Dynamic integration and segregation of amygdala subregional functional circuits linking to physiological arousal

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Abstract

The dynamical organization of brain networks is essential to support human cognition and emotion for rapid adaption to ever-changing environment. As the core nodes of emotion-related brain circuitry, the basolateral amygdala (BLA) and centromedial amygdala (CMA) are recognized as two major amygdalar nuclei that regulate distinct affective functions and internal autonomic responses via their unique connections with cortical and subcortical structures in rodents. However, little is known how the dynamical organization of emotion-related brain circuitry reflects internal autonomic responses in humans. Using resting-state functional magnetic resonance imaging (fMRI) with concurrent recording of skin conductance, we show robust dynamic integration and segregation states of amygdala subregion-related intrinsic functional networks linked to spontaneous autonomic arousal. Time-varying connectivity analysis of resting-state fMRI data with K-means clustering approach revealed two distinct states of BLA- and CMA-based connectivity patterns, with a segregation state showing generally stronger BLA- than CMA-based connectivity with cortical regions, and an integration state showing substantial overlapping, in a spatiotemporal manner, between BLA- and CMA-based connectivity networks. Critically, further analysis of skin conductance revealed that state-specific BLA- and CMA-based connectivity patterns were predictive of fluctuations of skin conductance, with higher predictive accuracy in the integration than segregation states. There are distinct BLA and CMA target network configurations in the integration and segregation states that predict spontaneous skin conductance levels and likely reflect spontaneous autonomic or physiological arousal. Our findings highlight dynamic functional organization of emotion-related amygdala nuclei circuits and networks and its links to spontaneous autonomic arousal in humans.

Keywords: Amygdala, fMRI, dynamic states, arousal, emotion

Introduction

The human brain, as an open and highly sophisticated system, spontaneously abounds with its dynamic nature, allowing a wide range of cognitive and affective functions to be operated in face of ever-changing internal and external demands. Spontaneous activity across large-scale brain networks does not remain constant but undergoes dynamic fluctuations over time (Bassett et al., 2011; Braun et al., 2015), likely at least in part reflecting affective and/or homeostatic states that are closely linked to autonomic and hormonal responses (Dolan, 2002; Calhoun et al., 2014; Deco et al., 2011). Dysregulated intrinsic dynamics of large-scale brain networks critical for emotion and related behaviors has been linked to mood disorders and related to psychiatric conditions (Insel et al., 2004; Sheline et al., 2009; Gentili et al., 2009). The amygdala lies at the core of emotion-related brain networks to broadcast affective state information across widespread brain regions (Murray, 2007; Bickart et al., 2014; Gothard, 2020). However, little is known about the dynamic nature of the amygdala and its functional circuits, and even less is known whether and how their dynamic features are associated with internal autonomic states in humans.

The amygdalar complex encompasses multiple anatomical subregions with distinct connections that support distinct affective functions (LeDoux, 2000; Roy et al., 2009). The basolateral amygdala (BLA) and centromedial amygdala (CMA) are two major groups of amygdalar nuclei that form dedicated networks for distinct functions via their unique pattern of interactions with other cortical and subcortical structures (LeDoux, 2000; LeDoux, 2007). Within the past decade, there has been great progress in functional neuroimaging techniques that allows researchers to map spontaneous functional coupling of the amygdalar nuclei with large-scale brain networks in vivo in humans (Roy et al., 2009; Etkin et al., 2009; Salzman et al., 2010; Sladky et al., 2015). Seed-based correlation analysis of spontaneous brain activity has been the mainstay of conventional approaches for examining intrinsic functional organization of large-scale brain networks including amygdala-based emotional networks (Raichle et al., 2001; Greicius et al., 2003; Bullmore et al., 2009; Roy et al., 2009). This provides useful information to identify specific target networks with the BLA and CMA, but offers insufficient insight into how these networks dynamically organize over time to regulate the brain's affective functions. Thus, novel

approaches from a dynamic and nonstationary systems perspective are required to mitigate this limitation. Beyond simple scan-length averages (so-called static methods), recent emerging innovative approaches by capturing time-varying properties of connectivity have begun to illustrate the dynamic nature of spontaneous brain activity across large-scale networks in humans (Calhoun et al., 2014). However, the dynamical organization of functional brain networks associated with the amygdalar nuclei still remains open.

There is now increasing evidence converging onto that the dynamic nature of brain functional organization is regulated by the ascending neuromodulatory systems such as locus coeruleus (LC) releasing noradrenaline by acting on widespread brain networks to alter the neuronal excitability and drive the integration of distributed neurons (Aston-Jones & Cohen, 2005). Indeed, the dynamics of network topology has been linked to autonomic arousal levels varying as a function of firing patterns of LC neurons (Aston-Jones & Cohen, 2005; Eldar et al., 2013; Shine et al., 2016). In particular, the amygdalar nuclei including BLA and CMA constitute a large amount of neurotransmitter receptors which could transiently modulate neuronal excitability of the information processing through their projections to specific target circuits and networks (LeDoux, 2007). Critically, one recent study in rodents shows that amygdala neuronal ensembles dynamically encode affective or homeostatic internal states, through two major populations of neurons of the basal nucleus of the amygdala that widely broadcasts internal state information via several output pathways to larger brain networks (Gründemann et al., 2019). Yet, how the dynamical organization of large-scale networks associated with the amygdalar nuclei represent internal autonomic states in humans remains unknown. Our study addresses this critical gap by examining time-varying connectivity patterns of functional circuits associated with the amygdalar nuclei and their links to internal autonomic responses.

Here we addressed the above questions by integrating resting-state functional magnetic resonance imaging (fMRI) with concurrent recording to skin conductance in young healthy adults across two studies to examine how time-varying states of intrinsic functional connectivity of the BLA and CMA reflect autonomic arousal levels. The prior observer-independent cytoarchitectonically determined

probabilistic maps were used to define BLA and CMA (Etkin et al., 2009; Qin et al., 2012). The classical sliding-window approach was implemented to identify time-varying spontaneous functional connectivity of coupling and connected networks of regions (Greicius et al., 2003; Fox & Raichle, 2007; Sakoğlu et al., 2010; Allen et al., 2014), and K-means clustering as one of the popular unsupervised machine-learning algorithms was used to identify dissociable connectivity states. Resting-state fMRI data from a second independent cohort of participants with higher spatial resolution were used to gain a better localization of the amygdala nuclei and ensure the reproducibility and robustness of the observed dynamic states. We further implemented elastic-net regression to examine whether time-varying connectivity patterns of the amygdalar nuclei are predictive of automimic arousal measured by skin conductance levels. Based on the neurophysiological models of network dynamics and autonomic arousal (Shine et al., 2016; Shine et al., 2018; Young et al., 2017), we predicted that intrinsic connectivity patterns associated with the amygdala nuclei would undergo dissociable time-varying states and such dynamics would predict spontaneous autonomic responses.

Results

Time-varying intrinsic functional connectivity patterns of the BLA and CMA

We first conducted separate seed-based functional connectivity analyses for the BLA and CMA in each hemisphere (see Methods). These analyses revealed a set of widely distributed regions in cortical and subcortical structures whose spontaneous activity are significantly correlated with BLA and CMA seeds, with prominently dissociable patterns in unimodal and polymodal association cortex along with overlapping patterns in limbic structures (**Fig. 1A-B**). Furthermore, we conducted whole-brain 2-by-2 ANOVA with subregions (BLA vs. CMA) and hemispheres (left vs. right) as within-subject factors to identify BLA- and CMA-based target networks (**Fig. S1**). Based on findings from previous studies (Roy et al., 2009; Etkin et al., 2009; Qin et al., 2012), we selected five target networks of our major interest in a set of widely distributed network (see Methods), including 1) limbic and paralimbic structures, 2) uni- and polymodal association cortex, 3) subcortical structures, 4) Cerebellum and 5) prefrontal cortex.

Thereafter, we examined conventional static of intrinsic functional connectivity associated with the BLA and CMA. This analysis revealed that spontaneous activity of the BLA seed showed stronger coupling with activity in a set of widely distributed cortical, paralimbic, and limbic structures, whereas spontaneous activity of the CMA showed stronger coupling with activity in subcortical regions as well as the cerebellum (**Fig. 1C**). This dissociation is in line with findings from previous studies on static intrinsic functional connectivity (Roy et al., 2009; Qin et al., 2012).

Next, we implemented a sliding window approach in conjunction with K-means clustering methods to examine time-varying intrinsic functional connectivity properties of five target networks associated with the BLA and CMA (**Fig. 1D**). The window length was set to 30 TR and movement step was set to 1 TR. The optimal number of clusters were determined by Silhouette coefficient (Rousseeuw, 1987) and CalinskiHarabasz criterion (Caliński and Harabasz, 1974), in which higher value indicates larger cohesion and less dispersity. This analysis revealed highest scores under both Silhouett coefficient and CalinskiHarabasz criterion scores at cluster numbers set to 2 (**Fig. 1E**). To ensure the stability of time-varying connectivity and the reliability of clustering, we additionally computed the two metrics using a set of window length (α) and steps (β) varying from 30 to 50 TRs and 1 to 3 TRs respectively (**Fig. 1F, S2**). We also test whether BLA and CMA seeds in two hemispheres showed distinct functional connectivity with target regions or not. Again, we observed a very similar pattern of results even separating seeds of BLA and CMA for each hemisphere (**Fig. S3**). Together, these results revealed consistent patterns of outcomes, with two clearly dissociable states of time-varying BLA and CMA connectivity patterns (**Fig. 2A**). Critically, these two states were reproducible in an independent Cohort 2 with 37 participants (**Fig. S4**).

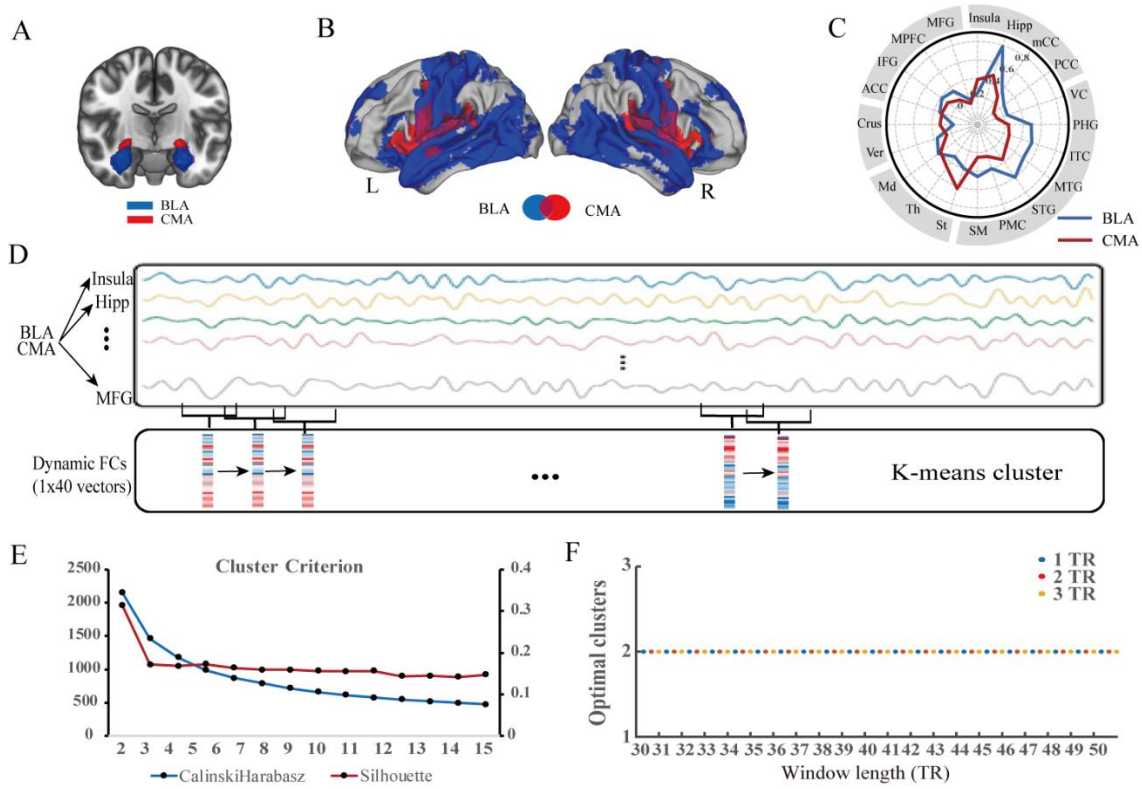

Figure 1. An overview of time-varying functional connectivity of emotion-related brain networks by sliding window and K-means clustering. (**A**) A coronal view of the BLA (blue) and CMA (red) region of interests. (**B**) Lateral views of significant clusters derived from BLA- and CMA-based intrinsic functional connectivity, and overlapping areas are colored in pink. (**C**) Polar plots show static BLA- and CMA-based intrinsic functional connectivity strength with target regions in uni- and polymodal association cortex, para-limbic and subcortical structures, and prefrontal cortex. (**D**) An illustration of K-means cluster analysis for Cohort 1. Connectivity between BLA/CMA seed regions and 20 target regions were computed in each window upon which K-means clustering was conducted. (**E**) Line curves depict the CalinskiHarabasz and Silhouette criteria as a function of cluster number K. (**F**) Different combinations of window length and step were selected to quantify the most optimal parameters. The vertical coordinate represents silhouette score and the horizontal axis represents window length varying from 30 TRs to 50 TRs. Different color dots represent different steps varying from 1 TR to 3 TRs. Notes: L, left; R, right; BLA, basolateral amygdala; CMA, centromedial amygdala.

Integration and segregation states linking to distinct spatiotemporal BLA and CMA connectivity patterns

To further examine the functional differences between two distinct states (denoted as State 1 and State 2), we compared the intrinsic functional strength of BLA and CMA-target networks within and between State 1 and State 2 across participants (**Fig. 2B).** Firstly, separate independent t tests for averaged functional connectivity (Fisher-z transformed) revealed significantly higher BLA-based connectivity strength than that of CMA, in both State 1 [$t_{(4308)} = 33.34$, two tailed $p < 0.001$] and State 2[$t_{(3922)} = 39.16$, two tailed $p < 0.001$]. These results are consistent with previous study found in human adults (Qin et al., 2012). More interestingly, we found both BLA-associated and CMA-associated connectivity in State 1 are significantly higher than that in State 2 (separate independent t tests, BLA: $t_{(8230)} = 78.34$, two tailed $p < 0.001$; CMA: $t_{(8230)} = 106.34$, two tailed $p < 0.001$). Additionally, edge by edge comparisons exhibited similar patterns mentioned above (**Table. S1, S2).** These results indicate distinct difference between the two states, as the one showing higher amygdalar subregional connectivity with associated target regions than the other. Furthermore, we calculated similarity between BLA and CMA-target networks for the two states, measured by their averaged Pearson correlation values (Fisher's r-to-z transformed). (**Fig. 2C**). This analysis revealed significantly higher similarity between BLA and CMA target networks in State 1 (r = 0.59), when compared to that in State 2 (r = 0.35, two sample t-test, $t_{(8230)} = 18.60$, two tailed $p < 0.001$). Additionally, we conducted a windowed time lagged cross-correlation (WTLCC) analysis (see Methods) to examine the temporal relationship between BLA and CMA-target networks in the two distinct states (Boker et al., 2002; Cryer et al., 2008). To do this, concatenated time series during two states across participants were binned, creating sequence of epochs (**Fig. 2D**). Then cross correlations at different time lags were computed for each epoch. We observed that the highest WTLCC in each epoch more frequently emerged around lag zero in State 1 compared with that in State 2. To validate this, we averaged WTLCC across all epochs for State 1 and State 2 separately (**Fig. 2E**), and separate independent t tests revealed that State 1 showed significant higher averaged WTLCC than that in State 2 at lag of zero (separate independent t tests, $ts_{(203)} > 2.92$, two tailed $p < 0.05$, FDR corrected), suggesting higher functional coupling between BLA- and CMA-target

networks in State 1 than that in State 2. Notably, all the results are reproducible in independent Cohort 2 (**Fig. S4**), indicating a robust characterization for these two dynamic states across cohorts.

Overall, by implementing sliding-window approach with K-means clustering method, we found a clear dissociation of spatio-temporal evolution patterns for BLA- and CMA-based intrinsic connectivity within two states. Based on the highly integrated nature for State 1 and less integrated behavior for State 2, we denote State 1 as Integration state and State 2 as Segregation state for the rest of the study.

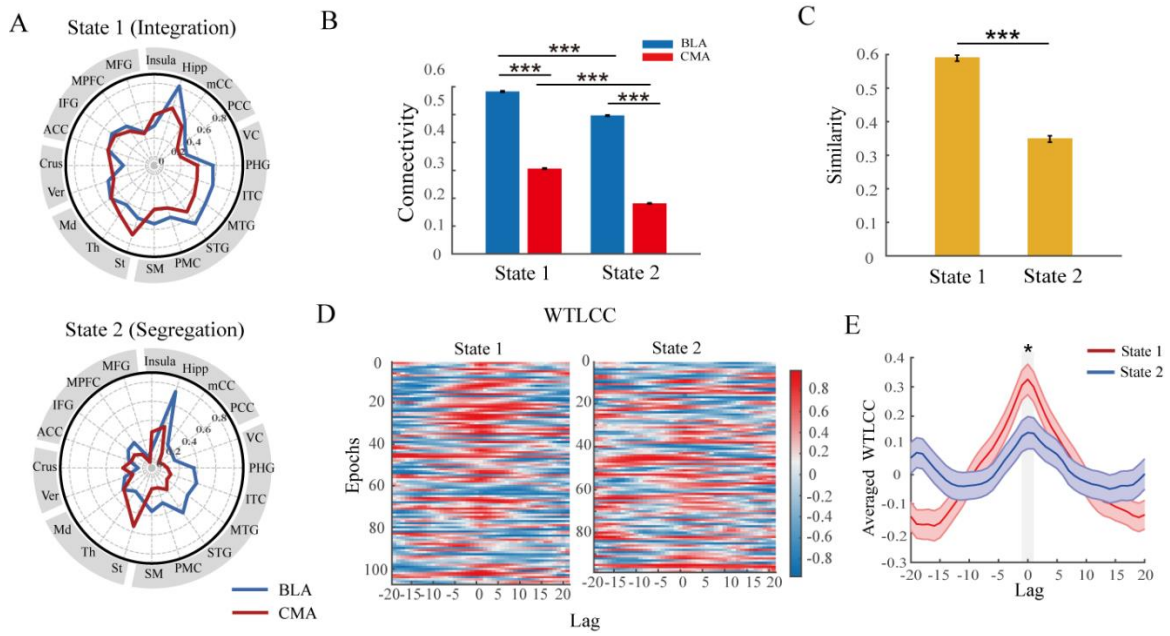

Figure 2. Time-varying integration and segregation states related to distinct spatial-temporal patterns for BLA and CMA connectivity networks. (**A**) Polar plots depict two distinct states, with generally stronger connectivity strength of both BLA (blue) and CMA (red) with target ROIs for integration state, while significantly weaker yet dissociable connectivity between BLA and CMA seeds. (**B**) Bar graphs show significant difference in averaged connectivity strength (Fisher-z transformed) between BLA- (blue) and CMA-based target regions (red) within and between each state. (**C**) Bar graphs shows averaged correlation of BLA- and CMA-target connectivity networks (similarity) within State 1 and State 2. (**D**) Heat map depicts windowed time-lagged cross-correlation (WTLCC) for State

1 and State 2. The x-axes represent cross correlation between BLA- and CMA-target networks under different time lags (offset). The y-axes represent the number of bins (epochs) for State 1 and State 2. Color represent correlation value for each lag per epoch. (**E**) The curves depict averaged WTLCC for State 1 (red) and State 2 (blue) separately and the shaded area depicts standard error of mean for each WTLCC. Ranges of lags showing significant higher averaged WTLCC of State 1 than State 2 are marked by gray area (FDR corrected). Notes: $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

Time-varying states of BLA and CMA connectivity predict spontaneous autonomic arousal

After detecting distinct dynamic states across cohorts, we further asked whether they can be robustly linked to spontaneous autonomic arousal. We implemented Cohort 2 (N=37) with concurrent recordings of spontaneous skin conductance level (SCL) and preprocessed SCL time series based on previous studies (see Methods). We excluded SCL signal of 9 subjects due to relatively poor representations of subject's autonomic arousal (**Fig. S5**). We first calculated averaged occupancy rate of the two states at each window for two cohorts. We found both cohorts showed distinct evolution patterns of integration and segregation states (**Fig. 3A, S6**). We then computed time-varying functional connectivity metrics of the BLA and CMA seeds by concatenating across subjects for the integration and segregation states separately. Likewise, corresponding SCL fluctuations at each window were also averaged accordingly for the integration and segregation states (**Fig. 3B**). Next, we applied elastic-net regression (see Methods) to examine whether state-specific time-varying functional connectivity (FC) networks of BLA- and CMA-seed can be robustly predictive of ongoing SCL fluctuations (Zou et al., 2005; Cui et al., 2018). Two elastic-net regression models were conducted for integration and segregation separately, and each window-wise FC from states is considered as a function of related SCL. This analysis revealed significantly correlations between the predicted and observed ongoing SCLs for both integration (r = 0.33, permutated $p < 0.001$) and segregation states (r = 0.19, permutated $p < 0.001$) (**Fig. 3C**).

We then conducted several control analyses to validate dynamic states of BLA/CMA intrinsic

functional connectivity linking to SCL. First, separate permutation tests were performed for the integration and segregation states separately, by shuffling the correspondence of state-specific connectivity and SCL values within each state before implementing the elastic-net models. This analysis revealed significantly higher predictive accuracy in integration (permutated $p < 0.001$) and segregation (permutated $p < 0.001$) states when compared to the shuffled ones. Next, to examine the state-specific associations between BLA- and CMA-based intrinsic connectivity networks with corresponding SCL, permutation tests were performed by randomly assigning total samples (i.e. window-wise FCs and related SCLs in integration and segregation) into two elastic-net models with the same sample size of those in integration and segregation. Again, this analysis revealed significantly higher predictive accuracy in both integration (permutated $p < 0.001$) and segregation (permutated $p < 0.001$) states as compared to randomly assigned ones. To examine the differences of predictive accuracies under integration and segregation states, we implemented bootstrap method (see Methods). Independent t test revealed a significantly higher predictive accuracy for SCLs in the integration than segregation state ($t_{(9998)} = 174.12$, two tailed $p < 0.001$), suggesting a tenser associations between SCL fluctuations and integration state, compared with segregation state. Together, these results suggest a tense link between state-specific time-varying BLA and CMA connectivity patterns are predictive of concurrent SCL fluctuations.

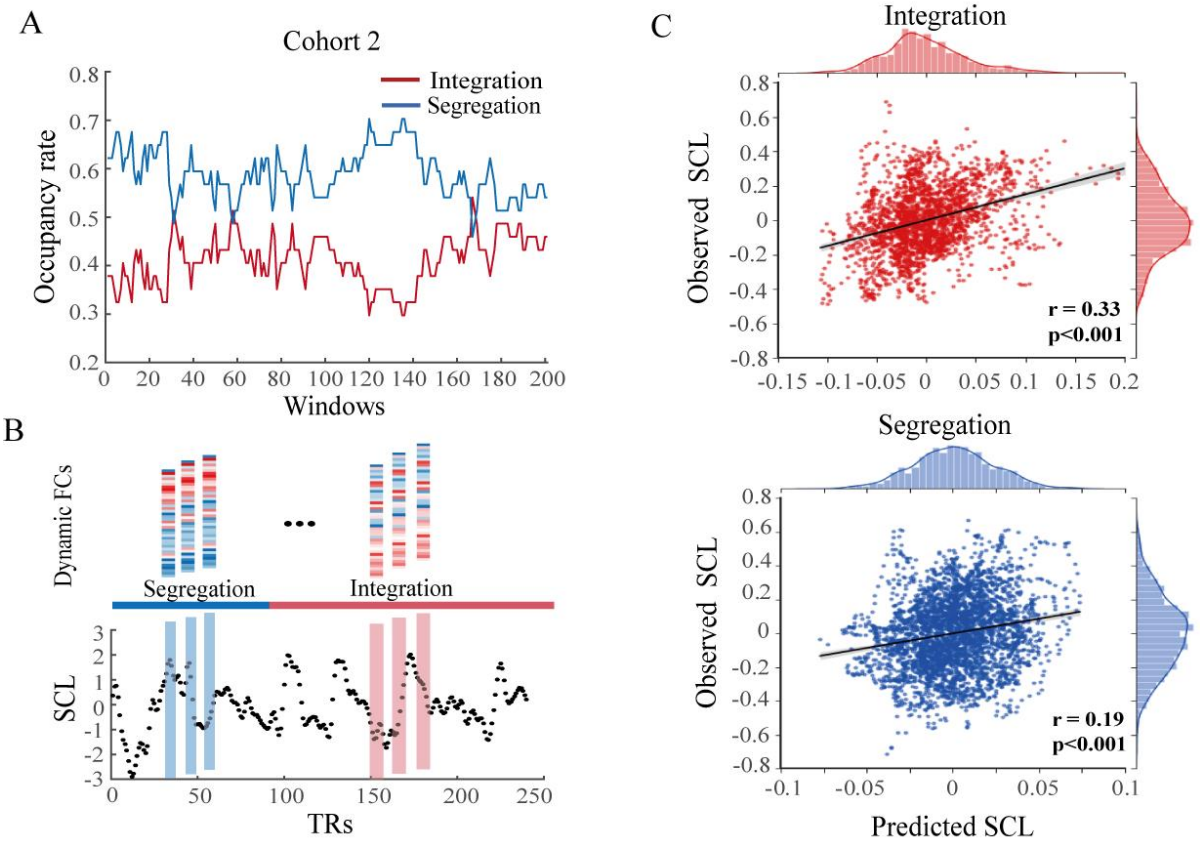

Figure 3. Time-varying integration and segregation states linking to spontaneous skin conductance level (SCL). (**A**) The occupancy rate of integration (red) and segregation (blue) at each window across all participants in Cohort 2 are plotted separately. Y-axis represents the occupancy rate and x-axis represents window sequence. (**B**) An example of dynamic FCs from integration and segregation states as a function of ongoing SCL fluctuations in one subject. (**C**) Scatter plots show the significant correlations between the predicted and actual SCL values using the elastic-net regression in the integration and segregation states respectively. Shaded area represents 95% confidence interval.

Distinct time-varying BLA and CMA target networks predict autonomic arousal

We further investigated how specific configurations of BLA and CMA target networks in integration and segregation states contribute to predicting spontaneous SCL fluctuations. By extracting contribution weights (absolute value of coefficients) derived from elastic-net regression models of the integration

and segregation state, we observed that only a fraction of connections is considered effective for predicting SCL (**Fig. S8**). In addition, more links is considered effective for predicting SCL (18 of total 40 features assigned non-zero weight), as compared to those in segregation state (25 of total 40 features assigned non-zero weight) (**Fig. 4A, 4C)**. We further computed the relative ratio of total contribution weights between BLA- and CMA-target connections and robustly observed an BLA-dominated phenomenon in the integration state while a CMA-dominated pattern in segregation state (**Fig. 4A, 4C**). This result is also consistent when only accounting for the most contributed connections under different thresholds (**Fig.S9**). Furthermore, we visualized the spatial distribution BLA- and CMA-targeted connections in the integration and segregation states separately (**Fig. 4B, 4D).** We found these connections showing distinct patterns between two dynamic states. For the integration state, these links mainly involved most prefrontal cortex, superior and medial temporal gyrus, subcortical structures like midbrain as well as middle and posterior portions of cingulate cortex. While inferior frontal gyrus, (para)limbic structures of (para)hippocampus are involved for the segregation state. In addition, visual cortex and cerebellum shows a general contribution to both integration and segregation states. Together, these results indicate that there are distinct BLA and CMA target network configurations in integration and segregation state for predicting spontaneous SCL levels.

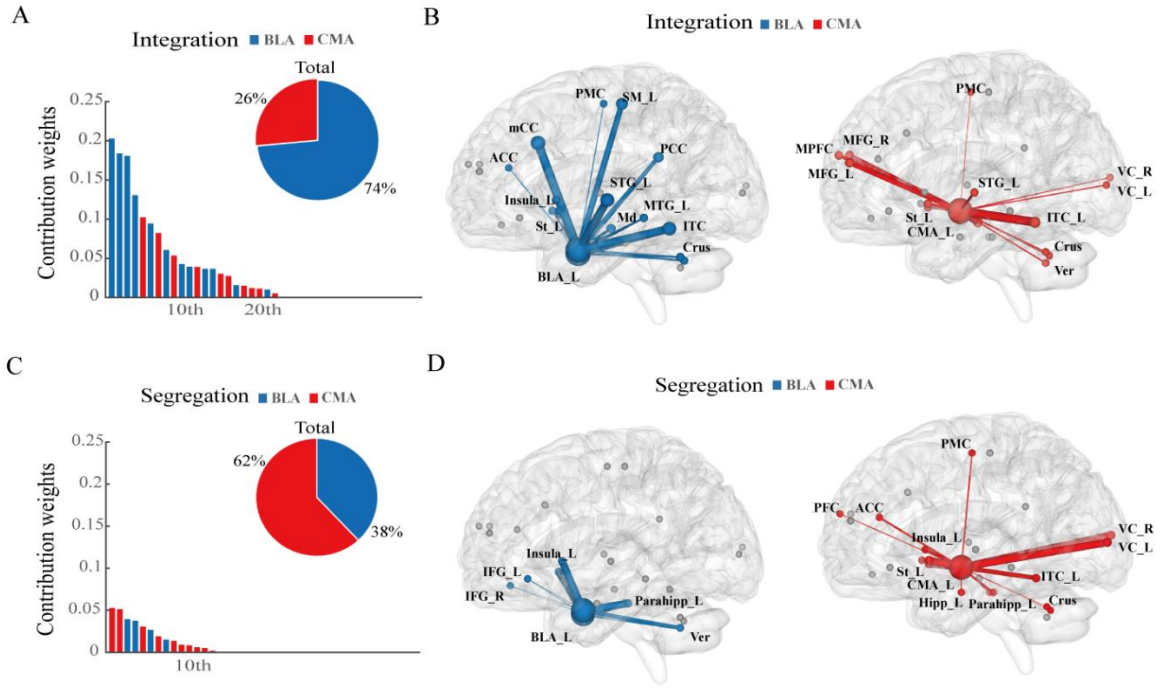

Figure 4. Predictive weights comparisons and spatial distributions of BLA and CMA-based target network configurations linking to spontaneous SCL fluctuations. (A, C) Bar graphs depict BLA and CMA target network connections derived from the elastic-net model, ranked by their absolute weights, for integration (top) and segregation (bottom) state. Relative ratio of total contribution weights between BLA and CMA-target networks are plotted in pie charts. (**B**, **D**) All connections of BLA (blue) and CMA (red) target networks during the integration and segregation are superimposed onto the glass brain in a sagittal view separately, with connections in the left hemisphere for visualization purpose only. Size of nodes and corresponding links represent the relative contribution weights of BLA- and CMA-target links derived from each elastic-net model separately.

Discussion

In this study, we investigated the dynamical organization of intrinsic functional connectivity networks associated with the amygdala nuclei and its contributions to autonomic arousal in humans. By leveraging machine learning and clustering approaches, we identified two distinct states of time-varying intrinsic connectivity networks: an integration state exhibits generally stronger connectivity but substantial integrated patterns between BLA- and CMA-based target networks, whereas a segregation

state exhibits relatively weaker yet dissociable BLA- than CMA-based connectivity with cortical regions. Next, we found a clear dissociation of spatio-temporal patterns for BLA- and CMA-based intrinsic connectivity within the integration and segregation states. Critically, such time-varying dissociable states of BLA- and CMA-based target networks are linked to spontaneous SCL – a measure of autonomic arousal, with integration state exhibiting significantly higher SCL and predictive accuracy as compared to the segregation state. Such time-varying integration and segregation states with distinct BLA- and CMA-based network configurations contribute to predicting spontaneous fluctuations of SCL.

We found two distinct states of time-varying intrinsic connectivity patterns for BLA and CMA target networks by implementing sliding-window and K-mean clustering methods. Specifically, the integration state showed generally stronger connectivity with all of target ROIs and substantially overlapping between BLA and CMA target networks, as compared with the segregation state. Unlike the integration state, however, the segregation state showed clearly functional dissociation between BLA and CMA target networks: the BLA showed stronger connectivity with widespread regions in uni- and poly-association cortical areas, (para)limbic structures and prefrontal cortex, while the CMA showed stronger connectivity with the striatum. This segregation pattern partially is somewhat in line with previous findings on functional segregation of BLA and CMA target networks using the conventional static averaging (static-like) approaches (Roy et al., 2009; Etkin et al., 2009; Qin et al., 2012). Building on the neuroanatomical models in rodents with the amygdalar nuclei via unique connections to form specific dedicated circuits in support of distinct affective functions (LeDoux, 2000; LeDoux, 2007), our observed time-varying integration and segregation states provide prominent evidence to highlight a dynamic functional reorganization of BLA- and CMA target networks over time in humans. Moreover, BLA and CMA target networks in integration state showed a highly coupling phenomenon both in spatial and temporal manners compared with segregation state, suggesting an integrated property for integration state. This observed highly coupling patterns between BLA and CMA target networks, in a spatio-temporal manner, are not reported by the conventional scan-length averaging functional connectivity approaches. Notably, such dynamic integration and segregation pattern is reproducible by another independent cohort of participants, suggesting the reproducibility and

robustness of our current findings. Together, these two dynamic states provide novel evidence to suggest that BLA and CMA intrinsic functional circuits do not remain constant, rather undergo spontaneously fluctuated over time. This extends previous findings on intrinsic functional organization of the amygdalar nuclei derived from conventional (static-like) approaches and animal models.

A second major finding of our study is that time-varying integration and segregation state were predictive of spontaneous fluctuations of SCL. Numerous psychophysiological studies have demonstrated a link of skin conductance levels with internal autonomic or physiological arousal (Critchley et al., 2010; Boucsein, 2012). Thus, it is conceivable that our observed associations may reflect a link of time-varying functional connectivity of the amygdala nuclei and SCL fluctuations that reflect autonomic or physiological arousal. From a system level, converging evidence from human functional neuroimaging suggests large-scale reconfigurations in neural networks detected by BOLD-fMRI signals are closely linked to changes of autonomic arousal due to the activation of (non)adrenergic systems (Chang et al., 2009; Phelps et al., 2005; Hermans et al., 2011; Kim et al., 2017). Animal studies have also demonstrated that LC releasing norepinephrine (Aston-Jones & Cohen, 2005) acts on corresponding receptors in widely distributed brain regions especially the amygdala and related networks, thereby prompting rapid increases in neuronal excitability and functional coupling among these disparate regions (Arnsten, 1998).

Moreover, our observed significantly higher predictive accuracy in the integration state, featured by its substantial overlapping between BLA and CMA target networks in the integration state, may reflect increased functional coordination of large-scale neural networks accompanying with highly associated autonomic arousal measured by pupillometry data in humans (Murphy et al., 2011; Shine et al., 2016). Such association has been observed in animal models. For example, acute stress can trigger a widespread cascade of neurochemical changes that rapidly prompt neuronal excitability of large-scale brain networks into a tonically sensitive mode (Joëls & Baram, 2009; Stujenske & Likhtik, 2017). Thus, it is possible that there are multiple neuromodulatory systems contributing to our observed stronger yet overlapping pattern between BLA and CMA target networks in the integration state. In other words, the

integration state may result from endogenous autonomic and hormonal stimulations promoting the excitability of neuronal ensembles in the amygdalar nuclei and related functional circuits, thereby promoting the flexibility of the brain's internal affective or homeostatic states to meet ever-changing environmental needs. Indeed, evidence from recent studies have suggested that integrated states may enable faster and more effective performance on a cognitive task, most likely through ascending neuromodulatory systems to regulate the transition between multiple modes of brain function (Shine et al., 2016; Shine et al., 2018).

A third important finding of our study is that distinct features (or connections) from time-varying states of BLA and CMA target networks contribute to predicting spontaneous autonomic arousal as evidenced by SCL. Specifically, a BLA-leading pattern relating to predicting autonomic arousal in integration state was observed, compared with a CMA-leading pattern in segregation state. Such divergence between two dynamic states may exhibit distinct arousing modes, with one owning preference of BLA-engagement phenomenon (integration state) and the other exhibiting preference of a CMA-engagement pattern (segregation state). Additionally, such highly dynamical phenomenon of amygdala-based intrinsic functional networks is somehow in line with newly emerging evidence from recent animal research, which demonstrates that amygdala ensembles can dynamically represent internal affective or homeostatic states (Janak et al., 2015; Beyeler et al.,2018; Zhang et al., 2018). Specifically, the dynamic assembly of two major populations of neurons in the BLA plays a role in regulating animal's internal autonomic or physiological states through several output pathways to larger brain networks (Salzman et al., 2010; Zhang et al., 2018; Grundemann et al., 2019).

Moreover, the divergence between two dynamic states were further supported by their distinct spatial distributions for the connections among various brain regions, including portions of prefrontal cortex, cingulate cortex, (para)hippocampus, as well as the medial temporal gyrus. These dissociable patterns may reflect a dynamic role of amygdalar nuclei (BLA and CMA) in converging information from multiple brain systems. In addition, insula and sensorimotor cortex appears to show general contributions to both states. This is consistent with many studies in humans and animal models showing

that functional coordination of these regions with the amygdala nuclei is responsible for information integration closely related to affective, homeostatic and cognitive states (Devinsky et al., 1995; Craig, 2002; Critchley, 2004; Pollatos et al., 2007), and with increased activation and connectivity within the salience network in response to stress (Hermans et al., 2011; McMenamin et al., 2014). This somehow resembles findings from previous studies showing that patients with seizures can alter consciousness, affective states and expression, as well as autonomic responses, through it is abundant projections into sensory-motor cortex and polymodal association areas (Devinsky et al., 1995). In addition, the amygdala is recognized to play a critical role in affective information processing likely through its functional coupling with regions in polymodal association areas and the prefrontal cortex in emotion perception, appraisal and regulation (Lim et al., 2009). Thus, it is likely to speculate that our observed BLA and CMA target networks in the integration and segregation states may reflect internal physiological responses with different responsive modes of arousal involved in a variety of cognitive and affective functions that can't be detected by the conventional methods. Furthermore, the dynamic transitions between these two distinct states may together build self-organized dynamics modulating temporally rapid autonomic arousal in a systematic level (Young et al., 2017).

The dynamical (re)organization of large-scale brain networks holds the promise to enable the flexibility of brain functioning and rapid adaptation in face of ever-changing environmental demands (Braun et al., 2015; Deco et al.,2010; McMenamin et al., 2014). To our knowledge, no studies to date have directly investigated the dynamical organization of amygdala subregional functional circuits and networks. Our findings thus extend the existing knowledge on functional organization of emotion-related brain circuitry which is theorized to play a critical role in regulating one's internal autonomic (and more broadly homeostatic) states. This line of research has its potential to extend into investigating function and dysfunction of emotion-related brain circuitry in affective disorders including anxiety and depression. The mainstay of previous studies using the conventional approaches have demonstrated emotion-related brain dysconnectivity in patients with affective disorders, with hyper- and/or hypo-connectivity patterns in limbic, paralimbic and prefrontal systems critical for vigilance, rapid detection and memories for threatening stimuli, emotion regulation and expression (Bishop, 2007; Clark, & Beck,

2010; Sturm et al., 2007). Thus, it would be highly relevant to investigate how dysregulated brain dynamics as well as functional circuits linked to the amygdalar nuclei in particular underlie the core symptoms of affective disorders. Understanding the dynamical organization of emotion-related brain circuitry represents an important step toward developing brain-inspired biomarkers of affective and psychosomatic disorders on a circuit-level (Insel et al., 2010; Deisseroth, 2014). Future studies are required to delineate how the dynamical organization of the amygdalar nuclei with broader networks regulates internal affective or autonomic responses in both healthy and psychiatric conditions.

In conclusion, our study demonstrates dynamic integration and segregation of the emotion-related brain networks that are linked to different internal autonomic states. Our findings provide important implications into understanding the neurobiological mechanisms of how the dynamical organization of emotion-related brain networks regulates internal physiological states, and eventually inform dysregulated brain dynamics in affective disorders and psychopathology.

Materials and Methods

Participants

This study included a total of 79 young healthy participants from two independent cohorts. The first cohort consisted of 42 young healthy participants (mean age ± SD: 22.62 ± 0.99 years ranged from 21 to 24, 27 females) after dropping out invalid participants because of excessive head motion (Cohort 1). A second independent cohort of 37 adults matched in age and sex (mean age ± SD: 22.08 ± 1.65 years ranged from 20 to 25, 18 female) was recruited to undergo fMRI with the concurrent recording of skin conductance (Cohort 2). All of the participants reported no history of any neurological or psychiatric disorders, and no current use of any medication or recreational drugs. The experiment and procedures were approved by the Institutional Review Board for Human Subjects at Beijing Normal University in accordance with the standards of the Declaration of Helsinki. Written, informed consent was obtained from all participants before the experiment.

Imaging acquisition

For Cohort 1, brain images were acquired from a Siemens 3T scanner (Siemens Magnetom Prisma syngo MR D13D, Erlangen, Germany) with a 64-channel phased-array head coil in Peking University. Participants were instructed to keep their eyes open and remain still for a period of 8-min resting-state fMRI scan. T2-weighted images were recorded using an echo-planar imaging (EPI) sequence, with 177 volumes (axial slices, 33; slice thickness, 3.5 mm; volume repetition time, TR, 2000 ms; echo time, TE, 30 ms; flip angle, 90; voxel size, 3.5 x 3.5 x 3.5 mm; field of view, FOV, 224 x 224 mm). High-resolution anatomical T1-weighted images were collected using three-dimensional sagittal T1-weighted magnetization-prepared rapid gradient echo (MPRAGE) sequence (192 slices; TR, 2530 ms; TE, 2.98 ms; slice thickness, 1 mm; flip angle, 7°; voxel size, 0.5 x 0.5 x 1.0 mm; FOV, 256 x 256 mm).

For Cohort 2, whole-brain imaging data were collected on a 3T Siemens Prisma MRI system in Peking

University. Functional images were collected using a multi-band echo-planar imaging (mb-EPI) sequence (slices, 64; slice thickness, 2 mm; TR, 2000 ms; TE, 30 ms; flip angle, 90°; multiband accelerate factor, 2; voxel size, 2.0 × 2.0 × 2.0 mm; FOV, 224 × 224 mm). Structural images were acquired through three-dimensional sagittal T1-weighted magnetization-prepared rapid gradient echo (MPRAGE) sequence (192 slices; TR, 2530 ms; TE, 2.98 ms; slice thickness, 1 mm; voxel size, 1.0 × 1.0 × 1.0 mm, interpolated to 0.5 × 0.5 × 1.0 mm; flip angle, 7°; inversion time, 1100 ms; FOV, 256 × 256 mm). Field map images were acquired with grey field mapping sequence (64 slices; TR, 635 ms; TE1, 4.92 ms; TE2, 7.38 ms; slice thickness, 2 mm; voxel size, 2.0 × 2.0 × 2.0 mm; flip angle, 60°; FOV, 224 × 224 mm).

Skin conductance (SC) recording

We implemented recorded SCL data in Cohort 2 (n=37). Data were recorded simultaneously with fMRI scanning using an MRI-compatible Biopac MP 150 System (Biopac, Inc., Goleta, CA). Two Ag/AgCl electrodes filled with isotonic electrolyte medium were attached to the center phalanges of the index and middle fingers of the left hand. The gain set to 5, the low pass filter set to 1.0 Hz to reduce scanner-induced noise, and the high pass filters set to DC. Data were acquired at 1000 samples per second.

Skin conductance level (SCL) analysis

Based on previous studies ((Boucsein,1992; Patterson et al., 2002; Fan et a., 2012), the SCR waveform was first down-sampled by averaging data points within each 2 s window to match repetition time (TR) of MR scanning during imaging data acquisition. The SCR waveform was then detrended to remove slow linear drift of the SCLs. Next, the detrended SCR data was bandpass-filtered within the frequency range of 0.008 - 0.1 Hz in accordance with intrinsic functional connectivity analysis of resting-state fMRI data. Finally, SCL data was normalized within each participant to facilitate the comparable and interpretable purposes (Braithwaite et al., 2013; Boucsein et al., 2012). We excluded SCL signal of 9 subjects due to relatively poor representations of subject's autonomic arousal (**Fig. S5**). Finally, similar

with previous studies (Tambini et al., 2017), the SCL levels were window-wise averaged to match the corresponding dynamic state (window length: 40 TRs).

Imaging preprocessing

Functional imaging preprocessing was performed using tools from Statistical Parametric Mapping SPM12 (http://www.fil.ion.ucl.ac.uk/spm). The first five volumes were discarded for signal equilibrium, and the last two volumes were also discarded in case participants' impatience. Images using multi-band EPI sequence were additionally corrected for distortions related to magnetic field inhomogeneity in combination with field map images. After that, functional images were corrected for slice acquisition timing. Subsequently, functional images were co-registered to each participant's gray matter image segmented from corresponding high-resolution T1-weighted image, then spatially normalized into a common stereotactic Montreal Neurological Institute (MNI) space and resampled into 2 mm. Finally, images were smoothed by an isotropic three-dimensional Gaussian kernel with 6 mm full-width at half-maximum.

Regions of interest (ROIs) definition

Four ROIs encompassing the BLA and CMA for each hemisphere were created separately using cytoarchitectonically defined probabilistic maps of the amygdala. Maximum probability maps were used to create nonoverlapping amygdala subregions using the Anatomy Toolbox (Eickhoff SB, et al. 2005). Voxels were included in the maximum probability maps only if the probability of their assignment to the BLA or CMA was higher than any other nearby structures with greater than 40% likelihood. Each voxel was exclusively assigned to only one region. Overlapping voxels were assigned to the region that had the greatest probability, resulting in two nonoverlapping ROIs representing CMA and BLA subregions for each hemisphere. Based on the previous study (Qin et al., 2012), we selected the same five target networks of interest – subcortical structures including striatum, thalamus and midbrain; crus and vermis/declive regions of the cerebellum; uni- and polymodal association cortex

including visual cortex (VC), parahippocampal gyrus (PHG), inferior temporal cortex (ITC), middle (MTG) and superior temporal gyrus (STG), premotor cortex (PMC) and sensorimotor cortex (SM); limbic and paralimbic structures including hippocampus (Hipp), insula (Ins), middle (mCC) and posterior (PCC) portions of cingulate cortex; and prefrontal cortex including anterior cingulate cortex (ACC), middle (MFG) and inferior frontal gyrus (IFG), and medial prefrontal cortex (MPFC).

Functional connectivity analysis

Time series of each seed (averaging across all voxels within ROI) were filtered with a bandpass temporal filter (0.008 to 0.10 Hz) and extracted. Six motion parameters, cerebrospinal fluid and white matter of each participant that account for potential physiological noise and movement-related artifacts were regarded as covariates of no interest. Subsequently, the resultant time series were demeaned. For each participant, two separate functional connectivity analyses were performed for both BLA and CMA for each hemisphere separately. The contrast parameter images for each of the four seed ROIs from the individual level analyses were submitted to a second-level group analysis by treating participants as a random variable in a 2-by-2 ANOVA with amygdala subregions (BLA vs. CMA) and hemispheres (left vs. right) as within-subject factors. Significant clusters were estimated with a height threshold of $p < 0.05$ (FDR corrected) and an extent threshold of $p < 0.1$ (voxel size: 30).

Similar to previous studies in adults, target ROIs of each seed were determined from the group-level analyses for significant BLA- and CMA-based connectivity networks in combination with conventional AAL template. Meanwhile, lateral BLA and CMA seed regions were combined separately for following analysis. Finally, both times series of each seed and associated target ROIs were extracted by the same procedure mentioned above and Pearson's correlation, representing the strength of functional connectivity of each seed with corresponding target masks, were computed between amygdala subregion-seeded time series and target time series.

Dynamic functional connectivity analysis

Dynamic functional connectivity was assessed using a widely used sliding-window approach (Sakoğlu et al., 2010; Bassett et al., 2011; Allen 2014; Shine et al., 2016) in MATLAB R2015b (MathWorks, Natick, USA). The entire temporal time series were divided into a series of windows with a specific window length ($\alpha = 40$ TR) and step ($\beta = 1$ TR). The total quantity of windows was defined by a parameter W,

$$\mathrm{W} = \lfloor (\mathrm{T} - \alpha)/\beta \rfloor + 1$$

where T is a total number of time points. Initial point S for each window i was defined as:

$$S_i = 1 + (i - 1)\beta\,, i = 1, \dots, W$$

while endpoint E was defined as:

$$E_i = (i - 1)\beta + \alpha\,, i = 1, \dots, W$$

First, Pearson's correlation coefficients between BLA and CMA seed and associated target ROIs were calculated within each time window. Each participant's BLA- and CMA-seed functional connectivity within each time window were transformed into one-dimensional vectors. Next, K-means clustering of windowed correlation matrices was implemented to quantify different states of dynamics of BLA- and CMA-based functional connectivity. The algorithm was repeated with 1000 random iterations to exclude the sensitivity of K-means to initial conditions.

A paramount step of clustering analysis is determining the optimal parameter set $(\mathrm{K}, \alpha, \beta)$. Various parameter sets were attempted to fulfill this goal ($K = 2 - 10$, sliding window length $\alpha = 30 - 50$ TRs, step $\beta = 1.0 - 3.0$ TRs). The optimal parameter set (2, 40, 1) were obtained after evaluation of silhouette coefficient (P Rousseeuw, 1987) and CalinskiHarabasz criterion (T Caliński & J Harabasz, 1974), in which the former evaluation considered cohesion and dispersity while the later criterion evaluated covariance between inter-group and intra-group.

Windowed time-lagged cross-correlation analysis for BLA and CMA-networks of dynamic states

We implemented time lagged cross correlation (TLCC) for the integration state and segregation states separately. We first sequentially concatenated all of the time series of target ROIs belonging to the different states across participants. We then averaged time series for the BLA and CMA target ROIs during different states separately. To calculate cross-correlation of the BLA and CMA-network evolution, we binned each time series according to the total length of time series of two cohorts (Cohort 1: 8221 TRs in total; Cohort 2: 7437 TRs in total). The time-lag range (offset) was set within -20 to 20 for each window or epoch (bin), resulting in the numbers of epochs (Cohort 1: 98 epochs for the integration state, 107 epochs for the segregation state; Cohort 2: 76 epochs for the integration state, 109 epochs for the segregation state:). After that, cross-correlation value for each offset in each bin was Fisher-z transformed for further statistical analyses (**Fig. 2D**).

Machine learning-based prediction analysis

To examine whether dynamic states, featured by their time-varying functional networks of BLA- and CMA-seed, can be robustly linked to ongoing SCL fluctuations, two elastic-net models with 10-fold cross validation were implemented for integration and segregation state separately. For each model, total 40 dynamic connections were extracted as a feature vector (i.e. 1×40 vector) and corresponding windowed SCL extracted as response variable at each temporal window. The Statistics and Machine Learning Toolbox in MATLAB 2015a (MathWorks, Natick, USA) was used to perform the elastic net regression (Boyd S., 2010). Elastic-net model earns the benefits of excluding little-contributed variables while reducing overfitting problem by implementing L1 and L2- regularization in the model l (controlled by parameter α and λ). To determine the optimal parameter set (α, λ) for the elastic-net model we applied a grid search, with alpha chosen from 20 values in the range of [0.05, 1.0] and lambda chosen from 100 values generated from a default lambda sequence pre-defined in Statistics and Machine

Learning Toolbox. Then model was applied 10-fold cross-validation to examine performance of elastic net regression at different parameter settings (**Fig. S7**). Finally, (α, λ) with minimum cross-validation error plus one standard deviation was selected for later analysis (Tsankov et al., 2015). The permutation tests were applied to determine whether the obtained final correlation for integration-SCL and segregation-SCL links were significantly better than expected by chance (Dosenbach et al., 2010). Specifically, the above prediction procedure was repeated for 5000 times and only temporal SCL of training data were shuffled within each resampling. The *p* value of the mean correlation *r* was calculated by dividing the number of permutations that showed a higher value than the actual value for the real sample by the total number of permutations.

Bootstrapping for comparison of correlation between integration and segregation state

A bootstrapping method was implemented to examine the difference of correlation between window-wise SCLs and associated two dynamic states. Specifically, we conducted repeated resampling from total SCL-state pairs of integration state and integration state separately. Then we employed elastic-net model with the same hyperparameters settings used in **Fig. 3C**, to estimate the correlation of resampled SCL- integration (integration) state pairs separately. We thus created simulated distribution of Pearson's correlation for integration (integration) states and associated SCLs. Then two sample t test was employed to compare the difference of these two distributions (Fisher-z transformed). The resample times was set to 5000 and the population size for each resample was set to 1000 (Efron et al., 1994).

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