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Mathematically Modeling Anhedonia in Schizophrenia: A Stochastic Dynamical Systems Approach

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Objective: **Anhedonia, traditionally defined as a diminished capacity for pleasure, is a core symptom of schizophrenia (SZ). However, modern empirical evidence indicates that hedonic capacity may be intact in SZ and anhedonia may be better conceptualized as an abnormality in the temporal dynamics of emotion.*Method:* To test this theory, the current study used ecological momentary assessment (EMA) to examine whether abnormalities in one aspect of the temporal dynamics of emotion, sustained reward responsiveness, were associated with anhedonia. Two experiments were conducted in outpatients diagnosed with SZ (n = 28; n = 102) and healthy controls (n = 28; n = 71) who completed EMA reports of emotional experience at multiple time points in the day over the course of several days. Markov chain analyses were applied to the EMA data to evaluate stochastic dynamic changes in emotional states to determine processes underlying failures in sustained reward responsiveness.*Results:* In both studies, Markov models indicated that SZ had deficits in the ability to sustain positive emotion over time, which resulted from failures in augmentation (ie, the ability to maintain or increase the intensity of positive emotion from time t to t+1) and diminution (ie, when emotions at time t+1 are opposite in valence from emotions at time t, resulting in a decrease in the intensity of positive emotion over time). Furthermore, in both studies, augmentation deficits were associated with anhedonia.*Conclusions:* These computational findings clarify how abnormalities in the temporal dynamics of emotion contribute to anhedonia.**

Key words: ecological momentary assessment/experience sampling/network analysis/Markov chain analysis/emotion/reward/anhedonia

Introduction

Anhedonia is prevalent in schizophrenia (SZ) and a critical treatment target because it is associated with poor clinical outcomes (eg, illness liability, recovery, well-being).[1–4] Unfortunately, currently available treatments are ineffective at remediating anhedonia.[5] Limited treatment progress is due in part to inadequate knowledge regarding mechanisms underlying the symptom.[6] Initially, it was assumed that anhedonia in SZ occurred similarly to major depression and that it reflected a diminished hedonic capacity.[7] However, laboratory-based studies provide little evidence for an impairment in initial reward response in SZ: Self-report and neurophysiological response to rewarding stimuli/outcomes are intact.[8–11] Rather, anhedonia in SZ has been proposed to reflect abnormalities in the temporal dynamics of positive emotion.[12] In particular, anhedonia may reflect a failure to *sustain reward response* over time.[13] Essentially, experiences of positive emotion, although fully intact initially, may be too fleeting to promote the initiation of frequent approach behaviors aimed at obtaining rewards.[12,13] Preliminary support for a deficit in the persistence of positive emotion after intact initial responsiveness has been found in 2 laboratory-based studies examining activation of the prefrontal cortex and the ability to sustain the affect modulated startle response following stimulus offset.[14,15] Deficits in emotion persistence also drive abnormalities in decision-making processes underlying motivated behavior.[16]

Although these initial laboratory-based studies offer promising initial support for the temporal dynamics of emotion theory,[12,13] they provide little insight into how failures in the ability to sustain reward responses may arise in the real world to contribute to anhedonia. The current study addressed this gap in the literature using ecological momentary assessment (EMA), a naturalistic technique for obtaining data in situ that has demonstrated good adherence and tolerability in SZ.[17,18] Markov chain analyses were constructed using EMA data to evaluate stochastic dynamic changes in emotional states and determine how the experience of emotion at a current time point (time t) influences the experience of emotion at a later time point ($t + 1$). We used these models to evaluate a novel hypothesis about 2 affective mechanisms underlying the failure to sustain reward responses: augmentation and diminution.

Augmentation refers to an increase in the intensity or duration of emotion from time t to $t + 1$.[19] Valence consistency is critical to augmentation. Specifically, when the valence of the current and subsequent emotional state are similar, there is an additive effect that results in an increase in emotional intensity over time or sustained experience of that emotion. Additive effects of consistent positive or negative emotions across time are critical for driving the initiation of approach or avoidance behaviors, respectively.[19]

In contrast, diminution occurs when emotions at time $t + 1$ are opposite in valence from emotions at time t or positive and negative emotions are tightly coupled and co-occurring. Either of these instances of diminution might result in a decrease in positive emotion intensity over time or a reduction in how long the original emotion is sustained.[19] Several diminution outcomes can occur. One set of outcomes depends on whether the initial emotion is negative or positive. When the initial emotion at time t is negative and followed by a subsequent positive emotion at time $t + 1$, it is typical for an "undoing effect" to occur, where the intensity or duration of the original negative emotional state is diminished.[19,20] In contrast, when the initial emotion at time t is positive and followed by a subsequent negative emotion at time $t + 1$, the result is either diminished intensity or duration of positive emotion.[19] Alternatively, another set of outcomes can occur when positive and negative emotions are densely connected. When positive and negative emotions are tightly coupled, the intensity or duration of positive emotion may diminish across time because of emotional co-activation that produces opposing emotion effects.[19]

Abnormalities in either augmentation or diminution could account for the reductions in sustained reward responsiveness that characterizes anhedonia in SZ. Importantly, these deficits may occur even in the context of fully intact initial reward responses. For example, if experiences of positive emotion at time t do not increase the probability of experiencing subsequent positive emotions of equal or higher intensity at times $t + 1$ and beyond (ie, augmentation), SZ may not have the affective "momentum" needed to initiate frequent pleasurable activities. Additionally, if SZ demonstrate an emotion network that has a greater number and intensity of temporal connections between positive and negative emotions, 2 diminution abnormalities may contribute to anhedonia: (1) a failure to exhibit normative "undoing effects" of positive emotion on negative emotion and (2) negative emotions may lower the intensity or duration of previously experienced positive emotions. In both instances of diminution, the temporal connections between negative and positive emotions may contribute to a reduction in pleasurable activity because the opposing valence effects result in a state that is not "pure" enough to motivate approach behavior.

In the current study, it was hypothesized that abnormalities in both augmentation and diminution would account for the reductions in the ability to sustain experiences of positive emotion in SZ and individual differences in anhedonia. Specifically, we hypothesized that: (1) Markov chain analysis would indicate that SZ have lower PageRank values for positive emotion and higher PageRank values for negative emotion than CN, consistent with reduced persistence of positive emotion and increased persistence of negative emotion (augmentation abnormalities); (2) Markov chain analysis would indicate that SZ have higher scores than CN for metrics measuring the number of nodes and density, consistent with a greater degree of connectedness and co-occurrence of positive and negative emotions; (3) Markov chain analysis would indicate that when CN experience moderate levels of positive emotion concurrently with high levels of negative emotions at time t, they would experience lower levels of negative emotion at time $t + 1$, consistent with an undoing effect of positive emotion on negative emotion. However, this was not expected to be true of SZ, for whom negative emotions were predicted to remain high at time $t + 1$. (4) The aforementioned deficits in hypotheses 1–3 were expected to occur even in the context of fully intact initial reward responses in-the-moment[21–23] and to predict clinically rated anhedonia.[14,15] Two experiments were conducted to evaluate these hypotheses. The first experiment was a preliminary test of the hypotheses in a smaller sample with a smaller number of daily EMA surveys. The second experiment attempted to replicate the results of the first experiment in a larger sample with more daily EMA surveys.

Method

Participants

Experiment 1. Participants included 30 individuals meeting Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision (DSM–IV–TR: American Psychiatric Association, 2000) criteria for SZ or schizoaffective disorder (SZ) and 30 healthy controls (CN).[24] SZ were recruited from outpatient mental health clinics and via advertisements. All patients were evaluated during periods of clinical stability, defined as no change in medication type or dose within the past 6 weeks. Diagnosis was established via a best-estimate approach that relied on psychiatric history and was confirmed via the Structured Clinical Interview for DSM-IV.[25] CN were recruited through printed, online, and television advertisements and word of mouth among enrolled participants. All CN underwent a diagnostic interview, including the SCID-I and SCID-II,[26] and did not meet criteria for any current Axis I disorder or Axis II SZ-spectrum personality disorder. CN also had no family history of psychosis and did not meet lifetime criteria for psychotic disorders. No participants met the criteria for substance dependence in the last 6 months and all denied lifetime history of neurological disorders.

Experiment 2. Participants included 105 individuals with SZ and 76 CN. Outpatients were recruited from board-and-care homes/supported housing residences, mental health clinics, and clubhouses in the UC San Diego Health, San Diego County Mental Health, and Veterans Affairs San Diego Healthcare Systems. All SZ patients met *DSM-5* diagnostic criteria for SZ or schizoaffective disorder based on *SCID interview*, were between the ages 18 and 65, prescribed antipsychotic medication(s), had no medication changes in month prior to study or anticipated changes in the near future, fluent in the English language, able to give valid informed consent, and able to identify 1 informant who agreed to provide real-world functioning ratings.[27] CN were recruited from posted advertisements and word of mouth among enrolled participants and had no *DSM-5* diagnoses of past or current mood, anxiety, or psychotic disorders (based on the *SCID-Nonpatient Version*), were aged 18 to 65, and fluent in English. Both SZ and CN participants were excluded for the self-reported history of neurological disorders, current substance dependence meeting *DSM-5* criteria in the past year, uncooperativeness with in-lab assessments, and sensory limitations, including vision uncorrectable to 20/40, color blindness, or hearing loss that interferes with the assessment.

Procedures

In both experiments, the study consisted of 3 phases: (1) a pre-EMA initial visit, (2) several days of in vivo EMA, and (3) a post-EMA visit to return the device.

Experiment 1. The first phase consisted of a single visit to the laboratory, where participants completed diagnostic (SCID I and II) and symptom interviews (patients only). In experiment 1, interviews included the Brief Negative Symptom Scale (BNSS),[28–30] Psychotic Symptoms Rating Scale (PSYRATS),[31] and Level of Function Scale (LOF).[32]

Participants were provided with an electronic Palm Pilot Personal Digital Assistant (PDA) (version m500) preprogrammed with Experience Sampling Program software (ESP: http://www.experience-sampling.org). This software restricted the use of the PDA to the researcher-generated EMA-specific questions and allowed participant responses to be stored on the PDA for secure download. Participants then received instruction in the use of the PDA and a demonstration of the questions that would be asked. Follow-up calls were made after this first day to answer participant questions and troubleshoot any problems encountered.

In phase 2, there was a 6-day EMA period between laboratory visits where surveys were administered 4 times per day between the hours of 9:00 AM and 9:00 PM at quasi-randomized times within specified epochs (9:00 AM–12:00 PM, 12:01 PM–3:00 PM, 3:01 PM–6:00 PM, 6:01 PM–9:00 PM). There were a total of 24 surveys across the 6 days. Participants had 15 min to initiate the survey once it became available. Attempts to answer the survey after 15 min were not accepted, but the next survey would initialize as scheduled irrespective of the missed survey. Once initialized, participants were able to take as much time as needed to answer the questions. The 3 surveys prompted between 9:00 AM and 6:00 PM focused on in-the-moment reports. The 1 evening survey (6:01 PM–9:00 PM) included questions that required the participant to retrospectively report on experiences throughout the day (not included in analyses here).

EMA surveys probed for the following information in experiment 1:

1. *Emotional intensity reports*: There were 5 positive and 5 negative emotion items rated on a 1 (not at all) to 5 (extremely) scale using a current timeframe (ie, "right now"). The 5 positive items included: (1) amused, fun-loving, silly; (2) content, serene, peaceful; (3) happy, joyful, glad; (4) love, closeness, trust; (5) proud, confident, self-assured. The 5 negative items included: (1) angry, irritated, annoyed, (2) sad, downhearted, unhappy, (3) scared, fearful, afraid; (4) ashamed, humiliated, disgraced; (5) anxious, nervous, pressured.
2. *Context reports:* Participants were prompted to provide information about their current activities, whereabouts, and companions at the time of each beep. They were also asked to provide an emotional context for the survey (ie, if the most emotional event during the past hour was positive, negative, or neutral).

In phase 3, participants returned to the laboratory 1 week after the initial study visit to return their devices and receive study payment ($20 per hour for laboratory testing, $1 for each EMA survey, and $40 bonus for returning equipment).

Experiment 2. The first phase consisted of diagnostic (SCID) and clinical interviews: brief Psychiatric Rating Scale (BPRS),[33] Clinical Assessment Inventory for Negative Symptoms (CAINS),[34] and measures of functioning (Specific Levels of Functioning, Independent Living Skills Survey, and UCSD Performance Based Skills Assessment-Brief).[35–37] An EMA training session (typically <20 min) was provided on how to operate and charge the phone and complete EMA surveys.

In phase 2, participants were provided with a Samsung smartphone with Android OS. EMA surveys were administered 7 times per day for 7 days via Samplex47 software. EMA surveys were set to occur at stratified random intervals, with on average1.5-h windows between them from 9 AM to 9 PM (adjusted to accommodate individual sleep/wake schedules). Survey alerts could be silenced for 30-min intervals (eg, driving, classes). Completed surveys were time-stamped and had to be completed within a 15-min period following the prompt. Devices were set to disallow any other cell phone features other than the study app. Research assistants called participants on the first and third days of phase 2 to troubleshoot and encourage adherence.

EMA Surveys probed for the following information:

1. Emotional intensity reports: In-the-moment reports of emotional intensity were captured on a 1 (not at all) to 7 (extremely) scale for 2 positive (happy, relaxed) and 2 negative (sad, worried) items.
2. Context: Participants were prompted to respond to check-box questions asking about activity, location, and social context over the past hour.

In phase 3, participants returned to the laboratory to return their devices and receive study payment ($50 for initial laboratory visit, $1 per EMA survey completed).

Data Analysis

The same analytic plan was applied to both experiments. EMA compliance was first evaluated per group. Linear mixed modeling with an autoregressive (AR1) covariance structure was performed to examine group (SZ, CN) differences in emotion intensity for in-the-moment reports of positive and negative emotions. Analyses were nested within day and within individual. Maximum likelihood estimation was selected to account for missing data.

To evaluate hypotheses related to *augmentation*, we developed stochastic dynamical systems models of transitions in emotional experience from the EMA data (see figure 1 for an overview, table 1 for equations and descriptions, Supplemental Materials for additional details). The input data used in model development were the time series data of the positive/negative emotional states from all days of data collection. The data were first preprocessed to reduce the emotional states into high, moderate, and low-intensity levels. Then the processed data with reduced states were translated into a stochastic Markov chain model of emotional transitions by measuring transition probabilities from one emotional state to another. This model allowed for evaluation of temporal connections between emotions from one time point to the next. PageRank, a measure of the persistence of positive or negative emotion across time (ie, the change in intensity from time t to $t + 1$), was the primary dependent variable on which groups were compared using ANOVA.

To evaluate hypotheses related to diminution, Markov chain analysis was conducted to examine: (1) the transitions between positive and negative emotional states across time and whether positive emotion has an "undoing effect" on negative emotion and (2) how tightly coupled negative and positive emotion states are and how the strength of those connections change across time. The input data were the time series data of the combination of positive and negative emotional states reduced to the high, moderate, and low-intensity levels. Crossing 2 reduced state sets results in a 3 × 3 positive emotion-negative emotion combined states, ranging from low-low to high-high. The resulting combinations allowed for an examination of the temporal effects of negative emotions at time t on the change in positive emotion from time t to $t + 1$. Density and number of nodes were used to estimate the extent that emotional states are interconnected in the network. Topographical maps were used to demonstrate the presence of the undoing effect by comparing transitions among emotional states of interest (eg, when positive and negative emotion are elevated at time t, does negative emotion remain elevated at time $t + 1$).

To evaluate hypothesis 4 related to anhedonia, correlations between key modeling metrics and clinically rated anhedonia scores were calculated with the BNSS in experiment 1 and CAINS in experiment 2. To visually illustrate the symptom effects found via Markov chain analyses, results were plotted for SZ patients divided into high (experiment 1: $n = 13$; experiment 2: $n = 52$) and low (experiment 1: $n = 15$; experiment 2: $n = 52$) anhedonia subgroups via a median split on the BNSS (items 1–3) or CAINS (items 3, 4, 6, 8, 9) anhedonia items. This was done solely for plotting purposes to depict effects; no analyses were conducted categorically using these subgroups. The effect of symptoms was evaluated using a continuous, dimensional approach using correlations.

Results

EMA Compliance

In experiment 1, 2 SZ and 1 CN were excluded for not reaching a priori compliance standards defined as responding to less than 25% of surveys administered. An additional CN was excluded from analyses due to a malfunctioning PDA. The remaining participants constituted the final sample: SZ: $n = 28$; CN: $n = 28$. In experiment 2, 3 SZ and 5 CN were excluded for not reaching a priori compliance standards. The remaining participants constituted the final sample: SZ: $n = 102$; CN: $n = 71$. Among the final samples, EMA compliance was high and comparable between groups and Experiments (experiment 1: CN: M = 87.5%; SZ: M = 90.2%; experiment 2: CN: M = 85%; SZ: M = 86%). In both experiments, final groups did not differ on age, parental education (collected only in study 1), sex, or

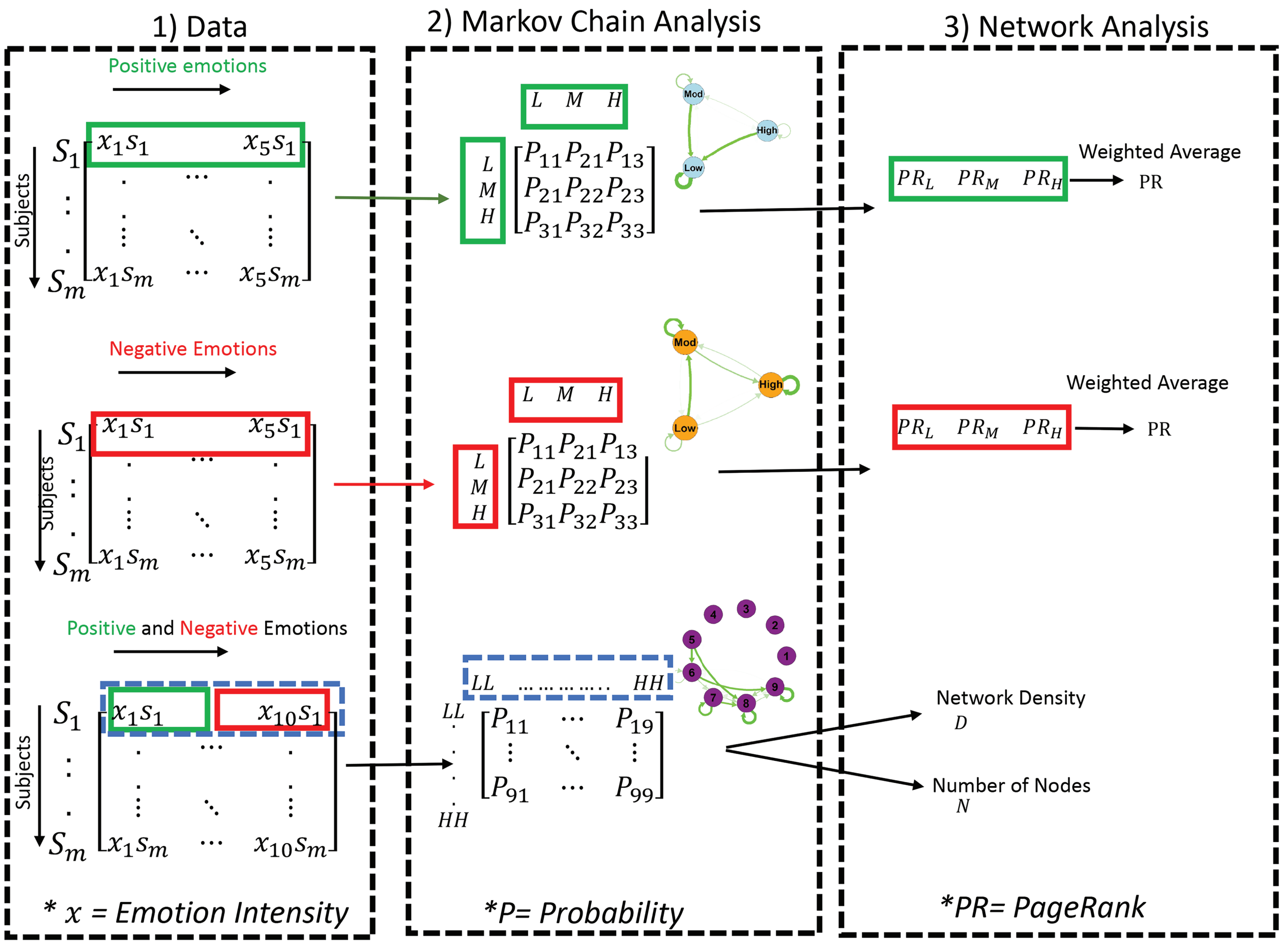


Figure 1. Schematic representation of the modeling framework. *Note*: For each participant, the EMA data were analyzed within each day. For the Markov chain analysis, the data were first discretized into low, moderate, and high emotional states. Two types of state spaces matrices were created from this process. One was a 3 × 3 and the other a 9 × 9 matrix. Density was calculated on the 9 × 9 transition matrix and PageRank was calculated for the 3 × 3 transition matrix.

ethnicity; however, SZ had significantly lower personal education than CN (see table 2).

In-the-Moment Emotion Reports

In experiment 1, groups did not differ on current positive emotion, and SZ experienced more negative emotion than CN. There was also no significant Group × Emotional Context interaction for positive emotion when we evaluated surveys where participants indicated the situation was positive, negative, or neutral: $F = .82$, $P =$ n.s. In experiment 2, SZ reported less positive emotion and more negative emotion than CN (see table 3).

Sustaining Emotional Experience Over Time

Augmentation. In experiment 1, results of the Markov chain analysis examining abnormalities in augmentation indicated that SZ had higher PageRank values than CN for negative emotion, $F(1, 54) = 7.53$, $P < .01$, indicating that negative emotion persistence across time is greater in SZ than CN. SZ and CN did not differ in PageRank for positive emotion, $F(1, 54) = 0.04$, $P = .84$. However, as hypothesized, the correlation between BNSS anhedonia and PageRank for positive emotion was statistically significant in SZ, $r = -0.48$, $P < .02$. This effect is depicted visually in figure 2A, which shows that CN and low anhedonia SZ were more likely to maintain or increase levels of positive emotion from one time point to the next than high anhedonia SZ (see thickness of lines and directionality, where SZ with anhedonia are more likely to transition from high or moderate to low positive emotion, but not to transition upwards from low to moderate or moderate to high positive emotion). PageRank for negative emotion was not significantly associated with BNSS anhedonia.

In experiment 2, SZ had lower PageRank values for positive emotion than CN, $F(1, 172) = 12.44$, $P < .001$, consistent with a deficit in sustaining reward responsiveness across time. SZ also had higher PageRank values than CN for negative emotion, $F(1, 172) = 19.01$, $P < .001$, indicating that SZ sustain experiences of negative emotion more than CN. The correlation between CAINS anhedonia

Table 1. Summary of the Mathematical Models

Type	Measure	Definition	Clinical Meaning	Equation
Markov chain modeling	Transition probability	Probability of transitioning from one emotional state at time t to another emotional state at time $t+1$	Strength of transition between emotional states from time t to $t+1$	$\bar{x} = \sum_{i=1x}^{m} x_i$ $S = \{1, 2, ..., s\}$ $P_{mm} = pr(\bar{x}_{t+1} = n \mid \bar{x}_{t=m}), m, n \in S$ $P_{mm} = pr(\bar{x}_{t+1} = n \mid \bar{x}_{t=m}), m, n \in S$
	PageRank	ith element of the dominant eigenvector v of the transition probability matrix	Temporal strength of emotions in the network (emotional states that send more connections are more important)	$PRi = vi$
	Density	Sum of the edge weights in the network	The extent that nodes of the network are interconnected	$D = \frac{\sum_{i,j \in N} w(i \to j)}{N(N-1)}$
	Number of nodes	Number of emotional states in the network (ie, constructed based on transition probability matrix)	The possible number of states that each emotional state transitions	$N = positive \begin{pmatrix} \text{low, moderate, and high} \\ \text{emotional states} \end{pmatrix} \times negative \begin{pmatrix} \text{low, moderate, and high} \\ \text{emotional states} \end{pmatrix}$

Note: x = Emotional response; $\bar{x}$ = Average emotional response; S = Discrete set of all possible emotional sates; P = Probability that one emotional state at time t will change to another emotional state at time $t + 1$; v = Dominant eigenvector of the transition matrix (P); i, j = Node (emotional state/intensity) index; N = Total number of nodes; $wi \to j$ = Weight between nodes i and j.

Table 2. Participant Demographics in Experiments 1 and 2

Experiment 1	SZ (n = 28)	CN (n = 28)	Test Statistic, P-value
Age	41.39 (10.76)	43.75 (11.75)	$F = 0.61$, $P = .44$
Parental education	13.45 (2.60)	13.20 (1.98)	$F = 0.15$, $P = .70$
Participant education	13.27 (1.94)	14.96 (2.12)	$F = 9.57$, $P < 0.01$
% Male	57.1%	64.3%	$\chi^2 = 0.30$, $P = .58$
Ethnicity			$\chi^2 = 3.02$, $P = .70$
Caucasian	78.6%	82.1%	
African American	3.6%	7.1%	
Biracial	7.1%	3.6%	
Hispanic	7.1%	3.6%	
Asian	0.0%	3.6%	
Native American	0.0%	0.0%	
Native Hawaiian/Pacific Islander	0.0%	0.0%	
Other	3.6%	0.0%	
Experiment 2	SZ (n = 102)	CN (n = 71)	Test statistic, P-value
Age	51.5 (9.6)	49.8 (11.2)	$F = 1.13$, $P = .29$
Participant education	13.0 (1.9)	14.6 (1.8)	$F = 29.5$, $P < .001$
% Male	71.3%	62.5%	$\chi^2 = 1.48$, $P = .15$
Ethnicity			$\chi^2 = 8.35$, $P = .21$
Caucasian	35.6%	45.8%	
African American	42.6%	25.0%	
Biracial	2.0%	0%	
Hispanic	11.9%	16.7%	
Asian	4.0%	8.3%	
Native American	3.0%	2.8%	
Native Hawaiian/Pacific Islander	1.0%	1.4%	
Other			

and PageRank for positive emotion, $r = -0.39$, $P < .001$, and negative emotion was significant ($r = 0.21$, $P = .03$). These augmentation abnormalities are depicted visually in figure 2B, which shows that SZ with high anhedonia are less likely to maintain or increase levels of positive emotion and less likely to decrease negative emotion from one time point to the next. 1) In Experiment 1, there were a total of 455 daily prompts completed in SZ and 441 in

Table 3. Positive and Negative Emotional Experience in Experiments 1 and 2

	Positive (M, SD)	Positive (F, *P*-Value)	Negative (M, SD)	Negative (*F*, *P*-Value)
Experiment 1		$F = .15$		$F = 8.56^{**}$
CN	1.59 (.83)	—	0.29 (0.30)	—
SZ	1.50 (.83)	—	0.73 (0.74)	—
Experiment 2		$F = 422.8^{***}$		$F = 922.3^{***}$
CN	5.37 (1.24)	—	1.54 (1.01)	—
SZ	4.68 (1.52)	—	2.54 (1.58)	—

Note: CN = healthy control; SZ = schizophrenia.
$^{*}P < .05$, $^{**}P < .01$, $^{***}P < .001$.

CN, with a total of 275 consecutive prompts used for these analyses in SZ and 275 for CN (ie, on average there were 9.82 consecutive reports used in SZ and 9.82 in CN throughout the 6 days), and 2) For Experiment 2, there were a total of 4318 daily prompts completed in SZ and 2989 in CN, with a total of 3612 consecutive prompts used for these analyses in SZ and 2492 for CN (ie, on average there were 34.4 consecutive reports used in SZ and 32.78 in CN throughout the 7 days).

Diminution. In experiment 1, the results of Markov chain analysis for combined positive and negative emotional states indicated that SZ had a higher number of nodes than CN, $F(1, 54) = 6.10$, $P < .02$, and a trend toward higher density scores, $F(1, 54) = 3.31$, $P = .07$. In experiment 2, SZ had a higher number of nodes than CN, $F(1, 172) = 40.48$, $P < .001$, and higher density scores, $F(1, 172) = 39.45$, $P = .001$. These findings indicate that SZ display stronger temporal connections between individual positive and negative emotions than CN (see figure 3A and 3B, increased number of and thickness of lines reflecting more dense connections). In both experiments, anhedonia was not significantly associated with network density or number of nodes.

Discussion

Consistent with hypotheses, we found evidence for a failure in the ability to sustain experiences of positive emotion over time in SZ (experiment 2), especially in patients with higher clinically rated anhedonia (experiments 1 and 2). Mathematical models provided evidence for a failure to sustain reward responsiveness in 2 ways, which we refer to as augmentation and diminution.

An augmentation deficit was evident in SZ patients, particularly those with high clinically rated anhedonia, who displayed a failure to increase or maintain the intensity of positive emotion from time t to $t + 1$ in Markov chain models evaluating PageRank. These findings are consistent with laboratory-based results, which demonstrated that although initial positive emotional responses are intact in SZ, they fail to persist for ~3–5 s.[14,15] The current findings extend these initial laboratory-based studies in an important way, by showing that deficits in positive emotion persistence also occur in the real-world and extend to much longer time frames and when emotion is not necessarily anchored to a specific stimulus/event. These findings offer a novel perspective on why individuals with SZ are less likely to engage in pleasurable activities. The extent to which positive emotion persists throughout the day may increase the likelihood of completing multiple pleasurable activities throughout the day in CN because the affective "momentum" generated is sufficient to motivate behavior. The degree of positive emotion persistence observed in SZ may not be sufficient to facilitate frequent approach behavior.

As hypothesized, a diminution effect was also present. However, the diminution abnormality was a diagnosis level effect that occurred in patients with low and high clinically rated anhedonia in both experiments. This suggests that the effect is relevant not only to anhedonia but also the diagnosis more generally. Two types of diminution abnormalities were observed. First, positive emotions shared abnormally strong temporal connections with negative emotions in SZ (figure 3). This finding is consistent with prior studies indicating that SZ is associated with increased emotional co-activation (ie, concurrent experiences of positive and negative emotion) that lowers the overall net hedonic value experienced in-the-moment.[38–40] Our findings extend prior laboratory-based findings by demonstrating that emotional co-activation persists across time and directly impacts the persistence of positive emotion. Second, positive emotions failed to result in the typical undoing effects on negative emotion in SZ. As can be seen in figure 3, when CN experienced moderate levels of positive emotion concurrently with high levels of negative emotions at time t, they were likely to experience lower levels of negative emotion at time $t + 1$ (thick arrow from nodes 5 to 8). However, this was not true of high anhedonia SZ, for whom negative emotions tend to remain high at time $t + 1$ despite moderately intense positive emotions at time t (no arrow from 5 to 8). Thus, for high anhedonia SZ, positive emotions fail to have the normative "undoing" effect on negative emotions (see figure 3). Positive emotions, therefore, fail

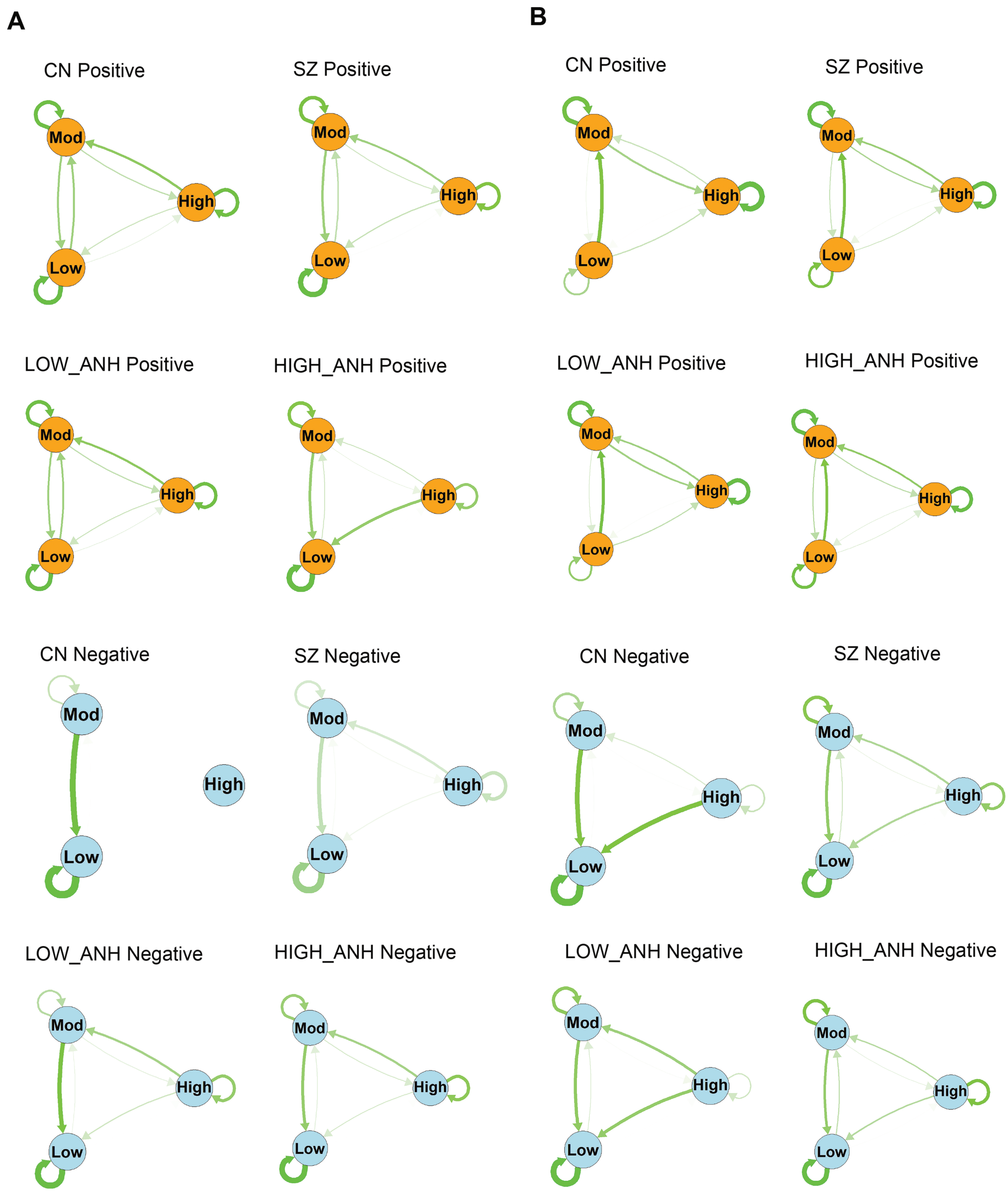
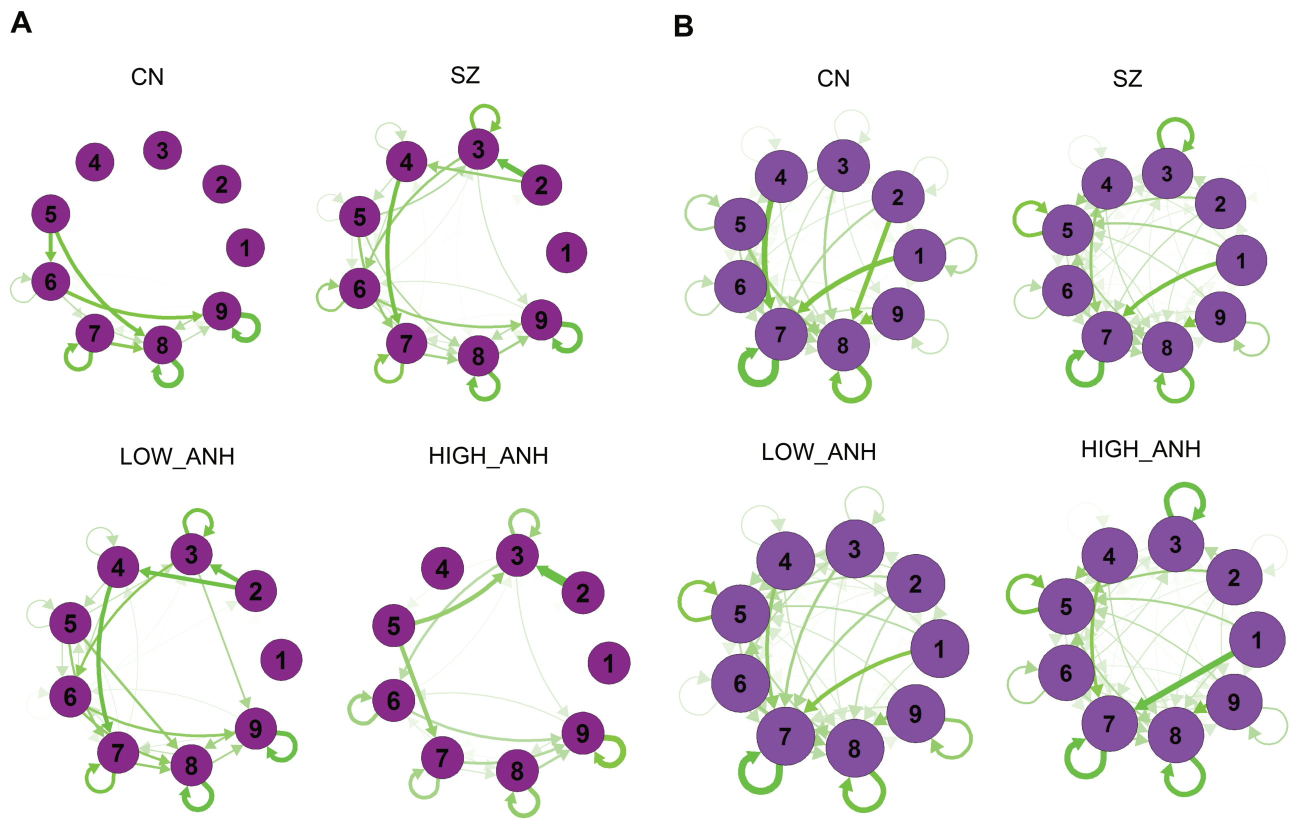


Figure 2. (A) Augmentation: Markov chain analysis transition matrix among positive (upper part) and negative (lower part) emotion states from time t to $t + 1$ in the experiment. (B) Augmentation: Markov chain analysis transition matrix among positive (upper part) and negative (lower part) emotion states from time t to $t + 1$ in experiment 2. *Note*: Graphic display of transition matrix obtained from Markov chain analysis for positive emotions. The nodes (circles) represent positive /negative emotional states (high, moderate, low). The arrows represent the transition from one emotional state at time t to another emotional state at time $t + 1$ within each day. Arrow thickness indicates the strength of transition. Orange = Positive; Blue = Negative

to have a typical benefit of reducing negative emotion, leaving negative emotions unchecked and chronically elevated over time. In both instances of diminution, the temporal connections between negative and positive emotions are maladaptive, contributing to a reduction in pleasurable activity because the opposing valence effects result in a hedonic state that is not "pure" enough to motivate approach behavior.

These findings extend Kring's[12,13] temporal dynamics of emotion model in several ways. First, they suggest that the increased persistence of negative emotion, not just decreased persistence of positive emotion, makes an important contribution to anhedonia. Second, negative and positive emotions are not static entities that function in isolation; rather, they have dynamic interactions and their interconnectedness may contribute to



	Positive High	Positive Moderate	Positive Low
Negative High	1	2	3
Negative Moderate	4	5	6
Negative Low	7	8	9

Figure 3. (A) Diminution: Markov chain analysis transition matrix of combined positive and negative emotional states in experiment 1. (B) Diminution: Markov chain analysis transition matrix of combined positive and negative emotional states in experiment 2. *Note*: Markov chain transition matrix. Nodes represent emotional states. Arrows represent transitions from one state at time *t* to another at time *t* + 1 within day. Arrow thickness represents transition strength. Numbers correspond to these states: 1: Neg High/Pos High, 2: Neg High/ Pos Mod, 3: Neg High/Pos Low, 4: Neg Mod/Pos High, 5: Neg Mod/ Pos Mod, 6: Neg Mod/Pos Low, 7: Neg Low/Pos High, 8: Neg Low/Pos Mod, 9: Neg Low/Pos Low.

anhedonia. SZ patients are prone to densely connected emotional states, where negative emotions have dysfunctional interactions with positive emotion that reduce the duration and intensity of pleasurable experiences. In CN, positive emotions have an adaptive quality in that they reduce concurrently or subsequently experienced negative emotions. A certain degree of positive emotion persistence may be needed for this undoing effect to occur, and positive experiences do not appear to persist long enough to undo negative emotions in SZ. Thus, it may be beneficial to update the temporal dynamics of emotion model to incorporate interactive negative emotion processes that impact positive emotion duration and intensity.

Experiment 1 had certain limitations. The EMA design included relatively few in-the-moment reports. The sample size was also relatively small, potentially making individual difference analyses related to anhedonia less reliable. These limitations were addressed by experiment 2, which had approximately 3 times as many participants and more than double the number of EMA surveys per day. Other limitations included: exclusively enrolling patients in the chronic phase of illness, examination of predominantly medicated patients, and reliance on a single method (EMA surveys) to measure the temporal dynamics of emotion. Additionally, the literature on whether EMA in-the-moment reports of positive emotion are intact or reduced is inconsistent[21–23]; the nonsignificant group effect in experiment 1 and significant group effect in experiment 2 highlight this inconsistency further. Future studies are needed to determine factors influencing inconsistent findings (eg, context, frequency of pleasurable activities).

Despite these limitations, our computational modeling results provide novel evidence that anhedonia reflects an abnormality in the temporal dynamics of emotional experience. Treatments focusing on enhancing the persistence of positive emotion have been developed for healthy individuals[41] and demonstrated efficacy for anhedonia in a pilot psychosocial trial in SZ patients.[42,43] The current findings suggest novel ways of modifying these interventions to target the dynamic and interactive emotion mechanisms that are associated with anhedonia.

Supplementary Material

Supplementary data are available at *Schizophrenia Bulletin* online.

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Author Contribution

Drs Strauss and Sayama formulated the research question and devised the analytic plan. Computational models were performed by Dr Zamani-Esfahlani. Basic analyses were performed by Dr Strauss, Ms Visser, and Ms Bartolomeo. Dr Strauss wrote the first draft of the manuscript, all other authors edited and contributed to the final draft of the manuscript.

Data Availability

Data will be made available upon request.

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