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The Affective Benefits of Real-World Exploration During the COVID-19 Pandemic

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Increasing daily exploration is linked to improvements in affective well-being. However, COVID-19 elevated uncertainty when leaving the home, altering the risk-reward of balance of geospatial novelty. To this end, we simultaneously collected real-world geospatial tracking and experience sampling of emotion, prior to and during the first year of the pandemic in 630 individuals. COVID-19 reduced exploration and subjective well-being. Yet, despite the health risks of exploring during the pandemic, the days of highest affective well-being were those when individuals explored the most. However, this was not true for everyone: during the first months of the pandemic, at the height of the uncertainty surrounding the transmissibility and prognosis of a COVID-19 infection, more anxious individuals experienced no affective benefit to leaving home. Taken together, real-world exploration improved well-being regardless of the presence of real-world threat, but anxiety mitigated these benefits.

General Scientific Summary

Evidence suggests that increasing the diversity of daily experience improves emotional well-being; however, the COVID-19 pandemic altered how we engage with our world, elevating the threat of leaving home. COVID-19 reduced exploration and subjective well-being, yet exploratory behavior still boosted positive emotion throughout the pandemic. During the first months of the pandemic, at peak COVID-19 uncertainty, heightened anxiety mitigated the emotional benefits of exploration.

Keywords: COVID-19, geolocation tracking, positive emotion, exploration; anxiety

Supplemental materials: https://doi.org/10.1037/abn0000888.supp

On March 11, 2020, the World Health Organization (2020) declared COVID-19 a global pandemic and 2 days later the United States government declared a national emergency. Due to the health risks of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) exposure, governments enacted social distancing, self-quarantining, and stay-at-home mandates. These orders reduced individuals' ability to leave their homes, explore their environment, and ultimately experience novelty. Moreover, particularly in the first months of the pandemic, when we knew virtually nothing about the prognosis and transmissibility of the coronavirus, the uncertainty and risks of going out and exploring new spaces was higher than it had ever been for many Americans.

The choices we faced during the initial months of the COVID-19 pandemic can be understood within the classic explore–exploit dilemma: humans continually face the decision to exploit locations with known properties or explore spaces of uncertain, but potentially greater value (Cohen et al., 2007). Not only does exploration expose organisms to novel and diverse environments (i.e., experiential diversity), but exploration also confers beneficial psychological consequences (van Praag et al., 2000). For instance, in rodents, novel environments drive increases in play, social affiliative behaviors, stress resilience, and optimistic evaluative biases (Brydges et al., 2011; Kempermann, 2019; Laviola et al., 2004; Marashi et al., 2003). Meanwhile, the benefits of exploration in humans have

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T. Rick Reneau served as lead for data curation, formal analysis, methodology, and writing–original draft and served in a supporting role for conceptualization. William J. Villano served in a supporting role for conceptualization, data curation, writing–original draft, and writing–review and editing. Brittany A. Jaso served in a supporting role for project administration and writing–review and editing. Aaron S. Heller served as lead for conceptualization, funding acquisition, and writing–review and editing and contributed equally to investigation and methodology.

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been characterized in multiple domains. For example, exploration in enriched environments has been suggested to potentially slow cognitive decline (Kempermann, 2019) and increased rate of rehabilitation after stroke (Janssen et al., 2010). Further, it appears that entropic environments lead to better spatial navigation (Coutrot et al., 2022). Additionally, behavioral activation, which often involves exploration of new spaces and experiences associated with uncertainty, is an evidence-based treatment for depression and anxiety symptoms (Boswell et al., 2017). Despite this characterization of the broader benefits of exploration, there is limited research investigating the direct association between geospatial exploration and well-being. We previously demonstrated that geospatial exploration in the form of experiential diversity is positively linked to positive affect (PA) (Heller et al., 2020; Saragosa-Harris et al., 2022), however, it is unclear whether or not such a relationship exists in the context of an environmental threat such as COVID-19.

Individuals with elevated anxiety may be particularly sensitive to the uncertain risks present in novel environments. Evidence suggests that anxiety and a sensitivity to uncertainty decrease the tendency to explore. For instance, in humans, generalized anxiety symptoms are associated with an increase in the likelihood of interpreting novel contexts as threatening (Chen & Lovibond, 2020; Grupe & Nitschke, 2013), and rodent and nonhuman primate models of anxiety all share a tendency to avoid novel contexts (Grillon, 2008; Hughes, 2007; Rosen & Schulkin, 1998).

We thus examined the impact of the COVID-19 pandemic on real-world exploration and emotion, and assessed whether the uncertain risks present in the initial months of the pandemic fundamentally altered the subjective emotional benefits of exploration. To do this, we recruited three large cohorts of human young adults, one enrolled before COVID-19 (September 2019–December 2019; $n = 135$), one enrolled prior to and during the initial months of the pandemic, when participants were confirmed to be under a stay-at-home lockdown (January 2020–May 2020; $n = 239$; which we refer to as the "acute" pandemic period), and one enrolled once the pandemic had already begun, but after we had begun to map the prognosis of a COVID-19 infection (September 2020–December 2020; $n = 400$; which we refer to as the "chronic" pandemic period). For all participants, we simultaneously collected cellphone-based geolocation tracking alongside experience sampling of positive and negative emotion and frequent assessments of depression and anxiety symptoms. We hypothesized that the pandemic would reduce geospatial exploration and affective well-being. Moreover, we hypothesized that because of the increased risk and uncertainty during the initial (i.e., "acute"; March–May 2020) months of the pandemic, there would be a decreased impact of experiential diversity on affective well-being as compared to before the pandemic. We further hypothesized that as time elapsed (i.e., during the "chronic" period September–December 2020) and humans began to better understand the manner of transmission and prognosis of a COVID-19 infection, that the positive association between experiential diversity and affective well-being would reemerge.

Lastly, given the tendency for people with anxiety to interpret uncertainty as threatening, we hypothesized that levels of anxiety would limit the affective benefits of exploration, specifically during the initial months of the pandemic. We focused on anxiety and novel locations for several reasons: First, in our previous work, we have found that the link between novel locations and positive affect is upwards of 50% larger than roaming entropy (RE) and positive affect (Heller et al., 2020). Second, face and construct validity sugests a clear link between novelty and anxiety, and their links to momentary emotion. For example, animal models show that individuals thought to have a high anxiety phenotype tend to be neophobic (i.e., fearful of novelty; https://www.nature.com/articles/s41398-021-01458-9) and human studies show adults with social anxiety often report low novelty seeking (Chung et al., 2022). In contrast, RE does not incorporate the novelty of the spaces the individual encountered on that day. We also explored depression symptoms as a moderator to address the question of how specific the effects were for anxiety and novel locations.

We did not preregister our hypotheses. Our research questions evolved as the pandemic did, and we chose to continue to gather data to further explore and explain the differences we observed.

Method

Data Collection and Sample

Data collection began on September 3, 2019 and was completed on December 12, 2020.

The sample consisted of three cohorts. Six hundred and thirty-two college students at the University of Miami comprised the three cohorts with some overlap; cohorts contained 135, 239, and 400 subjects, respectively (see Table 1 and Figure S7 in the online supplemental materials). Cohorts were enrolled at the start of academic semesters, and data collection continued until the end of the academic semester. There were 467 (73.9%) females; M_{age}: 19.5, $SD = 1.59$, range = 18–38. The sample consisted of 423 (66.9%) Caucasians, 85 (13.4%) Asians/Pacific Islanders, and 63 (10%) African Americans. Our sample included 183 (29%) individuals identifying as Hispanic. To enroll, participants were required to have a smartphone capable of receiving SMS text messages, and that met system requirements for the GPS application (FollowMee; iOS 9.0 or later or Android 4.1+). All participants provided informed consent through a study protocol approved by the Institutional Review Board at the University of Miami (study number 20180529).

During an initial laboratory session, participants provided informed consent, completed baseline psychopathology questionnaires, and installed the GPS application, *FollowMee*, onto their phones.

Table 1
Demographics of Participants

Sample characteristics	*N*	%	*M*	*SD*	Range
Gender					
Male	165	26.1			
Female	467	73.9			
Age			19.5	1.59	18–38
Race					
Caucasian	423	66.9			
Asians/Pacific Islanders	85	13.4			
African American	63	10			
Ethnicity					
Hispanic/Latino	183	29			
Psychopathology					
GAD-7			5.75	2.52	0–21
PHQ-9			5.85	2.51	0–27

Note. $N = 632$. GAD = general anxiety disorder; PHQ = Patient Health Questionnaire.

Timing of Data Collection Relative to the COVID-19 Pandemic

We divided data into three time periods: (a) pre-COVID-19 period: September 2019–March 7, 2020; (b) acute COVID-19 period: approximately late March 2020–May 2020; and (c) chronic COVID-19 period: September 2020–December 2020. Because the date on which lockdowns were enacted differed by county, we identified for each participant the first day their home county (using their modal geolocation each day) enacted a government-mandated stay-at-home order and used that date as the beginning of that participant's "acute" period.

Participant Locations

All participants were recruited and enrolled in Miami, Florida. However, approximately 63% of all participants left Miami as the acute period of the COVID-19 began (∼March 11, 2020). When participants left Miami, they dispersed across the United States (see Table S4 in the online supplemental materials for list locations).

Geolocation Data Collection and Processing

The FollowMee application collected geolocation data as participants went about their daily lives. FollowMee initializes location sampling whenever the phone's accelerometer detects movement.

Participants' GPS locations were tracked for approximately 3 months. Custom-built algorithms (https://github.com/manateelab/) filtered geolocation data to reduce noise caused by poor cellular connectivity (see Figure S8 in the online supplemental materials).

We quantified geolocation-based experiential diversity via RE and the number of novel locations one explored every day. RE, a measure of geospatial exploration, calculates the proportion of the day spent in each unique location and determines the variability in an individual's physical location over the course of said day (Freund et al., 2013; Heller et al., 2020). We also quantified the number of locations one visits that they have never previously encountered (within the sampling period) as an estimate of the amount of novelty experienced that day (Heller et al., 2020). While RE and novel locations per day are related at the within-person level, $B = 0.350$, $t(59550) = 296.72$, $p < .0001$, previous work (Heller et al., 2020) has demonstrated that the number of novel locations one visits on any given day is more strongly related to PA than RE. Indeed, in these data, we replicate this effect (novel location PA effect: $B = 18.697$; RE × PA effect: $B = 15.039$). As a result of the fact that geospatial novelty was more strongly related to PA than RE, we elected to focus most analyses using number of novel locations.

RE

For each day containing geolocation data, GPS coordinates were rounded to four decimal points of longitude and latitude, downsampled to 1-min temporal resolution, and converted into a measure of daily RE:

$$\mathrm{RE}_i = -\sum_{j=1}^{n} p_{ij} \times (\log_2 p_{ij}).$$

Here, p_{ij} is the within day probability that location j is visited by the participant i (i.e., the proportion of the day spent in each unique location). Thus, RE is higher on days in which one visits a greater number of locations and exhibits greater uniformity in the distribution of time spent in visited locations. A minimum RE value would be achieved by spending all day in a single location, whereas maximum RE would be achieved by spending every minute of the day (1,440) in a unique location.

Unique Geospatial Locations

We determined the number of unique locations each participant visited on each day by extracting the number of unique GPS coordinates (after rounding to four decimal points) per person, per day. Four decimal points approximates to 1,300 ft^2 (121 m^2) of precision. It is important to note that we define a location as any longitude, latitude coordinate that a participant inhabited, regardless of whether they are driving through a point or staying at a location for several hours. This operationalization of a "location" can result in a seemingly high number of novel locations one visits on a given day.

Geospatial Novelty

Geospatial novelty was defined as the number of geospatial locations a participant visited that day that they had not previously encountered during the sample period. Participants' mean number of novel locations per day was 48 ($Mdn = 28$, $SD = 21$, range = 0–126). We also calculated the total time spent at novel locations per day as the number of minutes spent at each novel location. To avoid inflated estimates of novelty early in the observation period, we did not designate a location as novel until 7 days had passed in the observation period.

Determining When a Subject Entered Lockdown

To quantify the date when each participant began their own "acute COVID-19 lockdown," we extracted the modal GPS coordinate for each day, for each participant. We determined the county/city in which the modal coordinate fell using Google's Geocoding API. We then cross-referenced newspapers and government websites to determine whether the state or local government at this modal location had yet mandated "stay-at-home" lockdowns (see Figure S9 and Table S4 in the online supplemental materials).

Experience Sampling of Emotion

Participants completed surveys assessing their current levels of positive affect and negative affect every other day at a pseudorandomly determined time between 10:00 a.m. and 8:00 p.m. Eastern Standard Time (EST). Participants rated the following adjectives to sample an array of affective experience: sad, tired, happy, upset, excited, irritable, content, attentive, stressed, relaxed, and anxious on separate visual analog scales that ranged from 0 (e.g., *not at all anxious*) to 100 (e.g., *very anxious*). We strategically elected to use only a subset of 11 affect items from the larger positve affect and negative affect schedule-X to minimize participant burden, given the high number of assessments used throughout the study. Items were selected to sample across the full dimensions of affective valence and arousal. Based on previous work (Heller et al., 2020), we averaged the scores of happy, excited, content, and relaxed to create a positive emotion measure and averaged the scores of upset, irritable, stressed, and anxious to create a negative emotion measure.

Reliability of positive emotion was .85 and reliability of negative emotion was .87. We cleaned survey responses using EMAeval (Jaso et al., 2021; see the online supplemental materials).

Symptom Measures

We measured depression and generalized anxiety symptoms approximately once per month. Assessments were sent via SMS text messages linked to a Qualtrics survey. The initial cohort did not differ from the cohort recruited during the pandemic in relation to baseline-reported psychopathology, anxiety: $B = 0.154$, $t(2448.05) = 0.536$, $p = .592$; depression: $B = -0.351$, $t(2411.7) = -1.192$, $p = .233$.

Depression

The Patient Health Questionnaire (Spitzer et al., 1999) was used to evaluate participants' depressive symptoms. The PHQ-9 contains nine questions and asks participants to report how often they experienced nine *Diagnostic and Statistical Manual of Mental Disorders* (5th ed.; DSM–5; American Psychiatric Association, 2013) symptoms of depression over the past 2 weeks. Participants answered on a scale from 0 "*not at all*" to 3 "*nearly every day*," with higher scores indicating more frequent depression symptoms. Internal consistency of the PHQ-9 in our sample was excellent (Cronbach's $\alpha = .90$). Subjects completed an average of 3.07 depression assessments ($SD = 1.22$). Participants' mean depression scores were 5.85 ($SD = 2.51$, range = 0–27; Figure S10 in the online supplemental materials).

Generalized Anxiety

Anxiety symptoms were assessed using the Generalized Anxiety Disorder-7 Item Scale (GAD-7; Spitzer et al., 2006). The GAD-7 assesses the frequency of seven primary generalized anxiety symptoms within the last 2 weeks. Item responses range on a scale from 0 "*not at all*" to 3 "*nearly every day.*" Internal consistency of the GAD-7 in our sample was also excellent (Cronbach's $\alpha = .91$). Subjects completed an average of 3.11 generalized anxiety assessments ($SD = 1.22$). Participants' mean anxiety scores were 5.75 ($SD = 2.52$; range = 0–21; Figure S10 in the online supplemental materials).

To link daily geolocation and experience sampling data with internalizing symptoms, monthly symptom scores were interpolated to achieve a per day time series of anxiety and depression severity. Interpolated anxiety variables were computed via two methods: "last observation carried forward" (LOCF) and linear interpolation using the "zoo" (Zeileis & Grothendieck, 2005) package in R. The LOCF symptom variables were created by repeating participants' symptom scores over missing time points between recorded symptom scores. The linear interpolation was performed in a similar manner over missing symptom data.

Data Analysis

Linear Associations Between COVID Periods and Variables of Interest

Multilevel models were conducted using R (Version 4.10) using the "lme4" package (Bates et al., 2015) to test whether COVID-19 phases predicted differences in experiential diversity (RE or novel locations), positive or negative emotion, and features of exploration (unique locations visited, distance traveled, time spent at home, and geospatial novelty). RE and novel locations were log transformed due to superior model fit (see Table S5 in the online supplemental materials). Multilevel models included varying intercepts for subjects. We extracted t statistics and p values for parameter estimates (Kuznetsova et al., 2017). Degrees of freedom (df) were calculated and extracted using the "lmerTest" package in R built around the "lme4" package (Bates et al., 2015), which uses the Satterthwaite method for estimating dfs (Satterthwaite, 1941; see the online supplemental materials).

Nonlinear Associations Between Geospatial Novelty and Positive Emotion by COVID Period

To test nonlinear associations between the number of novel locations and positive emotion, we specified generalized additive mixed models using the R packages brms (Bürkner, 2017) and mgcv (Wood, 2011; see the online supplemental materials).

We estimated Cohen's d, a measure of effect size (Kelley & Preacher, 2012), for the predicted level of positive emotion across geospatial novelty (2.303–6) as a function of pandemic period within days of the week. We computed Cohen's d from our spline models drawing 1,000 samples from the posterior predictive distribution of each model. We then computed Cohen's d

$$\text{Cohen's } d = \frac{M_1 - M_2}{SD_{\text{pooled}}},$$

from the positive emotion posterior predictions for each level of novelty per pandemic period per day of week. The mean posterior predicted value of positive emotion and its 95% credible interval for each level of the model are reported in Table S2 in the online supplemental materials.

Derivative Analysis

Because relationships between geospatial novelty and positive emotion during the chronic COVID-19 period displayed features similar to both the prepandemic and acute pandemic periods, we estimated the level of geospatial novelty at which the slope of positive emotion was steepest. To do this, we calculated derivatives of the geospatial novelty—positive emotion effect by subtracting the predicted positive emotion value at successive geospatial novelty values and dividing by the interval magnitude. Here, the interval size was 0.1 novel locations (log).

Bayesian Regression Models on Depression and Anxiety Symptoms

We examined whether the relationship between geospatial novelty and positive emotion by COVID-19 period was further moderated by anxiety. Anxiety was operationalized in two models. One model used a measure of momentary anxiety, assessed via the single experience-sampled survey item (assessed every other day). The other model utilized total generalized anxiety symptoms measured via the GAD-7 (assessed approximately every month and interpolated using LOCF or linear interpolation). Anxiety scores from each sampling method were included as a moderator of the relationship between number of novel locations and COVID-19 period on positive emotion respectively. We estimated these relationships using linear mixed effects models and we employed Bayesian generalized additive mixed models to estimate nonlinearities. From

these models we extracted predicted positive emotion from the posterior distributions for novel location levels and calculated Cohen's *d* effect sizes of the difference in predicted levels of positive emotion as a function of low and high anxiety (for momentary anxiety: scores of 20 and 80 [± 1 *SD* from the mean]; for generalized anxiety symptoms: GAD scores of 0 and 10 [indicating the absence of and moderate levels of anxiety, respectively]).

Transparency and Openness

This study's design and its analysis were not preregistered. We report our sample size, all data exclusions, all manipulations, and all measures in the study. The raw geolocation data sets analyzed during this study are not publicly available due to the inherently identifiable nature of geolocation data, but they are available from the corresponding author on reasonable request. The processed data and scripts necessary to reproduce the central findings in the article are available at https://github.com/manateelab/COVID-GPS/ . Data were analyzed using R, Version 4.10.0 (R Core Team, 2022).

Results

The Impact of COVID-19 on Experiential Diversity and Emotion

Acute Period

Compared to before the pandemic began, during the initial months of the pandemic, COVID-19 produced significant decreases in RE, $B = -0.555$, $t(64710) = -120.695$, $p < .001$; Figure 1, and the number of novel locations visited, i.e., a location that that person had never previously encountered; $B = -0.662$, $t(59490) = -60.191$, $p < .001$; Figure 1. In aggregate, daily positive emotion decreased during this period, $B = -4.3$, $t(27380) = -10.874$, $p < .001$; Figure 1, and negative emotion increased, $B = 2.65$, $t(27254) = 6.678$, $p < .001$; Figure 1.

Chronic Period

More than 6 months after the initial lockdowns began, COVID-19 continued to impact exploration and emotion, with decreases in daily RE, $B = -0.282$, $t(27330) = -49.968$, $p < .001$; Figure 1, and the number of novel locations visited per day, $B = -0.27$, $t(22590) = -19.954$, $p < .001$; Figure 1, persisting relative to prepandemic levels. However, when comparing the chronic to the acute pandemic periods, exploration had begun to return to prepandemic levels, RE: $B = 0.288$, $t(16010) = 36.378$, $p < .001$; novelty: $B = 0.396$, $t(14050) = 22.48$, $p < .001$.

When examining daily emotional well-being, the chronic pandemic period was associated with a lingering reduction in positive emotion compared to prepandemic levels, $B = -0.189$, $t(16550) = -4.446$, $p < .001$; Figure 1, although positive emotion was higher relative to the acute pandemic period, $B = 1.867$, $t(7507) = 3.003$, $p = .003$, indicating some recovery of daily positive emotion compared to the initial months of the pandemic. In contrast to positive emotion, however, by September 2020, daily negative emotion had returned to prepandemic levels, $B = 0.208$, $t(21830) = 0.476$, $p = .634$; Figure 1, with no differences in daily negative emotion compared with life before the pandemic. Substantiating such an asymmetry between recovery of negative and positive emotion, recovery of negative emotion during the chronic period was significantly greater than recovery of positive emotion, $B = -0.9360$, $t(48303) = -2.68$, $p = .007$, suggesting that during the chronic COVID-19 phase, negative emotion returned to prepandemic levels more rapidly than positive emotion.

The Impact of COVID-19 on the Weekly Cyclicity of Life

Prior to the pandemic, there existed a weekly cyclicity to emotion and behavior, with experiential diversity and mood increasing during the weekend compared to the beginning of the week (Golder & Macy, 2011). Before the pandemic, we clearly observed this cyclic fluctuation in our measures of behavior and emotion: RE, $F(6, 20774) = 324.82$, $p < .001$, novelty, $F(6, 18318) = 162.84$, $p < .001$, and positive, $F(6, 8727.1) = 53.69$, $p < .001$, and negative emotion, $F(6, 8715.7) = 38.085$, $p < .001$; Figure 1; see Figure S1 in the online supplemental materials. Yet during the initial months of the pandemic, there were substantial decreases in this cyclicity for all measures; RE, $F(6, 30948) = 72.82$, $p < .001$, geospatial novelty, $F(6, 28489) = 26.447$, $p < .001$, positive emotion, $F(6, 11812) = 9.992$, $p < .001$, and negative emotion, $F(6, 11802) = 9.9632$, $p < .001$, all displayed significant decreases in daily variation (Figure 1).

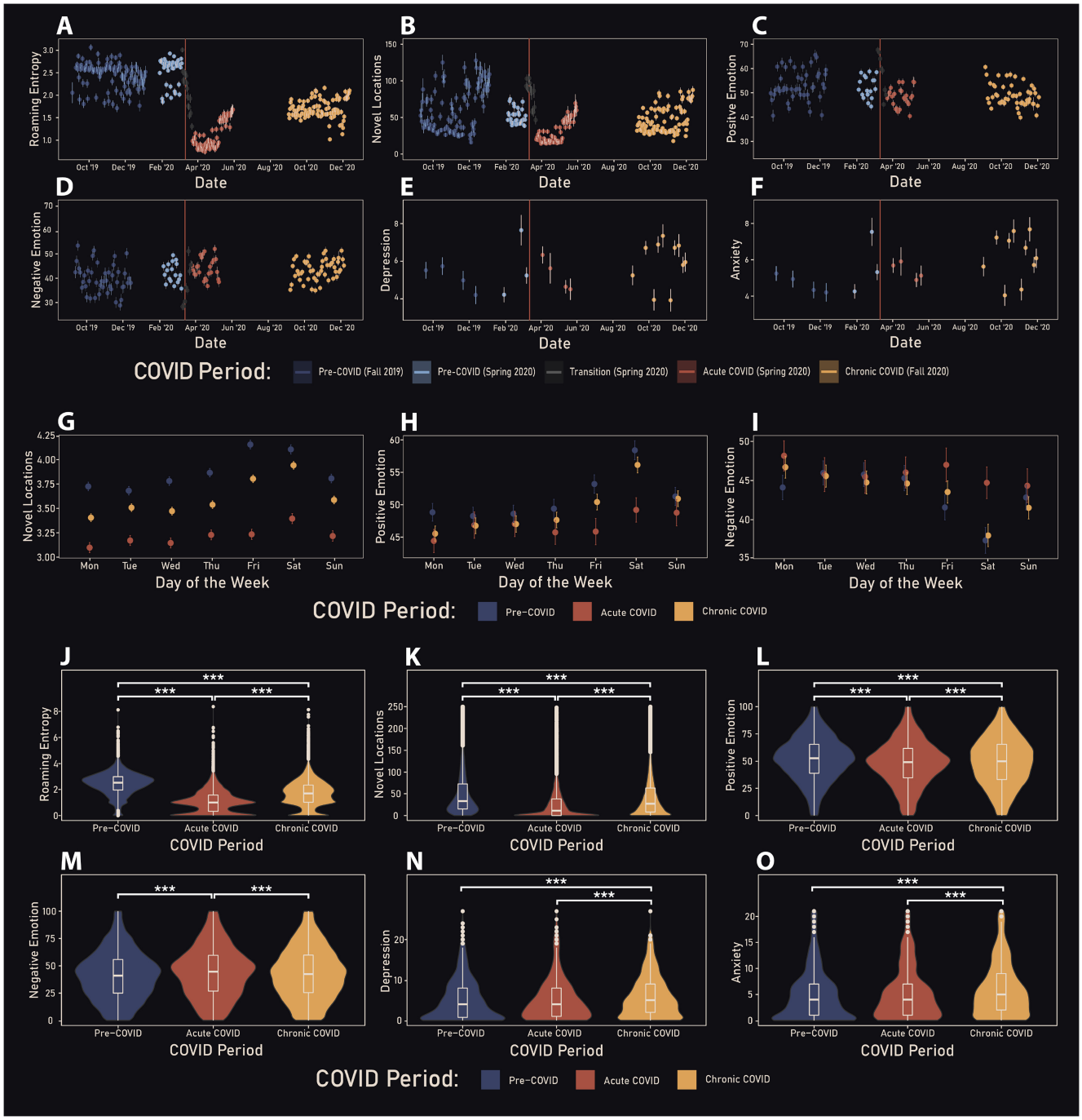
The Impact of the COVID-19 Pandemic on the Relationship Between Experiential Diversity and Positive Emotion

In previous work, we found that the number of novel locations one visits in a day is associated with increased positive emotion (Heller et al., 2020). As noted in the introduction, we hypothesized that the increased risk and uncertainty during the initial ("acute" March–May 2020) months of the pandemic would decrease the impact of experiential diversity on affective well-being—that is, compared to before the pandemic. We used Bayesian nonlinear models (i.e., basis splines) to flexibly approximate the functional relationship between geospatial novelty and positive emotion across all pandemic periods. However, contrary to our hypotheses, greater levels of experiential diversity predicted higher levels of positive emotion (Figure 2A) regardless of COVID-19 period, indicating no effect of COVID-19 period on the link between positive emotion and experiential diversity emotion, $B = -0.002$, $t(61940) = -0.293$, $p = .769$; Figure 2. Even during the earliest and most uncertain days of the pandemic, greater novelty was associated with higher levels of positive emotion.

There were, however, several interesting features that emerged from this model. While the pandemic did not remove the positive association between geospatial novelty and positive emotion, the nature of the relationship between novelty and positive emotion differed across time. The association between geospatial novelty and positive emotion was linear during the prepandemic and acute pandemic periods (i.e., similar slopes), yet the association between geospatial novelty and positive emotion appeared nonlinear during the chronic pandemic period. The association between geospatial novelty and positive emotion during the chronic period—when Americans were still grappling with the coronavirus—shared similarities to both prepandemic and acute pandemic periods. During the chronic period, days of no geospatial novelty yielded positive emotion levels similar to the worst of the pandemic (acute pandemic Cohen's $d = 0.051$, 95% CI [−0.110, 0.350]; Figure 2

Figure 1

COVID-19 Reduced Daily Experiential Diversity and Well-Being

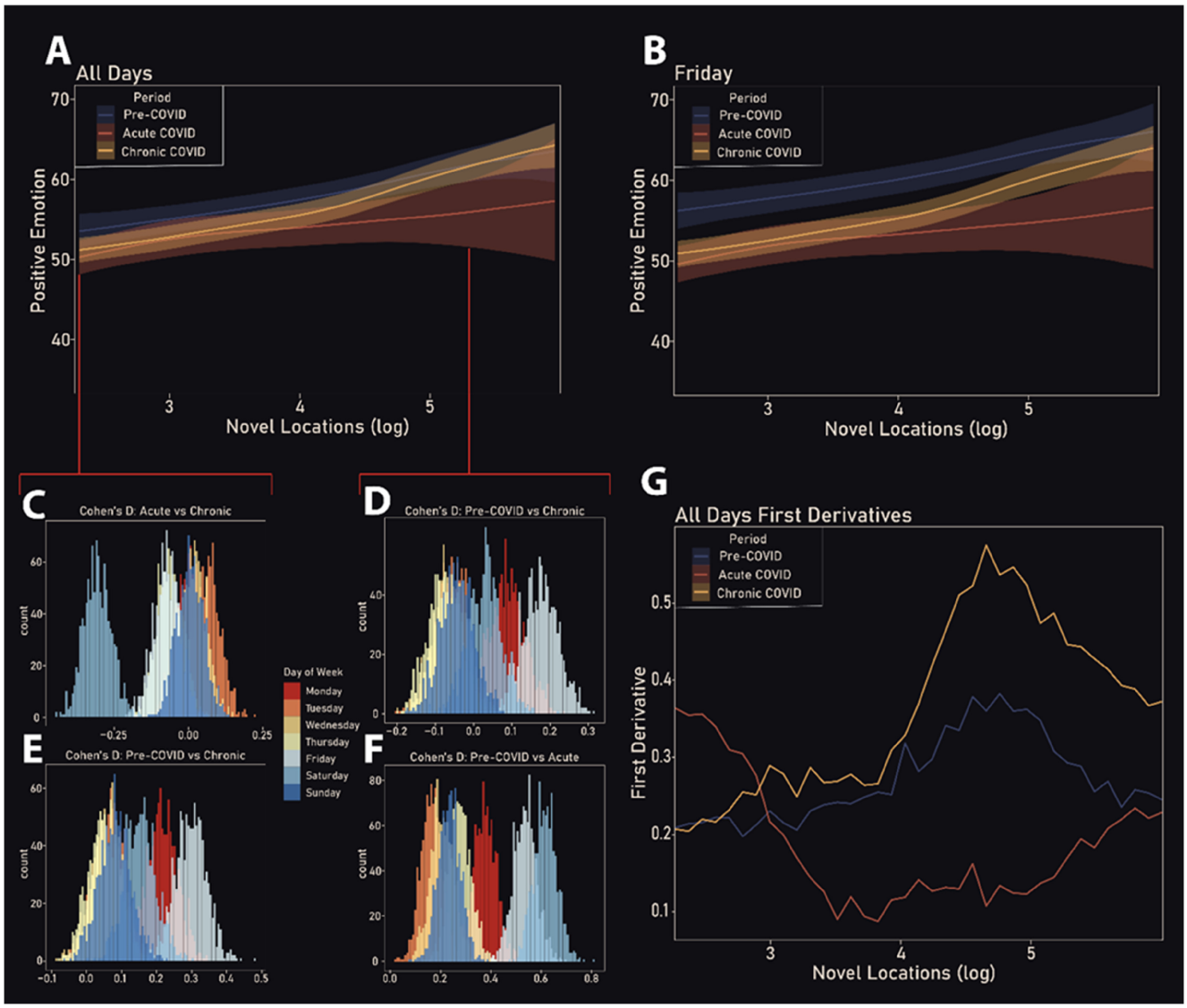


Note. (A–F) Averages among all participants across time for (A) roaming entropy, (B) novel locations, (C) positive emotion, (D) negative emotion, (E) depression, and (F) anxiety. Error bars represent standard error, and the data are broken up by COVID period. The red vertical line represents March 11, the day the World Health Organization declared COVID-19 a global pandemic. (G–I) Predictive values from Bayesian regression models for (G) novel locations, (H) positive emotion, and (I) negative emotion across days of the week by COVID period. Error bars represent the 95% credible interval for each predictive value. (J–O) Violin plots show differences in (J) roaming entropy, (K) novel locations, (L) positive emotion, (M) negative emotion, (N) depression, and (O) anxiety across COVID period. Boxplots inside represent the median, upper and lower quartiles, and upper and lower extremes. See the online article for the color version of this figure.

*** $p < .001$.

Figure 2

High Geospatial Novelty Was Associated With Recovery in Positive Emotion During the Chronic COVID-19 Period but Not the Acute COVID-19 Period



Note. (A–B) Bayesian regression model plots with predicted positive emotion values for different levels of novel locations visited for (A) all days and (B) Friday by pandemic period. Error bars represent the 95% credible interval for each predictive value. (C–F) Histograms of the effect sizes (Cohen's *d*) contrasting model predictions for the pre, acute, and chronic COVID-19 pandemic periods at low (0) and high (190) levels of geospatial novelty. Histograms are broken up by day of the week. (G) Plot of derivatives illustrating change in predicted level of positive emotion for different magnitude of geospatial novelty. See the online article for the color version of this figure.

and Table S2 in the online supplemental materials) such that positive emotion was below prepandemic levels (Cohen's $d = -0.132$, 95% CI = [−0.338, 0.016]; Figure 2 and Table S2 in the online supplemental materials). However, during this same period, days of greater novelty effectively recovered one's positive emotion to prepandemic levels (Cohen's $d = -0.008$, 95% CI = [−0.218, 0.137]; Figure 2 and Table S2 in the online supplemental materials). Thus, while geospatial novelty was positively related to affective well-being regardless of the pandemic period, the chronic period shared similarities with the acute period at lower levels of geospatial novelty and shared similarities with prepandemic period at higher levels of geospatial novelty.

We included first derivatives to capture in-the-moment changes in the relationship between novel locations and positive affect—the so-called velocity of the association between novel locations and positive affect. This helps identify precisely at what level of novel locations did COVID moderate the association between novel location and positive affect. First derivatives of the nonlinear association between positive emotion and geospatial novelty during the chronic pandemic phase were steepest at 89 novel locations, indicating that

visiting 89 novel locations within a day yielded the greatest change in positive emotion (Figure 2G). Roaming entropy displayed a similar pattern of results to geospatial novelty, such that during the chronic COVID-19 period, low RE was associated with positive emotion levels typical of the acute pandemic, while days of high RE recovered positive emotion to prepandemic levels (see Figure S3 in the online supplemental materials). We confirmed that these effects were not due to pandemic-related reductions in experiential diversity or positive emotion, as standardizing variables within pandemic periods yielded identical results (see Figure S4 in the online supplemental materials). Moreover, distance traveled did not account for the association between experiential diversity and positive emotion (see Table S3 in the online supplemental materials), suggesting that exploration and novelty exposure do not need to take place far from home for an individual to receive their benefits.

In line with this finding, during the initial months of the pandemic, when people's emotional well-being was most impacted, visiting a large number of novel locations (novel locations = 190 [log = 5.3]) did not overcome the global reduction in positive emotion caused by the pandemic (Cohen's $d = -0.339$, 95% CI = [−0.654, −0.112]; Figure 2 and Table S2 in the online supplemental materials). In fact, the model predicted that an individual would need to venture to at least 27 novel locations to experience positive emotion at levels commensurate with a prepandemic day of no novelty.

Anxiety's Role in the Association Between Geospatial Novelty and Positive Emotion During the COVID-19 Pandemic

We were surprised to find no support for our hypothesis that, during the initial months of the pandemic, when uncertainty and risk were maximal, heightened experiential diversity was nonetheless associated with increases in positive emotion. At the same time, regardless of the number of novel locations visited, positive emotion in the acute COVID-19 phase remained lower than before the pandemic. This discrepancy in the positive emotion-boosting effect of experiential diversity between pandemic phases suggests that there was something fundamentally different about the world, and thus, experiential diversity, as COVID-19 was first emerging. For example, due to the maximal uncertainty in transmissibility and prognosis of a COVID-19 infection during the first months of COVID-19, anxiety-prone individuals may have experienced novel spaces as more threatening during this time relative to the prepandemic and chronic COVID-19 period. Therefore, we hypothesized that experience-sampled ratings of subjective anxiousness, which here we term momentary anxiety, during the early stages of the pandemic would specifically modulate the affective benefit of novelty compared to the other (prepandemic and chronic pandemic) periods.

Indeed, we found that during the acute COVID-19 period, the impact of novelty on positive emotion was moderated by momentary anxiety: Days of greater novelty were associated with lower positive emotion, specifically for people who reported greater anxiety, Positive Affect ~ Novelty × Anxiety: $F(2, 21317) = 6.6203$, $p = .001$, such that on days of heightened anxiety during the acute COVID-19 period, high levels of novel locations yielded lower positive emotion levels relative to the other pandemic periods. Critically, the attenuation of novelty's positive emotion-boosting effect in anxious individuals was specific to the acute pandemic period. No such effect was present before the pandemic, nor during the chronic COVID-19 period.

Bayesian nonlinear models further corroborated these findings across pandemic phases. During the acute COVID-19 period only, a high anxiety individual encountering a high number of novel locations reported a lower level of positive emotion relative to the other periods and individuals with lower levels of anxiety (pre-COVID Cohen's $d = 1.532$, 95% CI = [1.423, 1.640]; acute COVID Cohen's $d = 1.762$, 95% CI = [1.649, 1.871]; chronic COVID Cohen's $d = 1.409$, 95% CI = [1.303, 1.517]; Figure 3A and B). These nonlinear models in fact revealed a reversal in the association between novel locations and positive emotion during the acute pandemic period for those with heightened anxiety: when visiting more than 44 novel locations, the predicted level of positive emotion decreased for those experiencing elevated momentary anxiety. These relationships were not present during the prepandemic or chronic pandemic periods, thus suggesting that anxiety uniquely impacts the affective consequences of exploration when environmental threats are most acute and uncertain.

These pattern of effects, whereby momentary anxiety moderated the link between geospatial novelty and positive emotion during the acute COVID-19 period, was not due to the mode through which we assessed anxiety. In addition to assessing momentary anxiety every other day using experience sampling, we also assessed generalized anxiety symptoms approximately monthly using the seven-item GAD-7 questionnaire (Spitzer et al., 2006). Replacing momentary, experience-sampled anxiety with this repeated measure of generalized anxiety symptoms yielded a similar three-way interaction, Novelty × Anxiety Symptoms × COVID-19 Phase: $F(2, 20653) = 6.131$, $p < .001$; see Figure S6 in the online supplemental materials. Moreover, these effects were specific to variation in anxiety, relative to other psychopathologies. Despite significant covariation between depression and anxiety ($b = 0.676$, $SE = 0.013$, $p < .001$), depression did not moderate the impact of geospatial novelty on positive affect by COVID-19 period, $F(2, 20734) = 2.081$, $p = .125$; Figure 3C. This suggests that anxiety specifically reduced the link between novelty and positive affect and did so exclusively when the pandemic was first emerging.

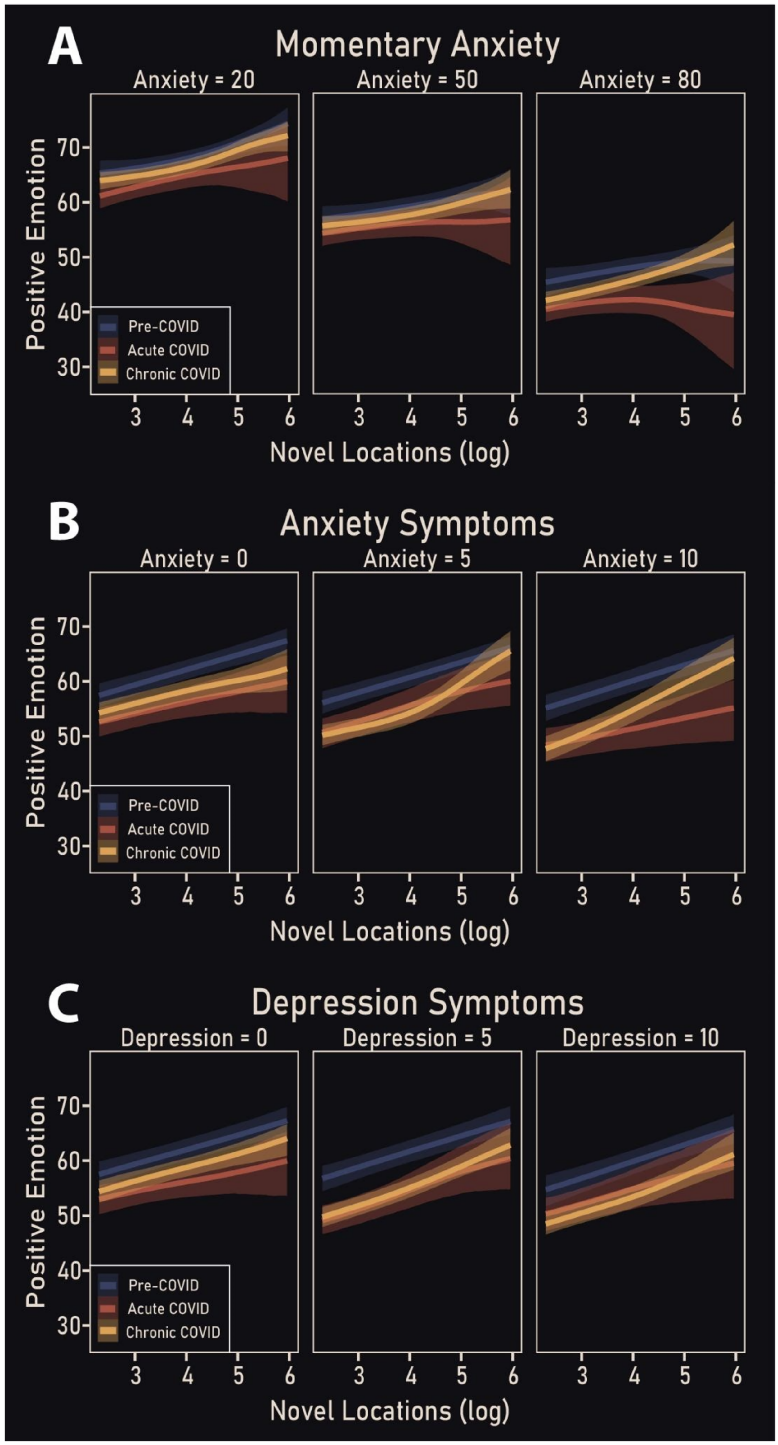
Discussion

The COVID-19 pandemic drastically impacted how we live our lives. As the pandemic first began to surge in March 2020, the threat and uncertainty of what a COVID-19 infection portended limited our ability to explore novel spaces and diminished our subjective well-being (Sibley et al., 2020). Lockdowns, stay-at-home mandates, and increasing risks associated with social contact shifted our patterns of exploration: we spent less time outside of our homes, we encountered less diversity, and our day-to-day experience became homogenized. Moreover, the COVID-19 pandemic imbued otherwise safe and predictable environments with an unprecedented degree of uncertainty, fundamentally altering the risk-reward tradeoff of geospatial exploration.

Despite elevated risks of leaving one's home throughout the pandemic, daily experiential diversity was associated with boosts in positive emotion, even during the strictest periods of the COVID-19 lockdown. This association between enhanced mood on days of increased experiential diversity is in line with animal and human literature demonstrating the affective benefit of novelty (Heller et al.,

Figure 3

Anxiety but Not Depression Attenuated the Association Between Geospatial Novelty and Positive Emotion Specifically During the Acute Pandemic Period



Note. (A–C) Bayesian regression models depicting how (A) momentary anxiety and (B) generalized anxiety symptoms altered the association between geospatial novelty and positive emotion during the acute COVID-19 period only. (C) This effect was not observed for depression symptoms. Error bands represent 95% credible intervals. See the online article for the color version of this figure.

2020). Yet, during the first few months of the pandemic, no amount of exploration or novelty led to positive emotion levels characteristic of before pandemic began. However, just 6 months after COVID-19 was declared a global pandemic, a day of high experiential diversity led to levels of positive emotion commensurate to positive emotion prior to the pandemic. These results suggest that even amidst the most acute period of the pandemic when people were primarily staying at home, people's moods were higher when they were exploring.

Yet, preclinical (Belzung & Berton, 1997) and clinical (Cockburn et al., 2022) laboratory research suggest that threat and uncertainty can modulate the subjective experience of novelty. For example, an increase in threat in the environment can induce neophobia (Corey, 1978), which, in some individuals, can lead to anxiety-like responses when exploring novel spaces. This led us to further hypothesize that the amount of anxiety one was experiencing would modulate the impact of geospatial novelty on positive emotion, but that this effect would be primarily evident when the pandemic was first emerging—when the risks of contracting the coronavirus were least certain. Indeed, the association between geospatial novelty and positive emotion was moderated by anxiety such that higher levels of anxiety reduced the link between novelty and positive emotion. Critically, this effect was specific to the initial months of the pandemic. In fact, during the first months of the pandemic, days of high novelty yielded a reduction in positive emotion only in those with high anxiety. One reason why these effects may not have been observed during other periods is that prior to the pandemic, exploration of novel spaces was broadly perceived as nonthreatening. Moreover, despite continued surges in COVID-19 cases and deaths in Fall 2020 (what we referred to as the chronic period), our understanding of the methods of transmission and a quickly emerging vaccine may have attenuated the perceived risk of geospatial novelty. Our findings suggest that anxiety diminishes the link between experiential diversity and positive emotion specifically when there are uncertain and ambiguous risks in one's environment.

It is notable that individuals with elevated anxiety experienced no affective benefit from heightened novelty specifically during the acute COVID period. One might expect that repeated encountering of novel spaces could function as a form of "exposure" therapy serving to lessen the aversiveness of novelty during the acute period. However, we believe we did not observe such an effect for at least two reasons. First, the continuous flow of new information about the virus, especially during the first few months of the virus, including transmission methods and symptoms, may have hindered extinction-based learning. Second, we defined a novel location as a GPS coordinate that the individual had never visited before. Consequently, the associations of novelty with positive emotion were inherently limited to unfamiliar locations, which may have limited any effects of exposure or extinction-based learning. As a result, individuals with high anxiety levels during the acute COVID period did not experience emotional benefits from exploring novel spaces.

It has previously been suggested that the lack of real-world experiential diversity caused by the pandemic may have impacted positive emotion more than negative emotion, referred to as "languishing." In our previous work, we found exploration to be significantly more associated with increases in positive affect compared to reductions in negative affect (Heller et al., 2020). Interestingly, following the large reductions of exploration brought about by COVID-19, we found that negative affect recovered substantially more than positive affect during the chronic COVID-19 phase. This suggests a sustained "languishing" of positive emotion specifically (relative to negative affect) and well-being as the pandemic persisted. This also fits with clinical data suggesting that it is easier to treat negative affective symptoms of mood disorders (e.g., sadness), than anhedonia (Treadway & Zald, 2011).

There are several limitations to note. First, despite the large sample size, because of the limited overlap in individuals across the three cohorts, we are unable to fully map the within-person longitudinal changes of real-world exploration and positive emotion from the first months of the pandemic through the extended (chronic) pandemic period. Thus, the changes in exploration and emotion we observed during the chronic period could be due to cohort differences and not to changes in behavior related to the pandemic. Second, while we determined when participants were under a mandated lockdown (based on their location), we did not measure people's attitudes or perceptions toward lockdowns and the pandemic generally. The amount of exploration may have been driven, in part by attitudes toward the lockdowns and pandemic and may not be fully attributable to the presence of COVID-19. Third, it's important to note that neither socioeconomic status nor transmissibility risk was measured in this study. These factors could influence participant's anxiety levels, affect, as well as exploratory behavior. Further, there are factors unique to Miami (e.g., cultural differences and political climate) that could potentially limit the generalizability of this study. Fourth, the decision to interpolate symptoms assumes that symptoms were changing in a linear fashion in between assessments. This may or may not have been the case, however. Lastly, because we did not experimentally manipulate exploration, we are unable to determine the direction of association between experiential diversity and positive emotion. Our previous work suggests that these effects are bidirectional (Heller et al., 2020), but experimental work is needed to fully elucidate the direction of effects.

In sum, we provide evidence for the link between experiential diversity and positive emotion by quantifying the behavioral changes surrounding a once-in-a-generation pandemic, whereby exploration of our modern environment has been filled with a heightened and life-threatening level of uncertainty. We suspect that the relationship between geospatial novelty and reductions in positive emotion specifically during the initial months of the pandemic was due to the appraisal of environmental uncertainty as riskier. Further, this study highlights the general importance of experiential diversity and traveling to new locations to maximize well-being.

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