceptions and modulating

emotional responses[39–41]. Consistent evidence from empirical studies across diverse samples demonstrated a negative association between IU and resilience[42–44]. However, this is the first study, to our knowledge, that will investigate how IU modulates resilience and its underlying neural correlates during movie-fMRI.

In the present study, we set out to address these gaps in the literature by examining the relationships between resilience and IU during naturalistic movie watching. Sixty-two younger adults from the local community were enrolled in the current study. We presented two types of emotionally-driven movie clips, including neutral and negative contents, allowing participants to watch the movie naturally, while they underwent brain imaging using an ultra-high field 7T MRI scanner (**Fig. 1a&b**). Our main objectives are twofold: first, to use intersubject representational similarity analysis (IS-RSA), an innovative approach that could robustly detect individual differences and the underlying brain dynamics in naturalistic settings[34], to examine the influence of resilience on individuals' neural responses towards naturalistic stimuli. We hypothesize that individuals with high resilience will display more consistent neural responses, , whereas those with low resilience will exhibit more idiosyncratic neural responses, especially when viewing negatively valenced movies. Second, we aim to investigate the role of IU in the relationship between resilience and neural synchrony during movie-fMRI in both negative and neutral movie conditions. We expect that IU will modulate the neural synchrony that is driven by resilience and this effect may vary depending on the emotional content of the movies.

Results

Behavioral results

Participants reported their emotional valence and arousal levels before and after each movie clip. After watching the neutral movie, no significant changes were observed in emotional valence (t = 0.095, df = 61, p = 0.925, d = 0.012) and arousal (t = 0.375, df = 61, p = 0.709, d = 0.048) compared with the baseline, prior to watching the movie. However, after watching the negative movie, compared to the neutral clip, a significant decrease in valence (t = -9.193, df = 61, p < 0.001, d = 1.167) and an increase in arousal (t = 7.298, df = 61, p < 0.001, d = 0.927) were observed (**Fig. 2**). These results demonstrate the validity of our naturalistic stimuli.

Furthermore, we didn't find significant correlations between resilience score and emotion ratings and alteration of emotional status ($\text{valence}_{\text{baseline}}$: r = 0.228, p = 0.075; $\text{valence}_{\text{neutral}}$: r = 0.067, p = 0.605; $\text{valence}_{\text{negative}}$: r = -0.010; p = 0.936; valuence $\Delta_{\text{neutral-baseline}}$: r = -0.164, p = 0.203; valuence $\Delta_{\text{negative-neutral}}$: r = -0.052, p = 0.689; $\text{arousal}_{\text{baseline}}$: r = 0.147, p = 0.254; $\text{arousal}_{\text{neutral}}$: r = -0.067, p = 0.948; $\text{arousal}_{\text{negative}}$: r = 0.049; p = 0.707; arousal $\Delta_{\text{neutral-baseline}}$: r = -178, p = 0.167; arousal $\Delta_{\text{negative-neutral}}$: r = 0.047, p = 0.715).

Full list of zero-order correlations of resilience (measured by the Connor-Davidson Resilience Scale), IU (measured by the Intolerance of Uncertainty Scale), and related questionnaire, including depression, anxiety, stress, and emotion regulation difficulties are presented in the **SI Appendix, Tables S1**. Resilience was negatively correlated with IU, anxiety, depression, and perceived stress. Moreover, negative associations were found between resilience and multiple difficulties in emotion regulation, including nonacceptance of emotional response, lack of emotional awareness, limited access to emotion regulation strategies, and lack of emotional clarity. The results suggest that low resilience may imply a higher risk of mood disorders, and it is related to various difficulties in emotion regulation which signifying different emotional and cognitive dysfunctions.

Negative movie elicits stronger neural synchrony

To test whether both neutral and negative movies elicited robust neural synchrony across all participants, we calculated the participant-level ISC for each brain region by correlating the BOLD signal time series of each participant with the mean BOLD signal time series of the rest of the participants (**Fig. 1e**). Here, we divided the whole brain into 216 regions, including 200 cortical areas and 16 subcortical regions (see the method section for more details).

The results indicated robust overall brain synchrony for both movies, with the strongest effects in auditory and visual brain areas (**SI Appendix, Fig. S3a**). Higher ISC values were observed in the

temporal lobe, prefrontal cortex, posterior cingulate cortex, precuneus, and subcortical areas (such as the hippocampus, amygdala, and caudate) during the negative movie compared to neutral movie (**SI Appendix, Fig. S3b** and **SI Appendix, Table S2**). Overall, participants exhibited higher levels of brain synchrony during the negative condition compared to the neutral condition (mean ISC of neutral movie = 0.191, mean ISC of negative movie = 0.291, t = 23.255, df = 217, p < 0.001, d = 1.582, **SI Appendix, Fig. s3c**). Additionally, the spatial distribution of neural synchrony was highly correlated across two conditions (r = 0.832, p < 0.001, **SI Appendix Fig. s3d**), suggesting a stable functional organization in response to naturalistic stimuli regardless of movies' emotional content.

Resilience drives neural synchrony in a convergent way

To test the first hypothesis that whether naturalistic stimuli elicited higher neural similarity in individuals depending on their resilience scores, we compared high and low resilience individuals by conducting the IS-RSA with dyad-level ISC (**Fig.1d**). The dyad-level ISC was calculated for each dyad (pair of participants) to indicate pairwise brain synchrony during movie-watching (see the method section for more details).

Participants were divided into two groups based on their resilience scores, resulting in three types of dyads based on the resilience group membership of the pairs: {high, high}, {high, low}, and {low, low} (**Fig. 3a**). The results of three contrasts (i.e., $ISC_{\{high, high\}} > ISC_{\{low, low\}}$, $ISC_{\{high, high\}} > ISC_{\{high, low\}}$, and $ISC_{\{high, low\}} > ISC_{\{low, low\}}$) for the neutral and negative conditions are illustrated in the **Fig. 3b.** Following False discovery rate (FDR) multiple comparison correction, in the neutral movie, ISCs of the postcentral gyrus, frontal eye fields, and ventral prefrontal cortex were higher in {high, high} dyads compared to the {low, low} dyads. We also found higher ISCs of the postcentral gyrus, lateral prefrontal cortex, and frontal eye fields in the {high, high} dyads than {high, low} dyads. No significant results were found in the comparison of {high, low} and {low, low} dyads (**SI Appendix, Tables. S3-S5**).

Similar patterns were observed in the negative movie, but the group differences in ISC were found across a broader set of brain areas in all contrasts. In other words, higher ISCs of multiple brain regions that mainly anchored in the dorsal attention network(DAN), control network (CN), and default mode network(DMN) were found in the {high, high} dyads than {low, low} and {high, low} dyads during the negative movie. Moreover, ISCs of several brain regions including the visual cortex, inferior parietal lobe, lateral prefrontal cortex, and postcentral gyrus showed differences between {high, low} dyads and {low, low} dyads (**SI Appendix, Tables. S8-S10**).

Taken together, higher neural synchrony was found in dyads of high-resilience pairs {high, high} compared to dyads of low-resilience pairs {low, low} or mixed pairs {high, low} during viewing both neutral and negative movies, suggesting that individuals with high resilience exhibit more consistent neural responses when compared to their peers. In contrast, individuals with low resilience display more variable neural responses among themselves.

To investigate the relationship between brain synchrony and resilience further, we performed the second IS-RSA that used resilience similarity to predict dyad-level ISC. The calculation of resilience similarity for each pair of participants follows the AnnaK model, where we extracted the minimum resilience score for each dyad (**Fig. 3c**). Thus, only pairs of high-resilience individuals show high similarity (i.e., high-resilience individuals are alike), while pairs of low-resilience or mixed pairs (a pair consists of one with low resilience and one with high resilience) are always described as having low similarity (i.e., low resilience individuals are different from their peers as well as high-resilience individuals).

The results demonstrated that resilience similarity significantly predicted neural synchrony in several brain regions, including the postcentral gyrus, frontal eye fields, and inferior parietal area, while participants were viewing the neutral movie (**Fig. 3d**; **SI Appendix, Table. S6**). Notably, many of these observed brain regions are core components of the DAN. For the negative movie, we found a positive association between resilience similarity and neural synchrony in brain areas that are involved in multiple brain networks including DMN (Inferior parietal lobe, posterior cingulate cortex, and precuneus), DAN (frontal eye field, postcentral gyrus, superior parietal lobule), CN (lateral prefrontal cortex and intraparietal sulcus), SMN, and VN (**SI Appendix, Table. S11**). Similar to the

findings of the first IS-RSA using the binarized resilience category, there was greater neural synchrony in individuals with higher resilience. That is, higher resilience contributes to more convergent brain responses.

Besides using IS-RSA, we additionally examined whether high-resilience individuals exhibited more typical neural responses than low-resilience individuals by fitting a general linear model (GLM) for each brain region. In this model, the resilience score was used as a predictive variable, and mean ISC served as the outcome variable. However, no significant results survived FDR correction. The uncorrected results are reported in **SI Appendix, Fig. S2**.

Intolerance of Uncertainty modulates resilience-driven neural synchrony

We tested our second hypothesis regarding the influence of IU on resilience-driven brain synchrony by performing the third IS-RSA, which introduces the interaction of resilience similarity and joint IUS, into the analysis. Here, the joint IUS, which is computed as the product of the IUS score of each pair of participants, indicates both the similarity of IUS between two individuals within the dyads and the absolute position of the dyad members on the IU spectrum.

We found that the resilience-IU interaction significantly predicted neural synchrony during the neutral movie in the regions that functionally associated with motor-sensory (e.g., precentral gyrus), spatial attention (e.g., intraparietal sulcus and superior parietal lobule), face recognition (e.g., temporal areas) functions (**Fig. 4a**; **SI Appendix, Table. S7** for list of regions). Our results indicated increased IU attenuated the positive association between neural synchrony and resilience similarity in these areas. Intriguingly, divergent results were revealed during the negative movie clip. We found that the resilience-IU interaction positively predicted ISC in dorsomedial prefrontal cortex, ventral prefrontal cortex, posterior cingulate cortex, precuneus, inferior parietal lobe, and insula (**Fig. 4b**; **SI Appendix, Table. S12** for list of regions) during the negative movie. This suggested that increased IU enhances the predictive ability of resilience similarity on neural synchrony of core regions of the DMN. Similar to the neutral movie, we found the resilience-IU interaction negatively predicted neural synchrony in motor- and attention-related areas (e.g., primary motor sensory cortex, postcentral gyrus, and intraparietal sulcus) during the negative movie. Taken together, these findings indicate the modulation effect of IU on the resilience-driven brain synchrony, and the effect may differ in stimuli with different emotional contents.

Discussion

Resilient individuals demonstrate the capacity to effectively cope with the negative impact of events and maintain their mental well-being[4]. This ability is likely linked to their adaptive approach to perceiving and processing emotional information[45–47]. In this study, we aimed to investigate the potential connection between individual differences in resilience and neural responses to ecologically valid emotional stimuli. To achieve this, we combined movie-fMRI and IS-RSA using an ultra-high field 7T MRI scanner. Our findings confirmed the hypothesis that individuals with high resilience exhibit synchronized neural responses, while those with low resilience display divergent neural responses to external stimuli. Furthermore, we found that IU, a trait associated with cognitive biases toward uncertainty, modulated resilience-driven neural synchrony.

In this study, we have identified a convergent pattern of brain synchrony impacted by resilience traits. This pattern aligns with the AnnaK model, which is commonly used to explain the vulnerability of multi-component systems[34,48]. According to this model, the dysfunction of the systems occurs when there are deficits in any of the necessary components. In the context of current study, the system refers to the entirety of emotional stimulus processing. To prevent imbalanced mental health after exposure to negative stimuli, the entire chain of emotional processing, including perception, evaluation, integration, and regulation, must be shaped adaptively[49,50]. Resilient individuals sustain adaptability throughout each stage or component of the processing, ultimately leading to successful responses to negative events. Conversely, malfunctioning of any stage or component of the processing may contribute to the risk of mental health disorders, and the risk may accumulate with an increasing number of failures within the process. Our behavioral results, which indicate a negative correlation between the resilience score and various emotion regulation difficulties, corroborate this

assertion. For instance, non-acceptance of emotional responses has been linked to hyperarousal symptoms and abnormal social-emotional evaluation[51,52], and lack of emotional clarity has been associated with impairment in emotion recognition and self-referential processing[53,54]. Our findings thus explain that resilient individuals can effectively maintain their mental health, while individuals with low resilience are more susceptible to various mental disorders[55,56] and emotion dysregulation[57,58].

Furthermore, we observed resilience-driven brain synchrony in brain areas that are anchored in the DAN. The DAN is responsible for top-down attentional processing, which involves regulating the perception of external stimuli based on expectations and goals[59,60]. In a naturalistic movie-watching setting, top-down attention enhances attention from specific perspective, aids to gather relevant information, and allows the information to spread across brain networks[61]. Consequently, the brain synchrony observed in the DAN may reflect the aligned neural encoding of external stimuli[62], implying a similar perspective that participants took during movie watching. As the emotional intensity of stimuli increased, during the negative movie clip, the resilience-driven brain synchrony engages other brain networks including the DMN and CN. Empirical evidence suggested that the high neural similarity of DMN and CN indicates shared narrative interpretation among audiences[63]. The DMN is reported as a key network in social cognition, and one of its core functions is to respond to the actions of other social agents and characterize interpersonal interactions[64]. Previous studies found that the increased DMN functional coupling between speaker and listener predicted a more similar understanding of the story between them[65]. Meanwhile, the CN is wildly implicated in cognitive control and emotion regulation, which is fundamental for facilitating the understanding of events[66,67]. Hence, the emotional narrative in the movie elicited similar responses in these brain networks, and this neural synchrony was affected by resilience traits among individuals. High brain synchrony within these two networks suggests a similarity in their interpretation of the movie among resilient individuals, possibly stemming from their similarity in emotional regulation and evaluation when processing emotional stimuli. Simultaneously, we observed brain synchrony in regions anchored in visual and sensorimotor network. This finding may be related to coordinated physiological responses to emotional stimuli by high-resilience individuals, manifesting similarity of action tendencies of facial expressions, eye movement, and body gestures[68]. Based on these findings, we speculate that resilience reflects the overall adaptability of emotional functions, which require coordination amongst multiple networks mainly including the DAN, DMN, and CN.

The current findings align with previous research indicating that resilience involves multiple brain networks and is closely intertwined with emotional processing. Building upon these neuroimaging discoveries and recognizing the intricate nature of emotional processes to negative events, it is prudent to consider resilience as an ongoing and dynamic neural process that encompasses dimensions of emotion, cognition, and attention[68]. This dynamicity characteristic is well manifested while participants engage in processing naturalistic stimuli that unfold over time. Importantly, through naturalistic movie-watching, we have identified that differences in individual resilience are associated with the engagement of multiple brain networks critical for social evaluation, emotion regulation, and attention orientation when encoding naturalistic movies with emotional valence. While our study did not specifically focus on emotional recognition, it extends previous hypotheses about emotions, such as the constructionist approach[69,70], to naturalistic movies, which posits that different brain networks are involved in processing emotional cues. Therefore, future studies should incorporate more naturalistic movies to test hypotheses and models of emotions, aiming to examine the generalizability of existing models to more dynamic and natural stimuli.

Additionally, we made a noteworthy discovery that IU plays a role in modulating resilience-driven brain synchrony. Specifically, when participants were exposed to a neutral movie, increased IU led to a reduction in resilience-driven brain synchrony, primarily in brain regions belong to the SMN and DAN networks. The inhibitory effect of IU on the DAN was replicated when participants were exposed to negative stimuli as well. Prior research has indicated a negative association between IU and attention inhibition, which is primarily governed by the DAN[71]. This suggests that weak goal-oriented attention processing, caused by high IU, may be linked with a lack of focused attention to external stimuli and highly variable activity in the DAN, leading to decreased resilience-driven brain synchrony. Another interpretation of our findings is that IU, as a risk factor for mental disorders, is associated with attention dysfunction[72]. Higher IU is linked to abnormal attentional functions, thus contributing to divergent neural activity within the DAN. Consequently, the inhibitory modulation of IU aligns with the AnnaK model, which emphasizes the importance of intact components in a system to maintain proper functioning. In other words, IU dampens resilience by impairing the attention functions critical for gating external information and gathering emotional cues. We also found that increased IU enhanced

the resilience-driven brain synchrony within the DMN when processing negative movies. Specifically, the DMN exhibited greater brain synchrony in individuals who were both highly resilient and uncertainty-intolerant. Considering the role of DMN in generating shared insights into events[64], these findings may suggest that increased IU promotes the formation of a coherent, clear, and certain interpretation and understanding of emotional narratives in resilient individuals. This could allow them to avoid negative feelings stemming from the uncertainty associated with novel emotional stimuli. In summary, our study highlights the role of IU in influencing resilience-driven brain synchrony and suggests that IU's impact on attentional and social-emotional processes may contribute to the differences observed in brain activity among resilient individuals.

Several limitations should be noted when interpreting our findings. Firstly, we relied on self-report questionnaire to measure individuals' psychological resilience, which may only capture a trait-like aspect of resilience and may not fully represent its dynamic nature over an extended period. Although we speculate that the trait or state-like characterization of resilience may not be mutually exclusive, conducting future prospective longitudinal studies would be beneficial in addressing this limitation and gaining a more comprehensive understanding of how resilience evolves over time. Secondly, the focus on young adults in our study may restrict the generalizability of the findings to broader populations. To overcome this limitation, future research should consider including more diverse samples, encompassing individuals from different age groups, such as the clinical sample and older adult samples. Thirdly, neutral and negative stimuli were exclusively employed in the current study. Although resilience typically functions when exposed to negative stimuli, previous works have shown that resilience could modulate responses to positive stimuli processing too[33,73,74]. Thus, incorporating positive stimuli in future studies would provide a more balanced perspective and enable us to examine how resilience influences neural responses to variety of emotional valences and arousal levels.

Conclusion

Understanding how resilience impacts the way we process external stimuli in our surroundings is important for ultimately developing new treatments and strategies to improve mental well-being in our societies. We argue that resilience plays a key role in eliciting neural synchrony among audiences during movie viewing. This resilience-driven brain synchrony aligns with the AnnaK model, wherein individuals with high resilience shared similar neural responses, in a synchronized manner with a coherency among multiple brain networks involving attention, cognitive control, and social cognition., while each low-resilience individual exhibits divergent neural activity and lower synchrony among themselves. Moreover, we propose the modulation effect of IU on resilience-driven synchrony, which highlights the role of intolerance of uncertainty in shaping resilience and its associated brain responses. individual differences in resilience could enhance synchrony between brain networks, affected by the individual differences in the intolerance to uncertainty This knowledge may potentially inform clinical interventions aimed at individualized approaches in fostering resilience, moving towards the precision medicine framework.

Materials and Methods

Participants

Seventy-eight younger adults were recruited from the local community via paper flyers and online advertisements to participate in this study. Due to technical issues, incomplete data, and excessive movement (i.e., average framewise displacement > 0.25 mm), 62 participants (33 males and 29 females, age range 19 to 35 years, mean age 25.68 ±4.30 years) were included for further data analyses. All participants provided written informed consent and were compensated with a gift card for their participation. All participants were healthy, right-handed, and reported no history of a neurological (e.g., epilepsy, stroke, or brain injury) or psychiatric diseases (e.g., depression and anxiety, schizophrenia, or autism spectrum disorder) over the past five years. They were not taking any medications for mood disorders at the time of experiment. The study was approved by the regional Ethics committee (approval #390390).

Procedure

The study consisted of two sessions: a brain imaging session and a behavioral session. First, participants took part in an MRI lasting approximately two hours, which included both functional and structural brain imaging protocols. Following the brain imaging sessions, the behavioral session took

place within two days and lasted about two hours, involving self-reported questionnaires and computerized tasks.

Before the brain imaging session, participants received instructions about the procedure and the experiment, both verbally and in a written format. During the scan, participants underwent an 8-minutes anatomical scan followed by a movie watching task. They were presented with a neutral movie, followed by a negative movie, and were asked to rate their emotional valence and arousal levels before and after each movie clip by verbally reporting their response on a 9-point Self-Assessment Manikin scale. Employing fixed movie sequences ensures consistent stimulus context across participants and effectively eliminates confounding factors arising from variability in stimulus presentation[29,75]. Participants were instructed to watch the videos naturally while trying to remain still during the scanning session. Foam padding was used to minimize head motion, and participants listened to the videos' sound through earphones (BOLDfonic, Cambridge Research Systems Ltd) compatible with 7T MRI scanner while watching the videos through a mounted mirror on the head coil.

Movie clips

Prior to the main study, a pilot behavioral study was conducted to select materials for the main experiment. Four movies from prior studies and online repository[76] were chosen for the pilot experiment. Twenty-four younger adults provided a series of ratings about valence, arousal, and emotion types, as well as a continuous intensity rating, for each movie clip. Based on the results of the pilot study, two movie clips were chosen for the subsequent brain imaging study (full details of the pilot study are reported in the **SI Appendix**). The neutral movie, titled "*Pottery*", depicts two women engaged in pottery-making, which lasted for 480 seconds. The negative movie, named "*Curve*", tells the story of a woman struggling to maintain her balance on the slope of a dam, desperately trying to avoid falling into the abyss below, which lasted for 494 seconds.

Questionnaires and behavioral index

As this study was part of a larger study, participants were asked to fill out a variety of self-reported questionnaires including anxiety, depression, and perceived stress, and to complete computerized tasks including theory of mind, emotion perception, and IQ tests. For the current study, two measures were included in the main analyses with the brain imaging data, namely resilience, which is measured by CD-RISC[77], and intolerance to uncertainty, which is measured by IUS[78] (see **SI Appendix** for more details).

To examine the influence of resilience on individuals' neural responses to external naturalistic stimuli and to test our first hypothesis that high-resilience individuals exhibit similar neural responses to naturalistic stimuli, while low-resilience individuals show distinct patterns, we employed AnnaK model based on Finn and her colleagues' work[33]. The resilience similarity was defined by the minimum resilience score for each dyad. To ensure the normality of the data, log-transform was further applied to resilience similarity scores. Besides, the product of the IUS score within each dyad was then normalized to a 0-1 range, resulting in joint IUS.

Imaging data acquisition

The imaging data were collected on a 7T MRI Siemens MAGNETOM Terra scanner with a 32-channel head coil. Functional images were acquired using a multi-band accelerated echo-planar imaging sequence (92 interleaved slices, multi-band acceleration factor = 8, echo time = 19 ms, repetition time = 2000 ms, matrix size = 160 × 160 mm, voxel size = 1.25 × 1.25 ×1.25 mm, field of view = 200 mm, slice thickness = 1.25 mm, and flip angle = 80°), resulting in 243 volumes for the neutral movie and 250 volumes for the negative movie.

The structural T1-weighted high-resolution scans were acquired using a MP2RAGE sequence (224 sagittal slices, echo time = 1.99 ms, repetition time = 4300 ms, inversion time 1 = 840 ms, inversion time 2 = 2370 ms, voxel size = 0.8 × 0.8 × 0.8 mm, flip angle = 5°/6° and slice thickness = 0.75 mm).

Imaging data preprocessing

The imaging data underwent preprocessing using fMRIPrep version 22.0.2[79], followed by post-preprocessing using XCP-D version 0.3.0[80]. A detailed description of the pipelines was automatically generated from fMRIPrep and XCP-D is provided in the **SI Appendix** . In brief, the preprocessing

pipeline included slice-time correction, head-motion correction co-registration between structural and functional images, normalization to MNI space, nuisance regression, band-pass filtering, and smoothing of the images using 4mm Kernel size. As part of the preprocessing, the first three dummy scans were discarded, leaving 240 volumes for the neutral movie and 247 volumes for negative movie conditions. Furthermore, Region Of Interest (ROI) signal extraction was conducted based on the Schaefer 200-parcel cortical parcellation[81] and Tian 16-parcel subcortical parcellation[82] atlases, resulting in time series from 216 brain regions for each condition and for every participant. These 216 regions were assigned to eight spatial independent brain networks (i.e., the visual network [VN], somatomotor network [SMN], dorsal attention network [DAN], ventral attention network [VAN], control network (CN), default mode network [DMN], Limbic network [LN], and subcortical network [SUB]).

Inter-subject correlations

To test whether both neutral and negative movies elicited robust neural synchrony across all participants, we calculated the participant-level intersubject correlation (ISC) by correlating the BOLD signal time series of each participant with the mean BOLD signal time series of the rest of participants (**Fig. 1e**). This procedure was conducted for each ROI and each participant, resulting in a 216 ROI × 62 participant-level ISC matrix. Furthermore, Pearson's correlation and paired t-test were performed to compare the ISC between neutral and negative conditions, allowing us to estimate the similarity and variation of brain synchrony between the two conditions.

The dyad-level ISC was calculated for each dyad (pair of participants) to indicate pairwise brain synchrony during movie-watching (**Fig. 1d**). To construct the ISC matrix, we computed Pearson's correlation between the BOLD signal time series in each of the 216 brain regions for each pair of participants. With a total of 1891 unique dyads generated from the 62 participants included in the study, this procedure resulted in two 216×1891 ISC matrices separate for neutral and negative movies. Subsequently, the ISC matrices were transformed using Fisher's *r* to *z* transformation to increase data normality.

Dyad-level analysis

In the current study, we conducted three IS-RSA using linear mixed-effects (LME) models with crossed random effects [34,83] to examine our hypotheses. To build these models, we utilized LME4 (version 1.1-32) and LMERTEST (version 3.1.3) in R[29]. The LME models were advantageous as they could account for the random effects and correlation structure of unique pairs of participants within dyads, effectively addressing the statistical dependencies between pairwise observations[83].

To test the first hypothesis that resilience-driven brain synchrony may follow the AnnaK model, with high-resilience individuals exhibiting similar neural responses while low-resilience individuals having idiosyncratic neural responses, we performed IS-RSA with binarized resilience scores. We first divided all participants into high resilience and low resilience groups based on the median of the resilience score (**Fig. 4a**). This characterization resulted in three types of dyads among the 1891 unique pairs: (1) {high, high} for dyads where both participants were in the high resilience group; (2) {high, low} for dyads with one high resilience and one low resilience participant; (3) {low, low} for dyads with both participants in the low resilience group. Subsequently, we conducted the first IS-RSA by constructing LME models, incorporating random effects of participants within each dyad. The model included the binarized dyad-level resilience as a fixed effect and the dyad-level ISC for a given brain region as the dependent variable. A planned-contrast analysis was then used to examine and compare the neural similarity among the three types of dyads.

To explore the first hypothesis in a greater detail, we further performed the second IS-RSA with resilience similarity as the independent variable. This allowed us to test whether resilience similarity, calculated based on the AnnaK model, could predict the neural similarity observed in dyads. By doing so, we aimed to gain deeper insights into how the similarity in resilience scores of dyads relates to the extent of neural similarity observed in their brain responses.

Lastly, to further examine our second hypothesis and investigate whether IU affects resilience-driven neural synchrony, we performed the third IS-RSA, which investigated the modulating effect of IU by introducing the interaction effect between resilience similarity and joint IUS.

Validation analysis

Because the similarity in neural responses is associate with demographic factors[32,34], we validated our results and accounted for the potential impact of demographic similarity on brain synchrony. In this analysis, we added the similarity of age, gender, and education as covariates into the LME models to assess the robustness of our findings. The validation analysis revealed consistent findings with our main results (**SI Appendix Figs. S3-S4**). Specifically, the observed neural synchrony is driven by the similarities in participants' resilience levels instead of the similarity in demographics including age, gender, and education.

Acknowledgments
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Figures and Tables

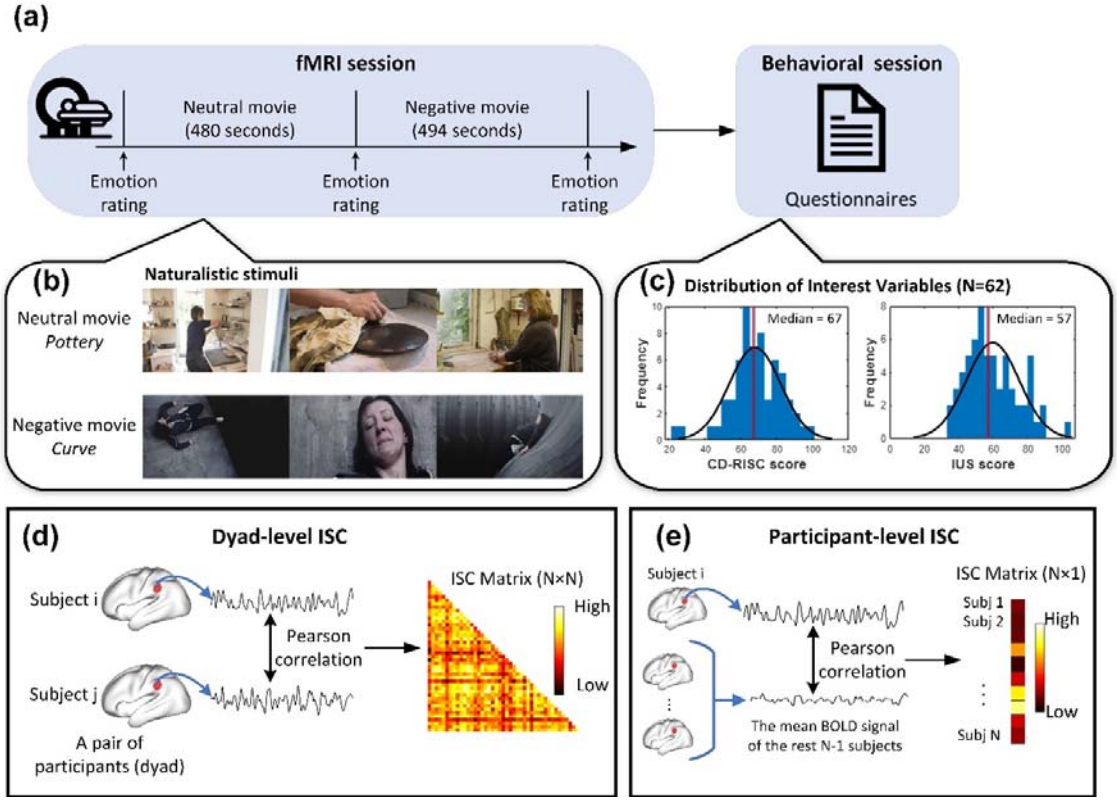


Figure 1. Study paradigm and calculation of inter-subject correlation (ISC). (a) Participants first underwent the fMRI scanning while they watched two movies. Before and after each movie, they reported their emotional valence and arousal. After the fMRI session, participants were invited back to complete a behavioral session comprising of self-reported questionnaires and cognitive testing as part of the protocol for a larger study on resilience and aging brain. (b) Participants first watched the neutral movie, "*Pottery*", and then the negative movie, "*Curve*", in the 7T MRI scanner. (c) Histogram plots for resilience score using Connor-Davidson Resilience Scale (CD-RISC) and intolerance to uncertainty (IUS) score using self-reported questionnaires. Scores of both questionnaires are normally distributed. (d) Dyad level ISC was computed by correlating the BOLD signal time series of the two participants within each dyad. (e) Participant-level ISC was computed by correlating the BOLD signal time series of the given participant and the mean BOLD signal time series of the rest of participants. The inferior parietal lobe is depicted here as an example for the analyses.

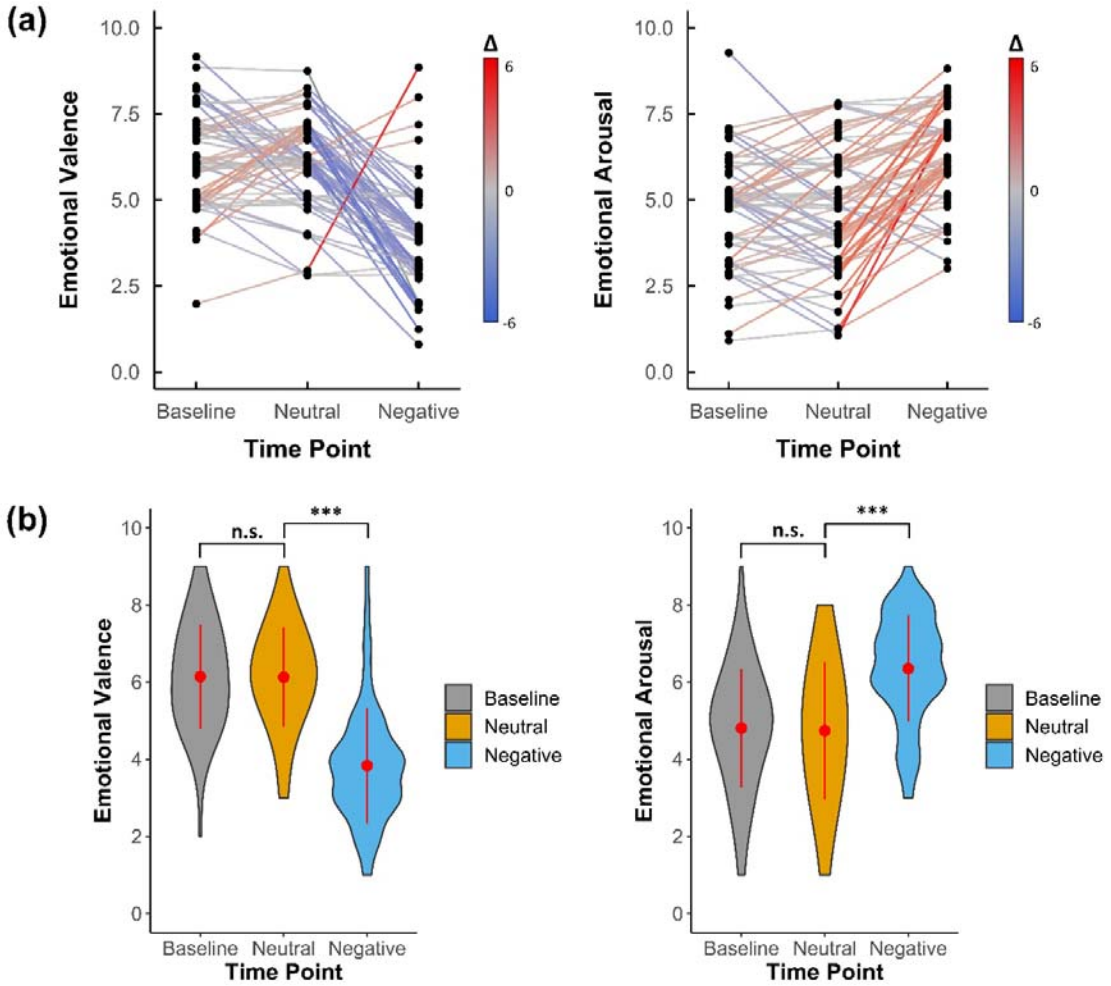


Figure 2. Emotional valence and arousal ratings before and after viewing the neutral and negative movies (participants N=62). (a) The emotional valence and arousal ratings for the before (baseline) and after each movie. The colors of the lines indicate changes in individual responses for the emotional ratings. (b) The violin plots of the emotional valence and arousal ratings. No significant differences were observed between baseline and after viewing the neutral movie in emotional valence, and the same results were obtained for emotional arousal. However, a significant decrease in emotional valence and a significant increase in emotional arousal were observed after participants watched the negative movie. The red points within the violin plots indicate the mean value of observation, and the red lines indicate the standard deviations. n.s.: not significant ; ***: $p<0.001$

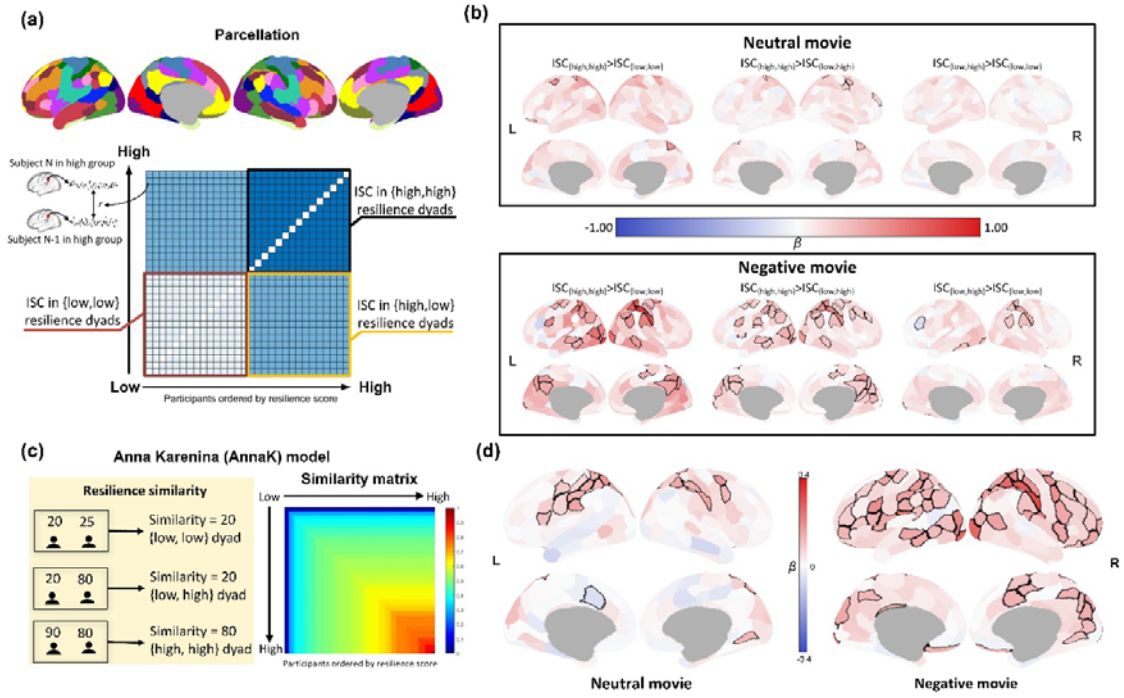


Figure 3. Results of dyad-level analyses on the relationship between resilience and neural synchrony. (a) All dyads were classified into three types, {high, high}, {high, low}, and {low, low}, based on the resilience levels of their respective members. The dyad-level Inter-Subject Correlation (ISC) was then calculated by correlating the BOLD signal time series of the two participants within each dyad. This allowed for the creation of a dyad-level ISC matrix for each brain region. (b) The results of the first IS-RSA that linked categories of resilience and neural synchrony. Brain regions with significant differences for each contrast are outlined in black. (c) The calculation of resilience similarity in accordance with Anna Karenina model. (d) The results of the second IS-RSA that link resilience similarity and neural synchrony. Regions with significant associations between their neural synchrony and resilience similarity are outlined in black. False discovery rate (FDR) corrections were applied for all analyses. L, left hemisphere; R, right hemisphere.

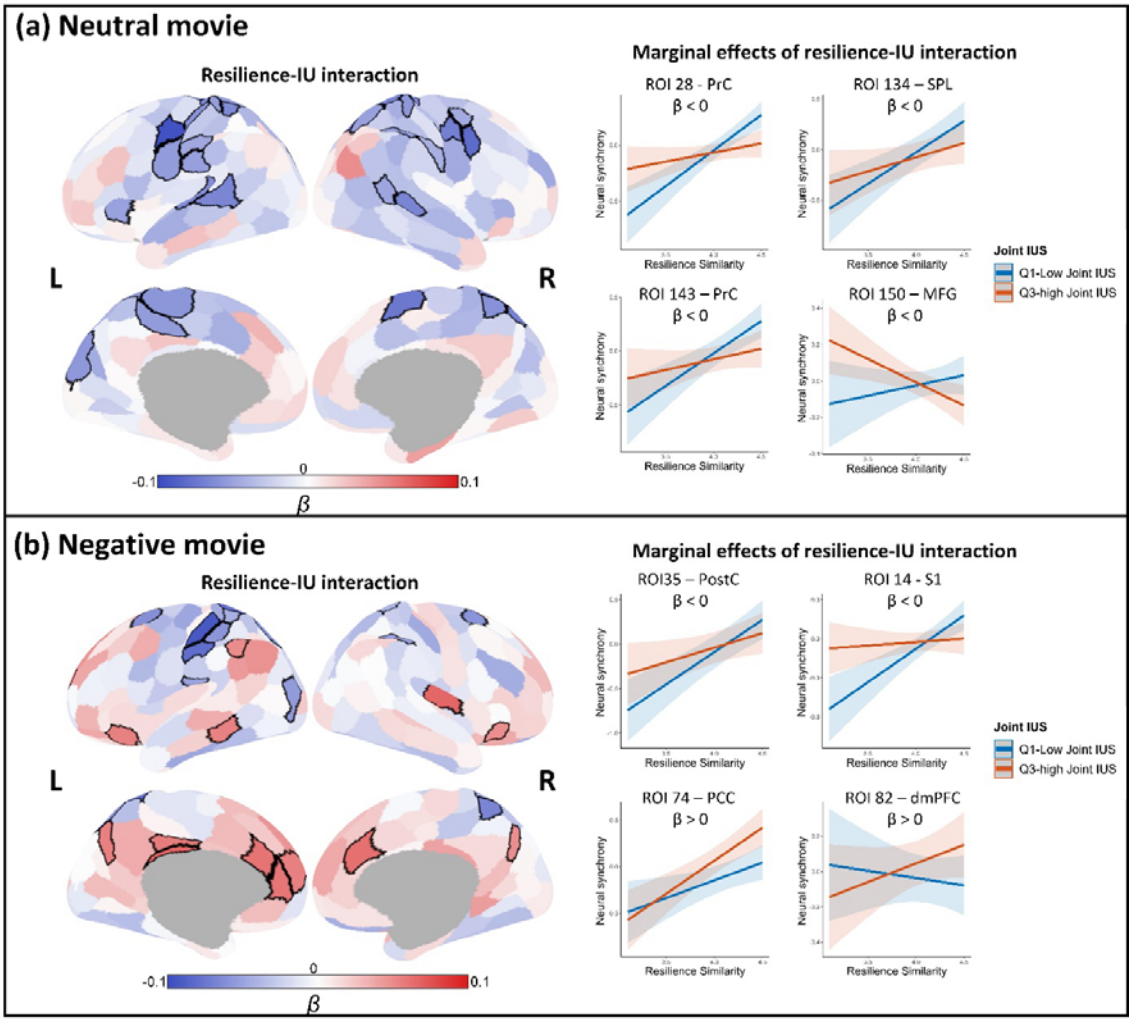
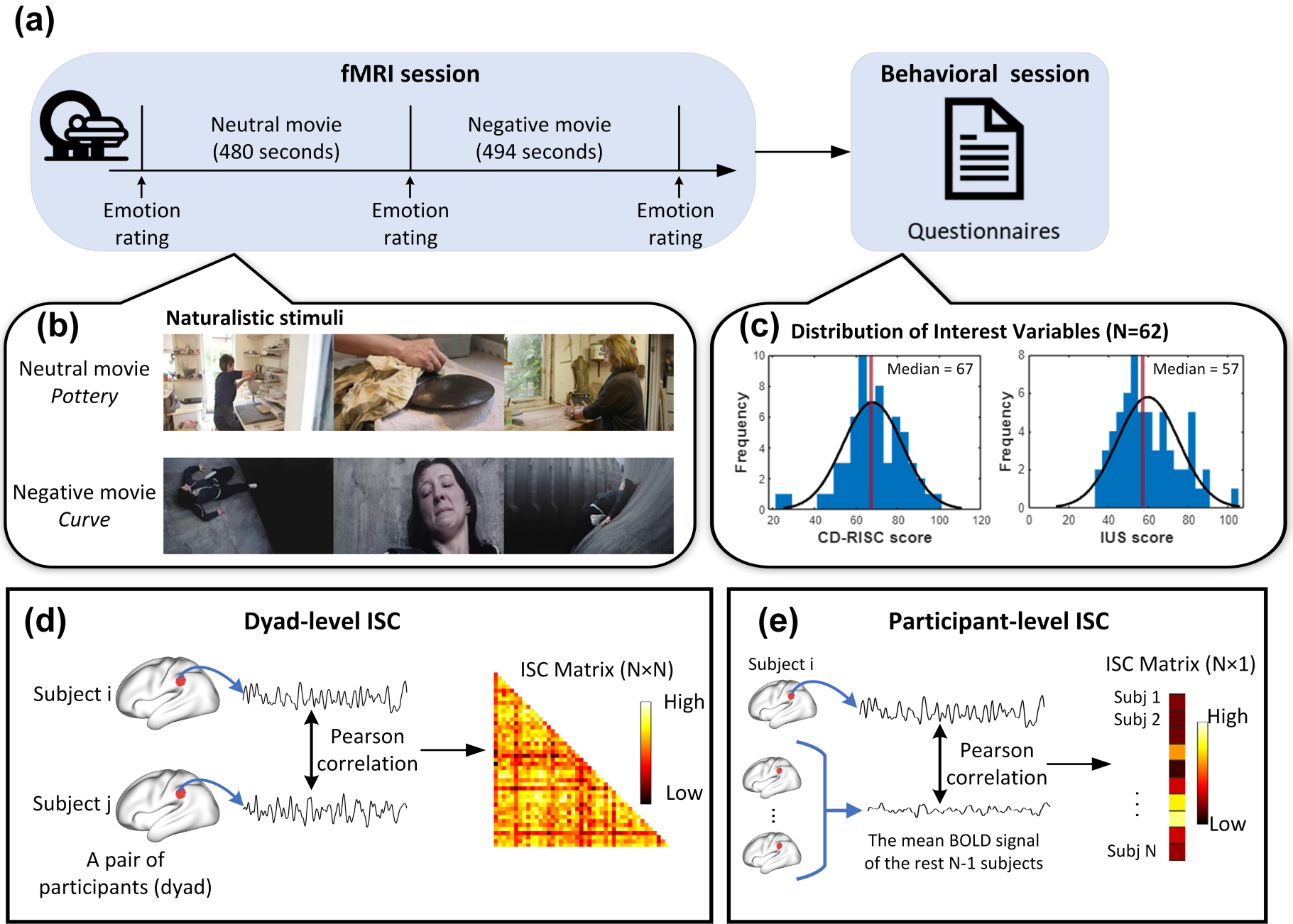
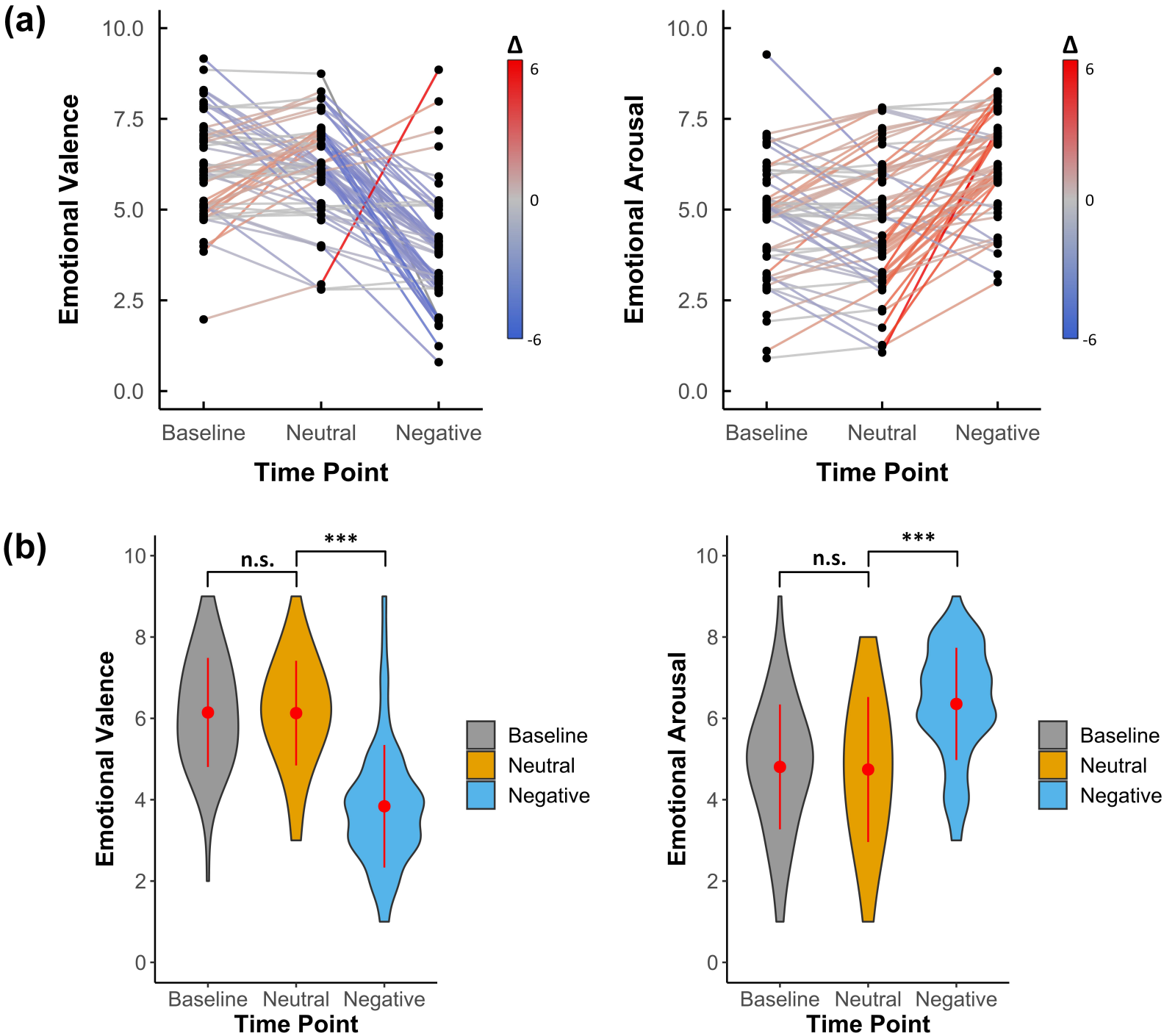
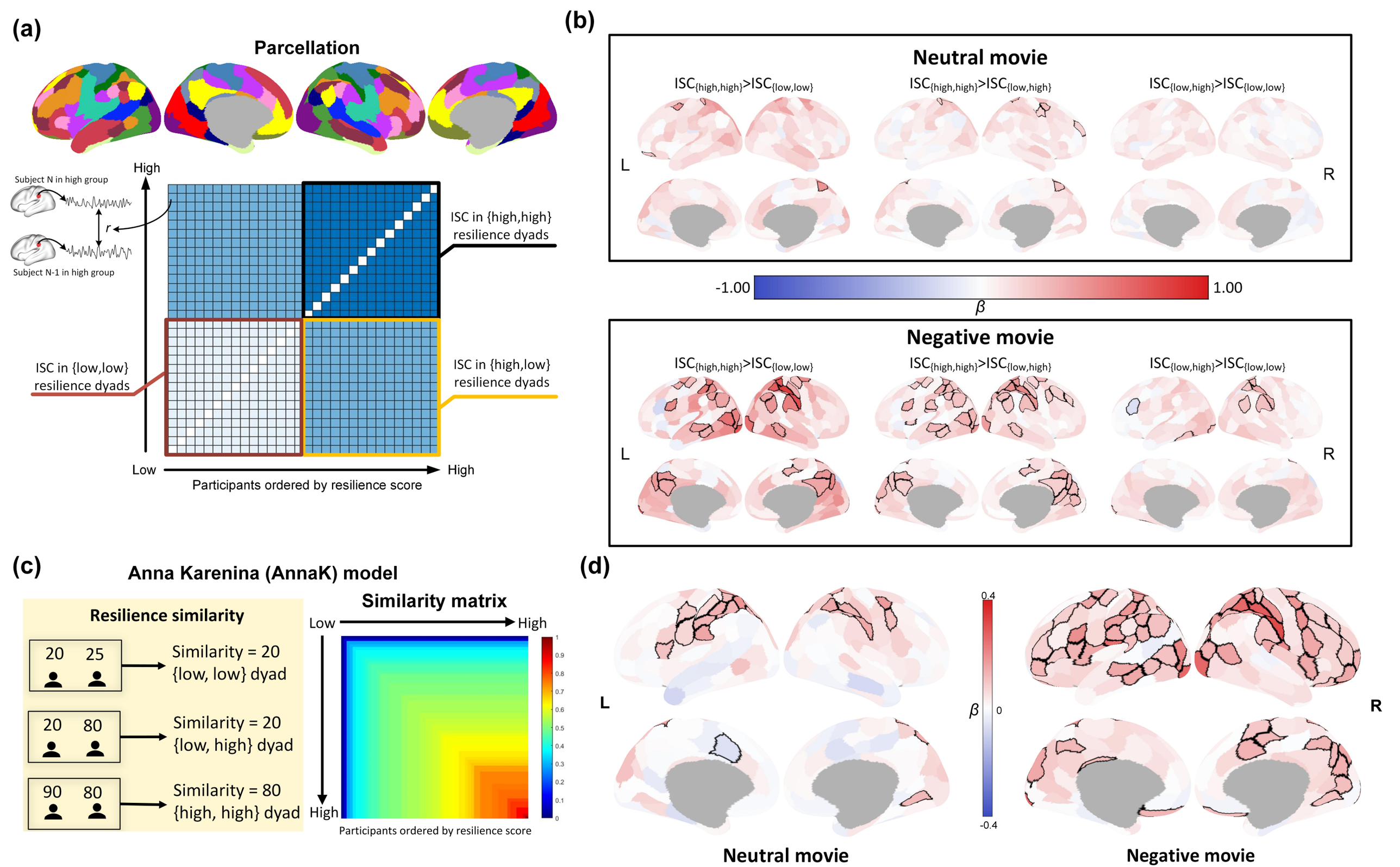
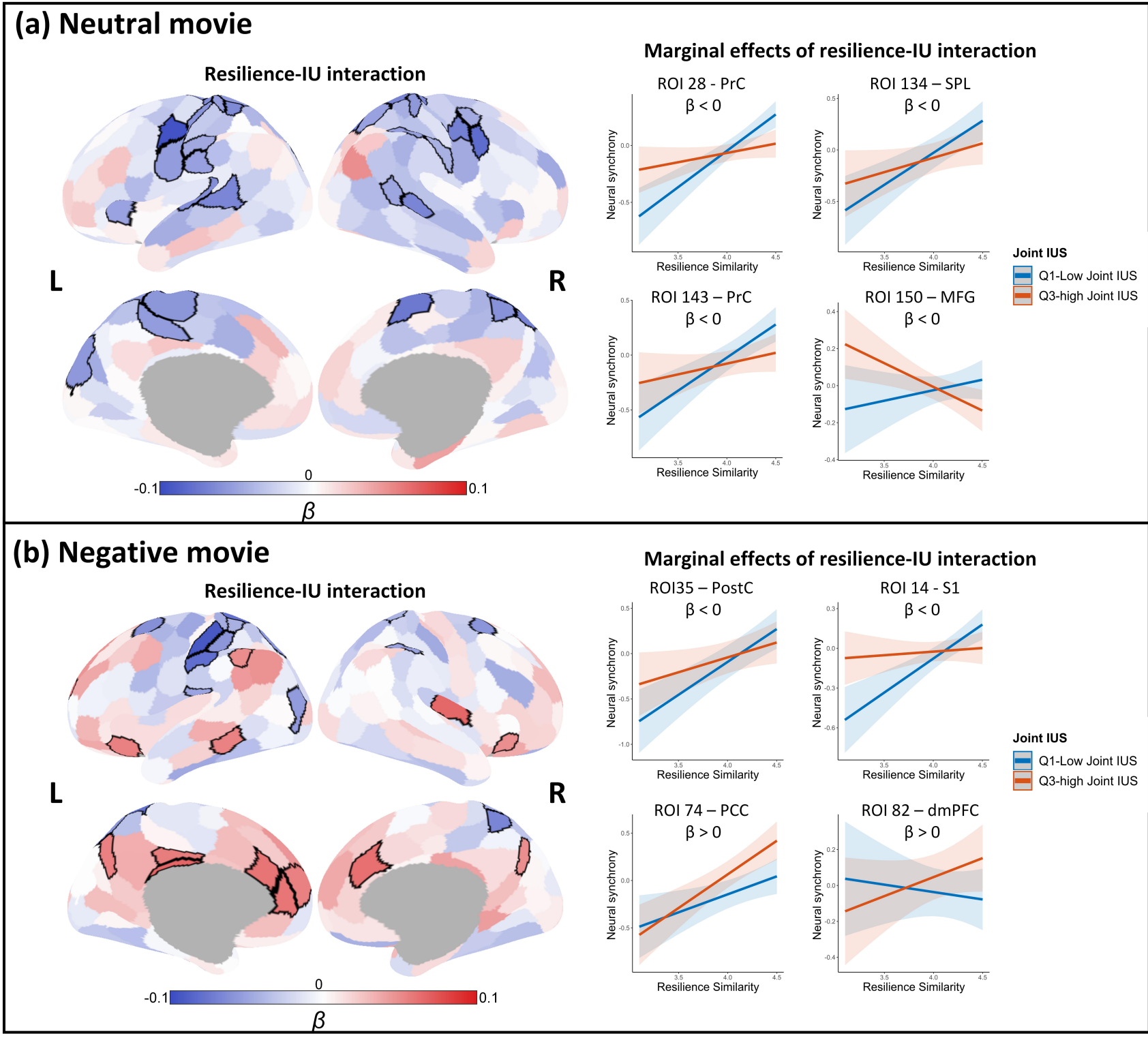


Figure 4. Modulation effects of intolerance of uncertainty (IU) on resilience-driven neural synchrony. (a) The results of the neutral movie. The brain maps illustrate that neural synchrony in brain areas, colored in blue and outlined in black, were dampened by the interaction between intolerance of uncertainty (IU) and resilience. Estimated marginal effects for neural synchrony by joint IUS indicated increased IU attenuated the resilience-driven neural synchrony. Four regions (bilateral precentral gyrus [ROI 28 and 143 - PrC], left superior parietal lobe [ROI 34 - SPL], and left middle frontal gyrus [ROI 150 - MFG]) that exhibited a large modulation effect of IU are presented as examples here. (b) the results of the negative movie. The brain maps illustrate that neural synchrony in brain areas, colored in blue and outlined in black, were dampened by the interaction between IU and resilience, and brain areas, colored in red and outlined in black, were enhanced by the IU-resilience interaction. Four regions (left postcentral gyrus [ROI 35 - PostC], left primary somatosensory cortex [ROI 14 - S1], left posterior cingulate cortex [ROI 74 - PCC], and left dorsomedial prefrontal cortex [ROI 82 - dmPFC]) that exhibited a large modulation effect of IU are presented as examples to demonstrate the estimated marginal effects. Q1 is the lower quartile, and Q3 is the upper quantile of joint IUS. Shaded areas represent 95% CIs.


(a)
fMRI session
Neutral movie
(480 seconds)
Negative movie
(494 seconds)
Emotion rating
Emotion rating
Emotion rating
Behavioral session
Questionnaires
(b)
Naturalistic stimuli
Neutral movie
Pottery
Negative movie
Curve
(c)
Distribution of Interest Variables (N=62)
Median = 67
Frequency
CD-RISC score
Median = 57
Frequency
IUS score
(d)
Dyad-level ISC
Subject i
Subject j
Pearson correlation
A pair of participants (dyad)
ISC Matrix (N×N)
High
Low
(e)
Participant-level ISC
Subject i
Pearson correlation
The mean BOLD signal of the rest N-1 subjects
ISC Matrix (N×1)
Subj 1
Subj 2
Subj N
High
Low


(a)
Emotional Valence
10.0
7.5
5.0
2.5
0.0
Baseline
Neutral
Negative
Time Point
Δ
6
0
-6
Emotional Arousal
10.0
7.5
5.0
2.5
0.0
Baseline
Neutral
Negative
Time Point
Δ
6
0
-6
(b)
Emotional Valence
10
8
6
4
2
0
n.s.
***
Baseline
Neutral
Negative
Time Point
Baseline
Neutral
Negative
Emotional Arousal
10
8
6
4
2
0
n.s.
***
Baseline
Neutral
Negative
Time Point
Baseline
Neutral
Negative


(a)
Parcellation
High
Subject N in high group
r
Subject N-1 in high group
ISC in {high,high} resilience dyads
ISC in {low,low} resilience dyads
ISC in {high,low} resilience dyads
Low
High
Participants ordered by resilience score
(b)
Neutral movie
ISC{high,high}>ISC{low,low}
ISC{high,high}>ISC{low,high}
ISC{low,high}>ISC{low,low}
L
R
-1.00
1.00
β
Negative movie
ISC{high,high}>ISC{low,low}
ISC{high,high}>ISC{low,high}
ISC{low,high}>ISC{low,low}
L
R
(c)
Anna Karenina (AnnaK) model
Resilience similarity
20 25
Similarity = 20
{low, low} dyad
20 80
Similarity = 20
{low, high} dyad
90 80
Similarity = 80
{high, high} dyad
Similarity matrix
Low
High
High
Participants ordered by resilience score
(d)
L
R
β
0.4
0
-0.4
Neutral movie
Negative movie


(a) Neutral movie
Resilience-IU interaction
L
R
-0.1
0
0.1
β
Marginal effects of resilience-IU interaction
ROI 28 - PrC
β < 0
ROI 134 – SPL
β < 0
ROI 143 – PrC
β < 0
ROI 150 – MFG
β < 0
Neural synchrony
Resilience Similarity
Joint IUS
Q1-Low Joint IUS
Q3-high Joint IUS
(b) Negative movie
Resilience-IU interaction
L
R
-0.1
0
0.1
β
Marginal effects of resilience-IU interaction
ROI35 – PostC
β < 0
ROI 14 - S1
β < 0
ROI 74 – PCC
β > 0
ROI 82 – dmPFC
β > 0
Neural synchrony
Resilience Similarity
Joint IUS
Q1-Low Joint IUS
Q3-high Joint IUS