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The role of emotion and social connection during the COVID-19 pandemic phase transitions: a cross-cultural comparison of China and the United States

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Leveraging substantial data from China's Weibo and datasets from Reddit and X (previously Twitter) in the United States, this research explores the disparities and complex dynamics of emotions and social connections among social media users in China and the United States during the COVID-19 pandemic. The findings indicate that the expression of three negative emotions (anxiety, sadness, and anger) and positive emotions exhibited distinctive dynamics under the impact of the pandemic, with China individuals expressing more anxiety but less sadness and anger than those in the US. Moreover, Chinese social media experienced a surge in positive emotional expressions under lockdown, whereas the US witnessed a conspicuous decline in positive emotions. Also, the expression of three types of social connections - "family", "collective", and "country"-exhibited significant differences under the impact of the pandemic, with Chinese individuals establishing deeper connections with their country and American individuals leaning towards familial connections. Further analysis on the moderating effects of social connections substantiated that the "country" connection in China and the "family" connection in the US mitigated the negative emotions affected by the pandemic. These findings facilitate a deeper understanding of how cultural contexts shape social and psychological responses in crises. Based on topic analysis and forward-looking orientation analysis, this study dissects the aforementioned findings through the dichotomy of collectivist and individualist cultures, providing new insights for social psychological support and emotional guidance in the development of public health communication strategies in the future.

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Introduction

The COVID-19 pandemic, due to its rapid transmission and severe clinical symptoms (Tan et al., 2020; Yang et al., 2020), has posed considerable public health challenges, resulting in a terrible global loss of life. Beyond the immediate health threats, the psychological turmoil induced by the virus and the subsequent quarantine measures, such as isolation or maintaining distance, has dramatically affected emotional and social well-being (Ashokkumar and Pennebaker, 2021). Such impacts underscore the imperative of investigating the emotion and social connections during the pandemic (Holt-Lunstad, Robles, and Sbarra, 2017; Pantell, 2020).

In the realm of crisis management, it is imperative to analyze public emotional reactions to understand societal processing of risks associated with pandemics (Duan and Zhu, 2020). Emotions, particularly anxiety, anger, and sadness, critically influence individual risk evaluation (Slovic et al., 2007). Anxiety, an inherent biological response to impending threats, facilitates alertness and equips individuals to either confront or avoid such threats (Öhman, 2000). During crisis situations, the heightened uncertainty amplifies these feelings of anxiety, primarily due to the unpredictability of outcomes (Tiedens and Linton, 2001; Holman et al., 2020). Concurrently, alterations in prevailing conditions and the ensuing losses during crises evoke sadness (Wortman and Boerner, 2011; Tugade and Fredrickson, 2004), whereas obstructed needs and objectives instigate anger (Berkowitz, 2012).

During crises, emotional responses exert varied influences on individual and societal behaviors, leading to multifaceted consequences. Unchecked anxiety, for example, can lead to heightened risk aversion and potentially irrational actions (Sweeny and Dooley, 2017). Anger, when not managed, might escalate into conflicts (Halperin and Pliskin, 2015). Meanwhile, prolonged sadness can detrimentally affect both mental well-being and the broader societal framework (Stroebe et al., 2017). Discerning the nuances among emotions like anxiety, anger, and sadness provides governments with insights to craft and execute more precise and efficacious crisis response strategies, aligning with public needs and anticipations during emergencies.

Empirical data suggests that there may be an amplification in the expression of negative emotions and a diminution in the expression of positive emotions on social media platforms during crises, which corresponds to both intuitive and cognitive expectations (Ashokkumar and Pennebaker, 2021). Nevertheless, extant literature also indicates the presence of underlying psychological and biological mechanisms capable of facilitating the emergence of augmented positive emotions in crisis contexts. For instance, individual self-efficacy, which describes one's belief in their capability to perform behaviors that can facilitate health compliance (Wei et al., 2021), can foster the generation of positive emotions in crises. Empirical studies have shown that when individuals possess confidence in their capacity to navigate adversities, their emotional disposition leans towards optimism and hope (Luszczynska et al., 2005). Moreover, during crises, there is a pronounced inclination among individuals to pursue existential meaning and purpose. Such endeavors have been associated with the cultivation of positive emotions, including hope and satisfaction, which ostensibly aid in enhanced crisis adaptation and coping mechanisms (Park, 2010). In addition, cultural paradigms play a pivotal role in shaping the expression of positive emotions during crises. Notably, collectivist cultures, underscoring communal harmony and identification, bolster individual feelings of belonging and security, subsequently fostering positive emotions (Jetten et al., 2012). Furthermore, the value placed on cooperation and mutual support, characteristic of collectivist cultures, has been postulated to enhance individual self-efficacy, thereby fostering a conducive environment for the emergence of positive emotions (Chen and French, 2008). Consequently, a rigorous examination of positive emotional responses during crises, particularly their variability across diverse cultural milieus, is of paramount importance. Such explorations afford invaluable insights into the multifaceted spectrum of human emotional experiences, thereby enriching our understanding of both societal and individual behavioral responses amidst crises.

In existing literature, scholarly focus has predominantly been directed towards the relationship between emotional responses during pandemics and social connections, examined from either micro- or macro-level perspectives. For instance, the study by Jo et al. (2021) at the micro-level revealed that post-pandemic onset, robust advice and friendship ties resulted in a discernible decline in work-related interactions. On a more macroscopic scale, Ashokkumar and Pennebaker (2021) discerned alteration in the social connections of urban residents in the United States, post-pandemic, indicating an intensified focus on familial connections over more expansive societal connections. Building upon existing literature, this research introduces a more nuanced examination by delineating three specific social connections: family, collective, and country. By probing into these distinct forms of connections, we aim to elucidate their potential role as instrumental pillars of support, which may have either buffered against the proliferation of negative emotions or facilitated the emergence of positive sentiments among social media users throughout the pandemic's course. This deepened exploration reinforces the inherent value and significance of understanding emotional dynamics in tandem with social linkages during such global crises.

To adequately comprehend and address the multifaceted risks posed by global crises at both individual and societal strata, the indispensability of a cross-cultural research methodology cannot be overemphasized (McDaniels and Gregory, 1991). Cultural frameworks play a pivotal role in shaping and reinforcing emotional responses, culminating in a spectrum of emotion regulation strategies (He et al., 2021; Kwon et al., 2013). Consequently, heterogeneous emotional expressions in response to the pandemic are discernible across varied cultural milieus. In Western societies, like the US, an adaptive norm of "living with" COVID-19 was swiftly established at the pandemic's outset. In contrast, China maintains a long-term dynamic zero-clearance policy. Previous research has illuminated a consistent structural framework of risk perception spanning cultures, distinctions in overarching risk perception and the prominence of associated factors persist (Butler et al., 2007; Kaptan et al., 2013; Shiloh et al., 2007; Slovic, 1992). The scholarly community increasingly underscores the significance of refining our cross-cultural understanding of emotions during crises, aiming to equip administrators and the broader public from diverse cultural backgrounds with enhanced empathetic capacities and emotion regulation skills (He et al., 2021; Nelson and Baumgarte, 2004; Schipper and Petermann, 2013).

While most crises, such as natural calamities or abrupt violent incidents, exhibit a discernible episodic nature with diminished public discourse typically after a six-week span (Gu et al., 2020; Wang et al., 2022), the current pandemic delineates an extended crisis with an indeterminate conclusion. This underscores the necessity for a longitudinal research approach, scrutinizing the evolution of emotional responses and social affiliations throughout various crisis phases.

Leveraging the pervasive reach and influence of social media, this study aims to explore the emotional dynamics and social connections in Chinese and American populations during the pandemic. Platforms such as Weibo for China, and Reddit and X (previously Twitter) for the U.S., serve not merely as

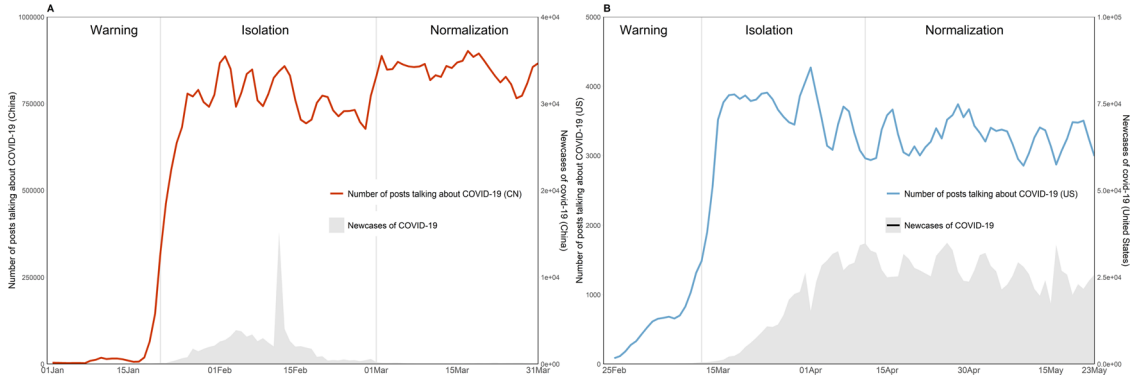

Fig. 1 Comparative analysis of COVID-19-related posts in China and the US. A (red curve) displays the three-day rolling averages of COVID-19-related posts on Chinese social media, showcasing the progression through the warning, isolation, and normalization phases. **B** (blue curve) represents the three-day rolling averages of COVID-19 posts on Reddit and X in the US. The shaded areas in both curves signify daily new confirmed cases.

communication channels, but as barometers for gauging public sentiment, offering invaluable insights into the societal psyche (Lu et al., 2023).

The dataset under examination consists of 53.99 million Weibo posts from December 1, 2019 to March 31, 2020. For the U.S. context, we referenced 1.8 million Reddit conversations as per the study by Ashokkumar and Pennebaker (2021), and amalgamated this with an additional 1.63 million tweets during the same timeframe. The depth and breadth of this dataset provide a granular lens for understanding emotional trajectories and societal connections during the pandemic's initial upheaval (see Appendix A1 for dataset details).

Figure 1 effectively illustrates the dramatic surge in social media discourse pertaining to COVID-19. The Chinese digital landscape observed a pronounced surge following the announcement from academician Zhong Nanshan on January 20 about the virus's potential for human-to-human transmission. Meanwhile, discussions on U.S. platforms like Reddit and X maintained a relative equilibrium until a sharp rise post-March 13, aligning with the U.S. President's state of emergency announcement. This juxtaposition elucidates the divergent timelines and reactions observed between the two nations, each shaped by defining events and official pronouncements.

Anchored in this comprehensive data milieu and drawing on a cross-cultural perspective, our investigation pursues three pivotal objectives. Firstly, we aim to analyze pattern differences of both negative (e.g., anxiety, anger, sadness) and positive emotional expressions on social media platforms in China and the United States during the COVID-19 pandemic. In tandem, the research endeavors to probe shifts in emphasis toward three distinct layers of social connections-family, collective, and country-within the social media narratives of both countries throughout the pandemic's duration. Lastly, and crucially, we strive to elucidate the potential moderating roles these social connections play in shaping the public's emotional responses to the pandemic.

Methods

Data sources. Our Chinese dataset is comprised of 53.99 million geocoded posts extracted from Weibo, China's predominant social media platform. Weibo, characterized by its distinct functionalities like posting, forwarding, and commenting, boasted approximately 550 million monthly active users and 241 million daily active users as of the first quarter of 2020[1]. This dataset encapsulates data from 335 Chinese cities between December 1, 2019 and March 31, 2020 (see Appendix A1 for details). For the U.S. context, we referenced a dataset from Ashokkumar and Pennebaker (2021), which amassed 1.8 million conversations on the Reddit platform spanning 18 major U.S. cities from January 25, 2020 to May 23, 2020. Additionally, our study integrated a dataset comparising 1.63 million tweets collected from January 25 to May 23, 2020, through, the official X Application Programming Interface (API), focusing on geocoded data from the same 18 cities conveyed by Reddit dataset.

Measures. This study investigated three dimensions of negative emotion (i.e., anxiety, anger, sadness), positive emotion, and three dimensions of social connection (i.e., family, collective, and country). To maintain consistency and ensure comparability between the US and China samples, we employed the method outlined by Ashokkumar and Pennebaker (2021). This approach utilizes the Linguistic Inquiry and Word Count (LIWC) dictionary repository, available at http://www.liwc.net/dictionaries. LIWC, a widely-recognized dictionary-based text parser, quantifies the proportion of words in a text file that correspond to various grammatical, psychological, and content categories. It's a popular tool for analyzing texts on social media platforms (Chung and Pennebaker, 2012). The efficacy of LIWC has been validated in multiple languages, including Chinese (del Pilar Salas-Zárate et al., 2014; Huang et al., 2012). For our study, we used the perspective Chinese and English language versions of the LIWC2015 dictionary to analyze the Chinese and American datasets.

Emotion. We quantified three types of negative emotions (anxiety, anger, sadness) and positive emotions for Chinese social media uses based on the frequency of corresponding emotion words in the LIWC2015 Dictionary-Chinese (Simplified). For the US data, in addition to utilizing the results from Ashokkumar and Pennebaker (2021) on anxiety, anger, sadness, and positive emotions from Reddit, we also conducted our own analysis on tweets from X based on the LIWC2015 Dictionary (English) during the same period.

Social connections. Metrics for social connections were derived from posts on Weibo and textual discussions on Reddit and X, with a spotlight on three distinct scales of social connections: family (representing closest social connection), collective (reflecting relatively close social connection), and country (denoting most macro-level social connection). Our hypothesis posits that as people feel a stronger sense of social connection, they tend to discuss groups and social affiliations more frequently. We utilized specific keywords from the LIWC2015 dictionary to capture mentions related to "family" and "collective". To gauge discussions associated with "country" on Weibo, we adapted the "country" dictionary initially developed by

Table 1 The phase division of the Chinese and American COVID-19 pandemic

Phases	China	United States
Baseline	Dec 1–31, 2019	Jan 25–Feb 24, 2020
Warning	Jan 1–20, 2020: COVID-19 was initially reported to WHO, and as more evidence surfaced, official warnings were progressively updated, advancing from acknowledging the possibility to confirming human-to-human transmission of the New Coronavirus.	Feb 25–Mar 10, 2020: The impending warning signs of the New Coronavirus crisis began to emerge, including the stock market plunge and the first fatal case occurred.
Isolation	Jan 21–Feb 29, 2020: Various regions initiated emergency responses to the public health crisis; Wuhan enacted the strictest preventive measures. Across China, the majority isolated, causing intercity population flow to decrease by over 70%.	Mar 11–Apr 6, 2020: The WHO declared the COVID-19 a global pandemic. And on March 13, the President of the US declared a state of emergency.
Normalization	Mar 1–Mar 31, 2020: The pandemic has been essentially contained nationwide, with the number of new confirmed cases reaching zero for the first time.	Apr 7–May 23, 2020: Six weeks after the first warning, people began to adapt to the new normal.

Ashokkumar and Pennebaker (2021) for the U.S. context to ensure its pertinence to the Chinese linguistic environment.

Pandemic phases. In analyzing the progression of the COVID-19 pandemic, Ashokkumar and Pennebaker (2021) identified four distinct phases based on related events in the United States: the baseline phase, warning phase, isolation phase, and normalization phase. Inspired by this classification, our study similarly maps the pandemic's trajectory in China, taking into account major COVID-19-related events (refer to Appendix A2 for details).

The initial phase in China commenced when COVID-19 was categorized as a Class B infectious disease by the National Health Commission. During this period, numerous cities declared isolation mandates, urging residents to self-isolate. Consequently, many businesses and organizations suspended in-person operations. National mobility metrics, as per Baidu's data, revealed a significant decline, with daily movements across the country decreasing by over 57%[2].

Approximately six weeks post the initial alerts, the normalization phase ensued. While previous research indicates a decline in public interest about six weeks after a sudden crisis event (Ashokkumar and Pennebaker, 2021), the persistent global implications of the COVID-19 pandemic maintained consistent public engagement. By March 1, there was a discernible trend toward pandemic mitigation in China. To gauge public risk perceptions during the normalization phase, we analyzed data spanning nearly four weeks (from March 1 to March 31).

Though the specific trajectories differed, both China and the United States experienced the pandemic's impact in comparable ways. Table 1 outlines our delineation of the pandemic timeline for both nations, segmented into four phases-baseline, warning, isolation, and normalization-based on the framework proposed by Ashokkumar and Pennebaker (2021).

Data analysis

Topic analysis. Understanding the specific subjects of discourse is essential for capturing the richness and depth of emotional expressions and social connections. To gain comprehensive insights into the specific topics resonating with individuals from both China and the US during the pandemic, we embarked on a topic analysis. Such an analysis allows us to unravel the intricacies of public discourse and the nuances of emotional and societal connectivity they convey, going beyond mere emotional categorization.

To sift through the extensive datasets from X and Weibo, we employed topic modeling techniques, recognizing the substantial diversity and volume of topics. This methodological choice draws inspiration from successful applications such as the research by Kwon and Park (2022), which utilized X data to explore varied responses to the COVID-19 pandemic in the US, the UK, and India. Such precedent underscores the efficacy of topic modeling in diverse analytical contexts.

Our methodology commenced with a rigorous preprocessing of the datasets, ensuring the exclusion of less informative tweets or posts and those embedding URLs or HTML tags. After preprocessing, the Latent Dirichlet Allocation (LDA) technique was employed, with each tweet or post regarded as a distinct document, and separate analyses for each country. Our tool of choice was the Python package Gensim, specifically the 'LdaMulticore' function. After a series of iterative trials to determine the optimal number of topics, 15 distinct themes for each nation were eventually identified. Specific parameters were meticulously set, including a random state of 100 and 20 passes during training with 100 training chunks to ensure model reliability and robustness, thereby yielding meaningful insights into various issues associated with the coronavirus in the chosen locations.

Once the LDA yielded high-frequency topic keywords for each nation, we moved into the interpretation phase. The most probable tweets or posts for each topic were extracted, and human analysts refined and categorized the findings. Any inconsistencies in topic labeling were addressed through discussions within the research team, ensuring that our insights were coherent and unified.

Statistical methods. Our analytical approach entailed multiple statistical methods. First, for the cross-country comparisons, contrasting emotions between Chinese and American users, we utilized an independent sample *t*-test. Rooted in daily data, this analysis delineated the evolving trends in emotional expressions for each country. Moreover, to probe emotional volatility, we integrated the standard deviation measurements across the three phases.

To compare emotional expression across different pandemic phases in each country (China and the U.S.), we employed a one-factor analysis of variance (ANOVA), using data from the baseline phase as the benchmark. Subsequently, we employed event study methodology to gauge the dynamic influence of lockdown measures on emotional expressions and social connections. This method employs a difference-in-differences (DID) design to account for the non-random assignment of processing, a situation where randomized controlled trials are not feasible (Borusyak et al., 2021).

Our model delineates the implementation of this methodology to explore the unique impacts of the lockdown policies on public emotion and social connection expressions over a timeline, aiming for high accuracy and thoroughness in our analysis,

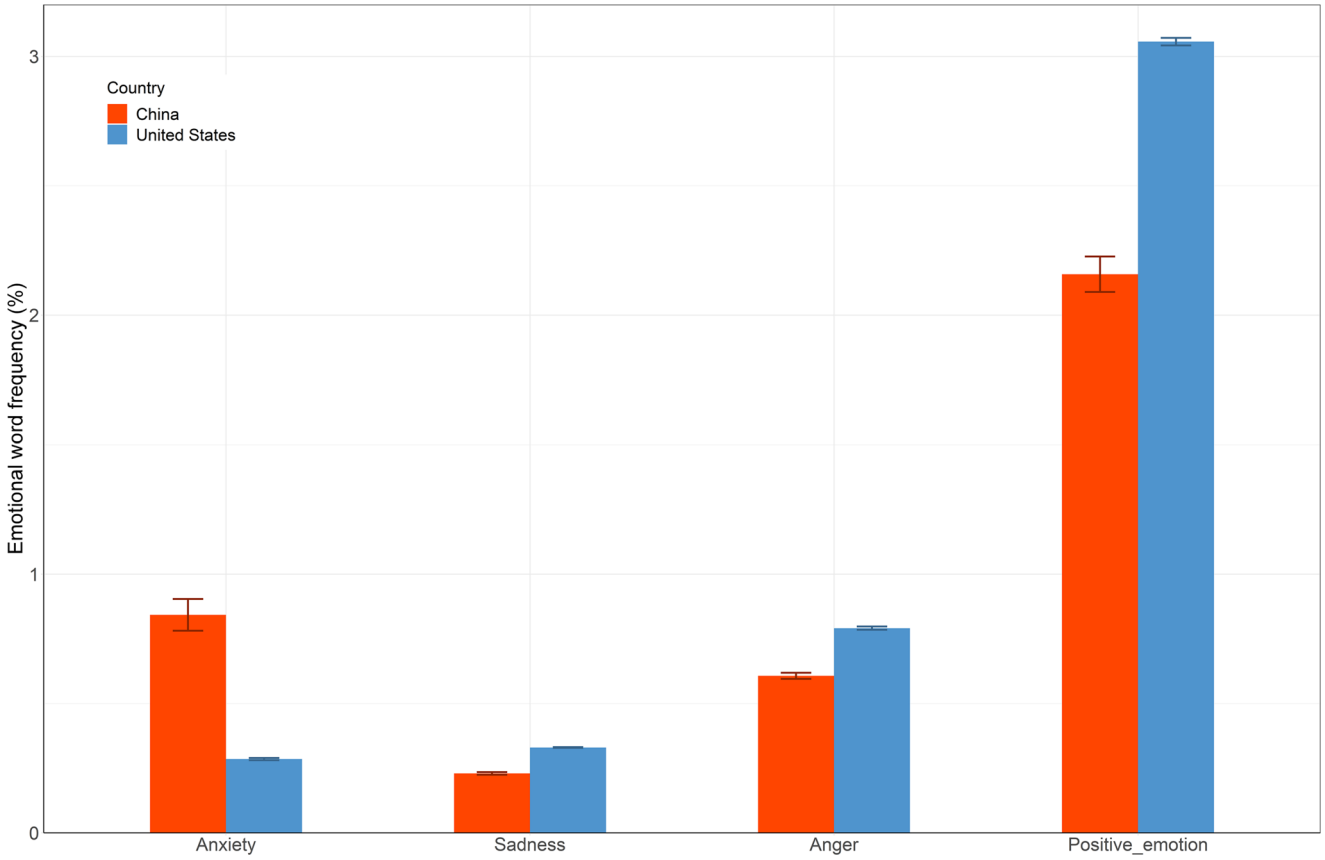

Fig. 2 Comparative analysis of emotional expressions between China and the United States. This figure delineates the comparative representation of various emotions in China and the United States, showcasing the mean values for each emotion in the respective countries. The error bars represent 95% confidence intervals. Due to the narrowness of the confidence intervals, some portions of the error bars may not be distinctly visible.

congruent with the standards set by Berniell et al. (2021) The configured model for the event study method is articulated as follows:

$$Public\_emotion_{it}/Social\_connetion_{it} = \alpha + \beta_1 D_{it}^{-5} + \beta_2 D_{it}^{-4} + \cdots + \beta_{12} D_{it}^{+6} + \gamma X + A_i + B_t + \varepsilon_{it}$$

$Public\_emotion_{it}/Social\_connection_{it}$ represents the weekly average values of four types of emotions and three kinds of social connections at the city level. The D's equal zero, except as follows: D^{-j} equals one for cities in the jth week before lockdown, while D^{+j} equals one for cities in the jth week after lockdown. X are vectors of control variables including the natural logarithm of newcases, mean temperature, and total amount of rainfall in city-level. A_i and B_t are vectors of city and week dummy variables that account for city and week fixed effects, respectively.

Finally, to elucidate the role of social connections, we assessed their moderating effect on the relationships between new COVID-19 cases and public emotions. This involved analyzing urban panel data using a two-way fixed effects model. To ascertain the significance ranges, we conducted Johnson-Neyman tests.

Results

Impact of COVID-19 on public emotion. To assess the public's emotional response to the pandemic, we analyzed expressions of anxiety, sadness, anger, and positive emotions across social media platforms in both China and the US. Figure 2 provides a comparative snapshot of distinct emotional expressions between China and the US. Figure 3 maps the temporal progression of these emotions, marking distinct phases associated with the pandemic. Figure 4 examines the dynamic effects of lockdown policies on public emotional responses. Table 2 elucidates the central discussion topics associated with these emotional expressions in both countries.

Focusing on anxiety, Chinese Weibo users exhibited significantly elevated anxiety expressions, employing related terms almost three times as frequently as their American counterparts ($Mean_{CN} = 0.843$; $Mean_{USA} = 0.285$; $MD_{\text{Anxiety}} = 0.557$, $t = 9.065$, $p = 0.000$), a trend indicative of the prevailing uncertainties and information deficiencies characteristic of the initial outbreak phase of COVID-19 (Bavel et al., 2020; Gu et al., 2020). This spike in anxiety during the warning phase ($Mean_{\text{CN\_warning}} = 2.001$; $Mean_{\text{USA\_warning}} = 0.303$; $MD_{\text{anxiety}} = 1.698$, $t = 8.869$, $p = 0.000$) was further corroborated by dynamic effect test results (as shown in Fig. 4A, B). Notably, Chinese users' anxiety peaked with a dynamic effect coefficient of 0.250 in week -1, while for American users, this peak was observed later, registering at 0.100 in week +2. Following this period of intense anxiety, a marked decline in anxiety expressions was observed among the Chinese users in the ensuing phases.

Regarding expressions of sadness, American social media users consistently expressed higher levels of sadness compared to their Chinese counterparts, a difference that was statistically significant ($Mean_{CN} = 0.230$; $Mean_{USA} = 0.330$; $MD_{\text{Sadness}} = -0.100$, $t = -19.212$, $p = 0.000$). While dynamic effect tests showed the lockdown policies had no marked impact on the sadness levels among American users (as shown in Fig. 4D), a consistent upward trend in sadness was evident (as shown in Fig. 3D). Conversely, Chinese users exhibited variable sadness expressions across distinct pandemic phases. Importantly, as the number of cases started to decline and regions in China began lifting their

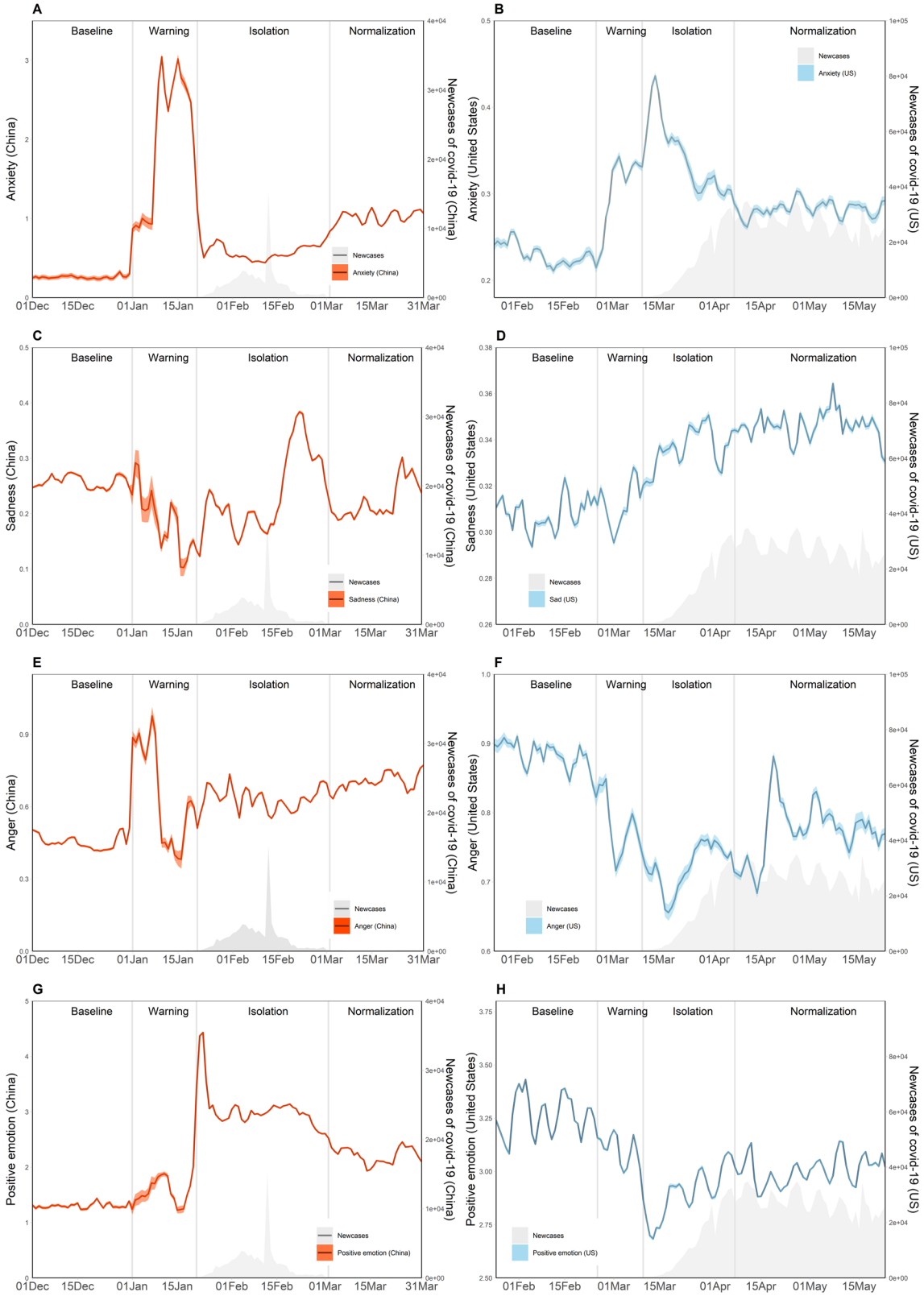

Fig. 3 Temporal evolution of emotions related to COVID-19 in China and the United States. This figure illustrates the phase transition of emotions related to COVID-19, comparing social media users from China and the United States. The red curve represents a three-day rolling average of the proportions of anxiety (**A**), anger (**C**), sadness (**E**), and positive emotion (**G**) expressed by Chinese users. The blue curve depicts the equivalent data for American users, with anxiety (**B**), anger (**D**), sadness (**F**), and positive emotion (**H**). Four distinct temporal phases are demarcated by vertical bands: baseline, warning, isolation, and normalization. The shaded regions correspond to the daily count of newly confirmed COVID-19 cases, providing a contextual backdrop for the emotional response trajectories in each country.

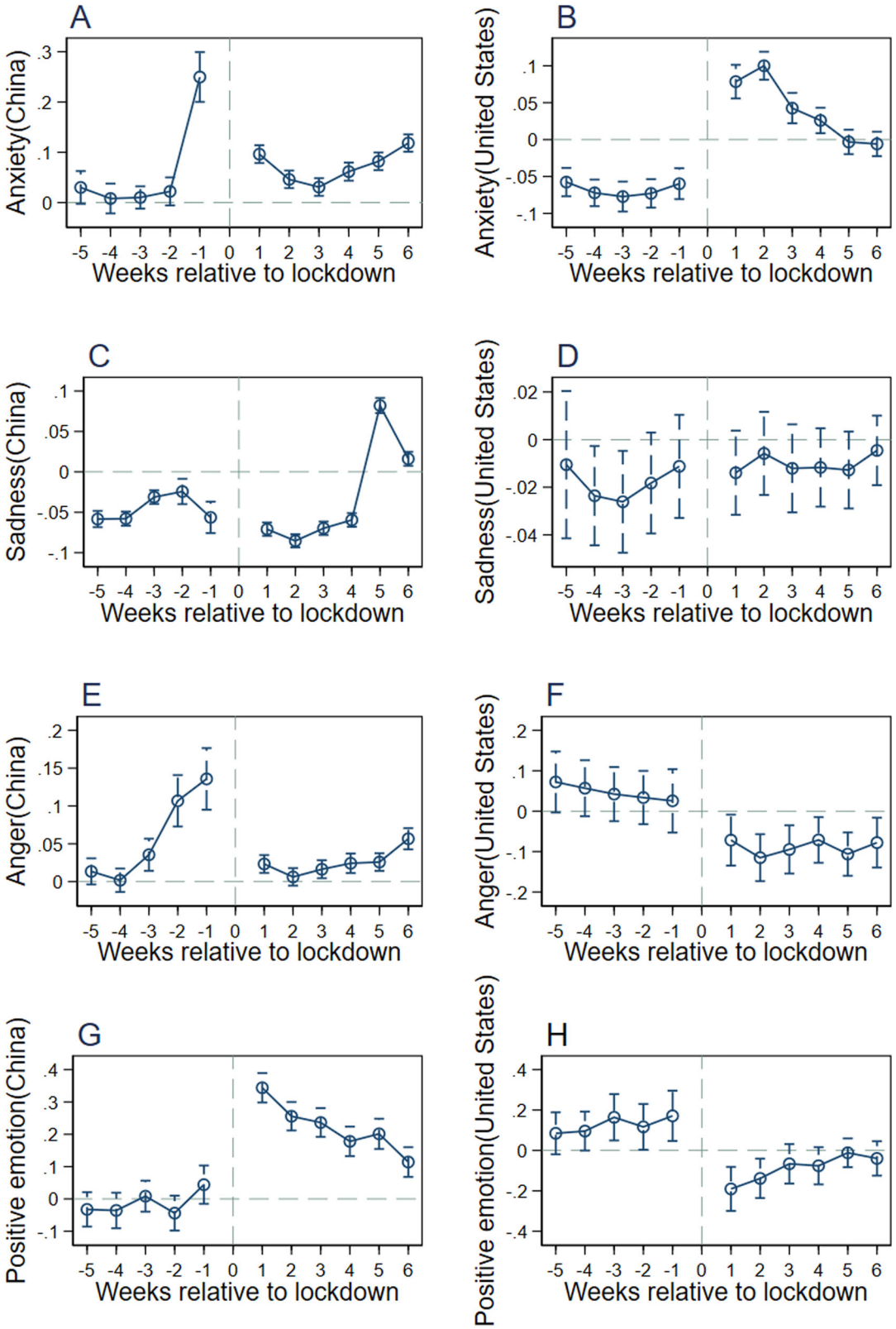

Fig. 4 The dynamic effects of lockdown policy on public emotions expressions. The figure illustrates the dynamic effects of policy changes on the natural logarithm of public emotion change rate over a 12-week time span, ranging from 5 weeks before the policy change to 6 weeks after the policy change. The dashed lines indicate 95% confidence intervals, accounting for relevant statistical adjustments. The subfigures labeled **A** (anxiety), **C** (sadness), **E** (anger) and **G** (positive emotion) track the changes in China, and the subfigures labeled **B** (anxiety), **D** (sadness), **F** (anger) and H (positive emotion) chart the corresponding changes in the United States.

Table 2 Comparative topic-focused analysis on emotional expression

Rank	United States		China	
	Topic Label	Percentage (%)	Topic Label	Percentage (%)
Anxiety				
1	State Politics	14.89	Pandemic	10.98
2	US Elections	8.51	Public Health	9.57
3	Global Affairs	7.77	Daily Activities	7.23
4	Public Health	7.25	Global Affairs	5.41
5	Finance	6.79	Rumor	3.66
Sadness				
1	State Politics	11.52	Encouragement	13.13
2	Global Affairs	8.76	Pandemic	11.55
3	Finance	7.52	Public Health	7.87
4	Daily Activities	6.58	Local affairs	4.64
5	Public Health	6.26	Global Affairs	4.07
Anger				
1	State Politics	16.49	Global Affairs	11.71
2	US Elections	10.25	Pandemic	11.32
3	Global Affairs	8.61	Public Health	5.49
4	Finance	7.82	Communication	4.33
5	Public Health	5.59	Local Affairs	3.22
Positive_emotion				
1	State Politics	10.10	Pandemic	9.74
2	Global Affairs	8.28	Public Health	8.8
3	US Elections	6.09	Encouragement	8.14
4	Encouragement	6.01	Entertainment	5.75
5	Entertainment	5.02	Relationships	5.46

lockdowns, a pronounced rise in sadness expressions was observed among Chinese users. This surge peaked with a dynamic effect coefficient of 0.082 at week +5, within a confidence interval of [0.073, 0.091].

In our exploration of anger, American users on social media manifested a heightened intensity of anger expressions relative to the Chinese. This divergence was statistically marked ($Mean_{CN} = 0.607$; $Mean_{USA} = 0.791$; $MD_{\text{Anger}} = -0.184$, $t = -13.814$, $p = 0.000$). A closer inspection of Fig. 3E, F paints a clearer picture. Chinese users displayed a consistent and stable pattern in their anger expressions ($F_{CN} = 42.252$, $p = 0.000$), while their American counterparts showcased a more fluctuating trend ($F_{USA} = 113.493$, $p = 0.000$), resonating with the highs and lows of the pandemic's trajectory. The dynamic effect tests (as shown in Fig. 4E, F) provided further clarity, emphasizing the pronounced differences in the emotional landscapes of the two nations.

Shifting our focus to the expression of positive emotions, the data illuminates a consistent trend among American users, who maintained a sustained positive emotional disposition throughout the pandemic ($Mean_{USA} = 3.407$; $F_{USA} = 89.758$, $p = 0.000$). Conversely, Chinese users manifested a more nuanced trajectory. They initially showcased volatility in their positive emotional expressions, which was followed by a pronounced surge post-lockdown. This surge peaked with a dynamic effect coefficient of 0.344 in the first week, as depicted in Fig. 4G. The significance of this trend among Chinese users is emphasized by a substantial variance, supported by an F value of 351.807 ($p = 0.000$).

To further understand the roots of these emotional expressions, we delved into the subjects that dominated discussions during these heightened emotional states. Identifying the predominant discussion topics can provide deeper insights into the specific concerns, hopes, and fears that fueled the emotional reactions in both countries. A comprehensive topic analysis was executed to identify subjects predominantly discussed within emotional contexts in both nations. Table 2 elucidates the top five topics in both Chinese and American social media that are predominantly associated with expressions of emotion.

In the context of expressing emotions such as anxiety, anger, and sadness on social media, American users predominantly focused their discussions on "State Politics", a topic that not only garnered the most attention but also consistently accounted for over 10% of the discussions in these emotional contexts. Even when expressing positive emotions, "State Politics" remained the most prominent focal point for American users. Additional topics that caught the attention of American users while expressing their emotions included "Finance", "US Elections", and "Global Affairs".

On the other hand, for Chinese users expressing emotions like anxiety, anger, sadness, and positive emotion, the dominant subject of discussion was the "Pandemic" with the proportion of discussions on this topic either surpassing or nearing 10%. Particularly notable is the prevalence of the term "Encouragement" or "make a greater effort", which emerged as a high-frequency keyword on Weibo, ranking just after Covid-19 related discussions when expressing sadness and positive emotions. Other central topics for Chinese users included "Public Health", "Global Affairs", and "Local Affairs".

These detailed disparities in emotional expressions and their associated topics of focus can shed light on the psychological and behavioral responses of populations in China and the United States during the different phases of the pandemic.

Impact of COVID-19 on social connection. To explore the societal impact of the pandemic, we delved into the expressions and discussions surrounding social connections across the two nations. Figure 5 presents a comparative snapshot of distinct social connection expressions between China and the US. Figure 6 maps the temporal progression of these social connections, marking distinct phases associated with the pandemic. Figure 7 indicates the dynamic effects of lockdown policies on public expressions about social connections. Table 3 conducts a topic-focused analysis, spotlighting the distinct subjects of discussion in relation to social connections in both countries.

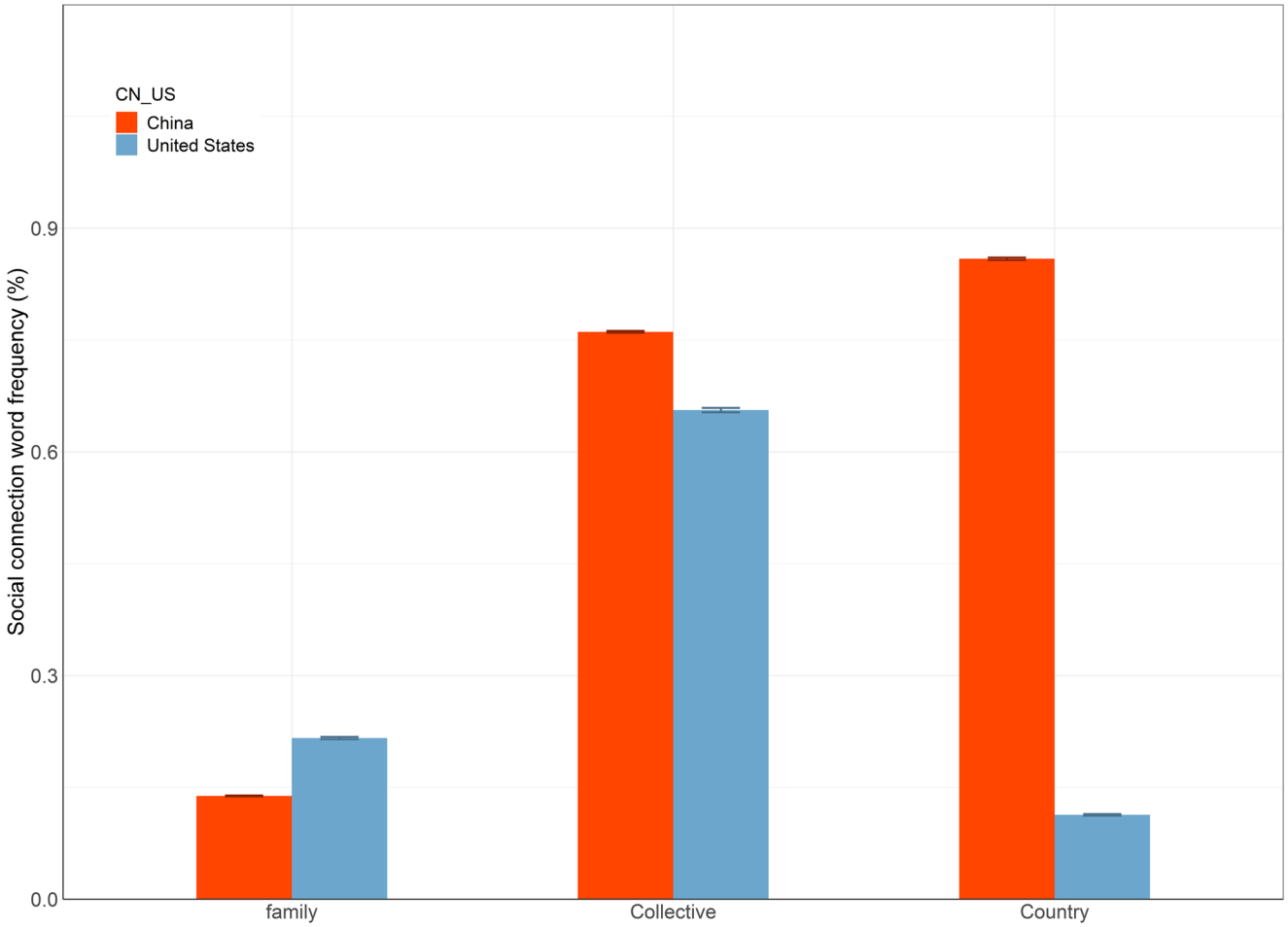

Fig. 5 The comparison of social connections between China and the United States. The bars represent mean value of social connection word frequency in China and United State respectively. Error bars indicate 95% confidence intervals. The confidence intervals are narrow, which makes part of error bars hard to see.

Focusing on the family connection, American dialogs, in particular, displayed a pronounced emphasis on "family", especially after initial warnings ($Mean_{CN\_family} = 0.138$; $Mean_{USA\_family} = 0.216$; $MD_{\text{family}} = -0.078$, $t = -16.908$, $p = 0.000$). Critically, Fig. 7 indicates the transformative influence of lockdown on family-focused discussions in the US, with a pronounced peak at 0.053 in week +1, a surge likely attributed to the stringent lockdown measures. While Chinese dialogs also reflected the sentiment, it was manifested more subtly, peaking later at 0.012 in week +5. These varied timelines and intensities of discussions are well-articulated in Fig. 6, underscoring the distinct dynamics of family-related dialogs between the two nations.

In the realm of collective connections, Chinese dialogs dominated, particularly evident when contrasted with their American counterparts ($Mean_{CN\_collection} = 0.761$; $Mean_{USA\_collective} = 0.656$; $MD_{\text{collective}} = 0.105$, $t = 2.852$, $p = 0.005$). Dynamic effect tests highlight a sharp spike in Chinese discussions during the isolation phase, significantly outpacing the American trends. This spike underscores China's unique emphasis on collective connections compared to the steady trend in American dialogs.

Regarding to country connection, Fig. 5 underscores China's strong nationalistic focus, a sentiment markedly elevated compared to US discourse ($Mean_{CN\_country} = 0.859$; $Mean_{USA\_country} = 0.113$; $MD_{\text{country}} = 0.746$, $t = 32.357$, $p = 0.000$). The dynamic effect test results further corroborate this observation, indicating a sustained focus on national issues by Chinese users as the pandemic unfolds, with the discourse maintaining consistently high levels ($mean_{CN\_warning} = 1.027$; $mean_{CN\_isolation} = 1.010$; $mean_{CN\_normalization} = 0.876$). Conversely, discourses within the United States exhibit minimal deviations, reflecting a consistent approach to similar subjects throughout the studied period ($mean_{USA\_warning} = 0.123$; $mean_{USA\_isolation} = 0.115$; $mean_{USA\_normalization} = 0.115$).

To delve deeper into the underlying cultural and societal nuances, a meticulous topic-focused analysis was undertaken, the details of which are encapsulated in Table 3. This analysis unravels the nuanced societal priorities and cultural orientations embedded within the discussions related to "family", "collective", and "country" in both nations.

When discussing "family", American discourse predominantly revolved around "Employment" and "Education", revealing a societal inclination towards individual concerns. In contrast, Chinese discourse was primarily anchored in "Public Health" and "Pandemic" reflecting a heightened collective concern for problem solving and broader societal well-being.

Discussions related to "country" among American social media users predominantly focused on "State Politics" and "US Elections", showcasing a discernible emphasis on political and governmental affairs. On the other hand, Chinese discourse was characterized by "Encouragement" and "Pandemic", depicting a societal resilience and collective spirit.

In discussions regarding "collective", both nations exhibited a shared interest in "Entertainment", indicating a universal

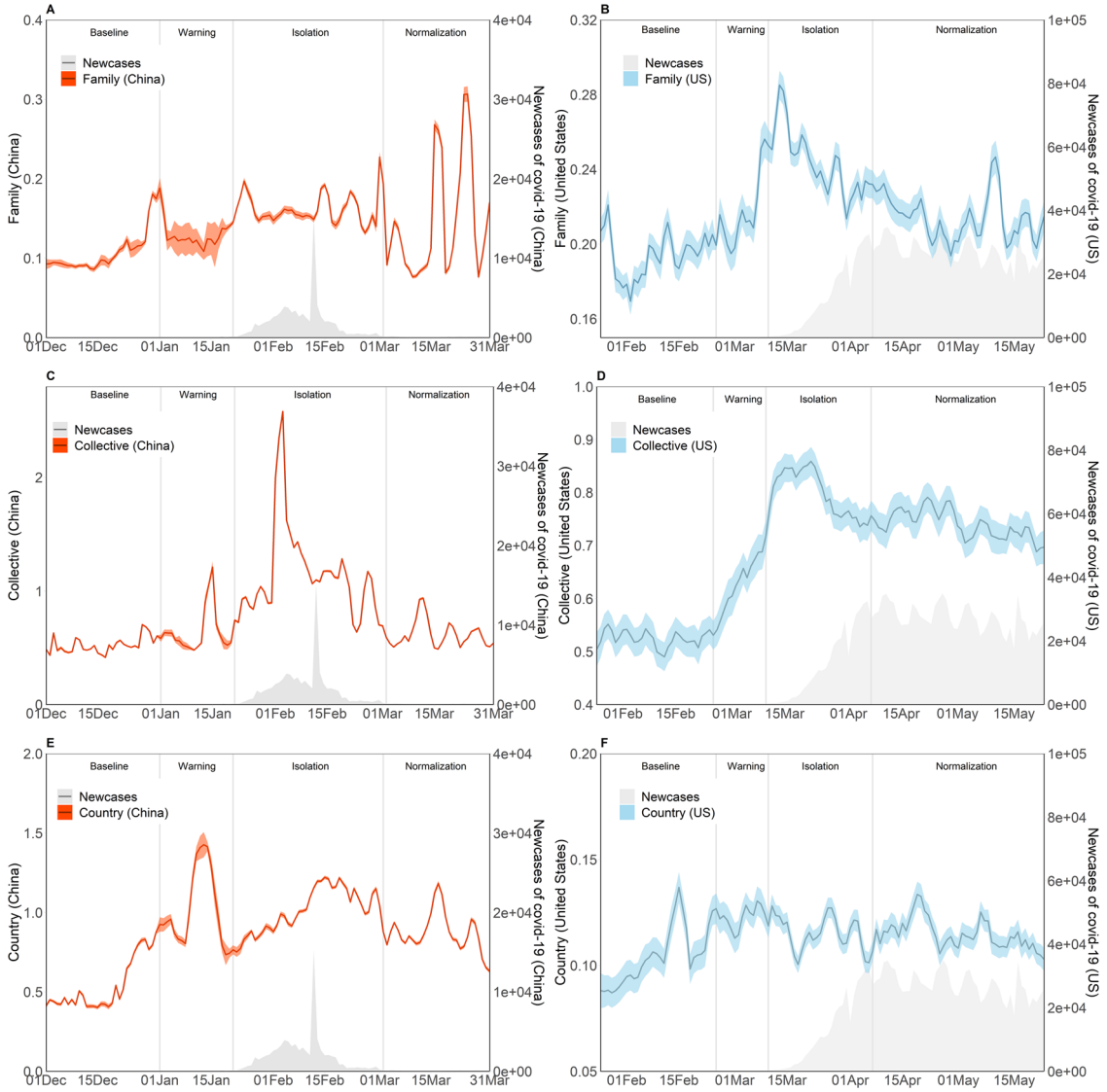

Fig. 6 Comparative analysis of social connection expressions in China and the United States. This figure illustrates the variances in expressions related to social connections between China and the United States, depicted through three-day rolling means on respective social media platforms. The red curves labeled **A**, **C**, and **E** denote the percentages of words related to family, collective, and country by users in China. In contrast, the blue curves labeled **B**, **D**, and **F** represent the percentages of words referring to family, collective, and country by users in the United States.

inclination towards cultural and recreational pursuits amid crises. However, while the discourse in the United States leaned heavily towards "Global Affairs" and "State Politics", reflecting interpersonal and governmental concerns, Chinese discussions lean more towards "Encouragement" and "Pandemic", representing a societal preference for communal solidarity and well-being.

The moderating roles of social connections on emotional responses to the pandemic. Social connections serve a crucial function in managing the repercussions of the pandemic by assisting individuals in modulating their emotions, dealing with stress, and maintaining resilience during trying times (Bavel et al., 2020). Individuals often gravitate towards intimate social connections, such as those found within communities and families, to mitigate the negative emotions induced by the impact of COVID-19, including loneliness, anxiety, and sadness. Alternatively, individuals might also seek affiliation with various groups with which they identify, providing a space to express and vent negative emotions.

To understand how social connections moderate the impact of the pandemic on public emotions in Chinese and American social media, we constructed a city/day panel dataset by calculating the mean levels of social connections and public emotions. The analysis focused on exploring the interaction coefficients between country, collective, family, and the number of newly confirmed cases.

To construct the index of negative emotions and social connection, we calculated the sum of the word frequency ratios of negative (comprising sadness, anger, and anxiety) and positive emotions, and terms related to family, collective, and country. Additionally, variables such as the number of newly confirmed COVID-19 cases in cities, cumulative death cases, temperature, and precipitation were incorporated as control variables. Bidirectional fixed effects of city and date were also controlled to ensure the robustness of our results.

Panel A of Table 4 presents the examination results of samples from Chinese social media platforms. From the perspective of direct effects, the results demonstrate that the impact of "family" social connection ($b = -0.146$, $SE = 0.045$, $p < 0.01$), and

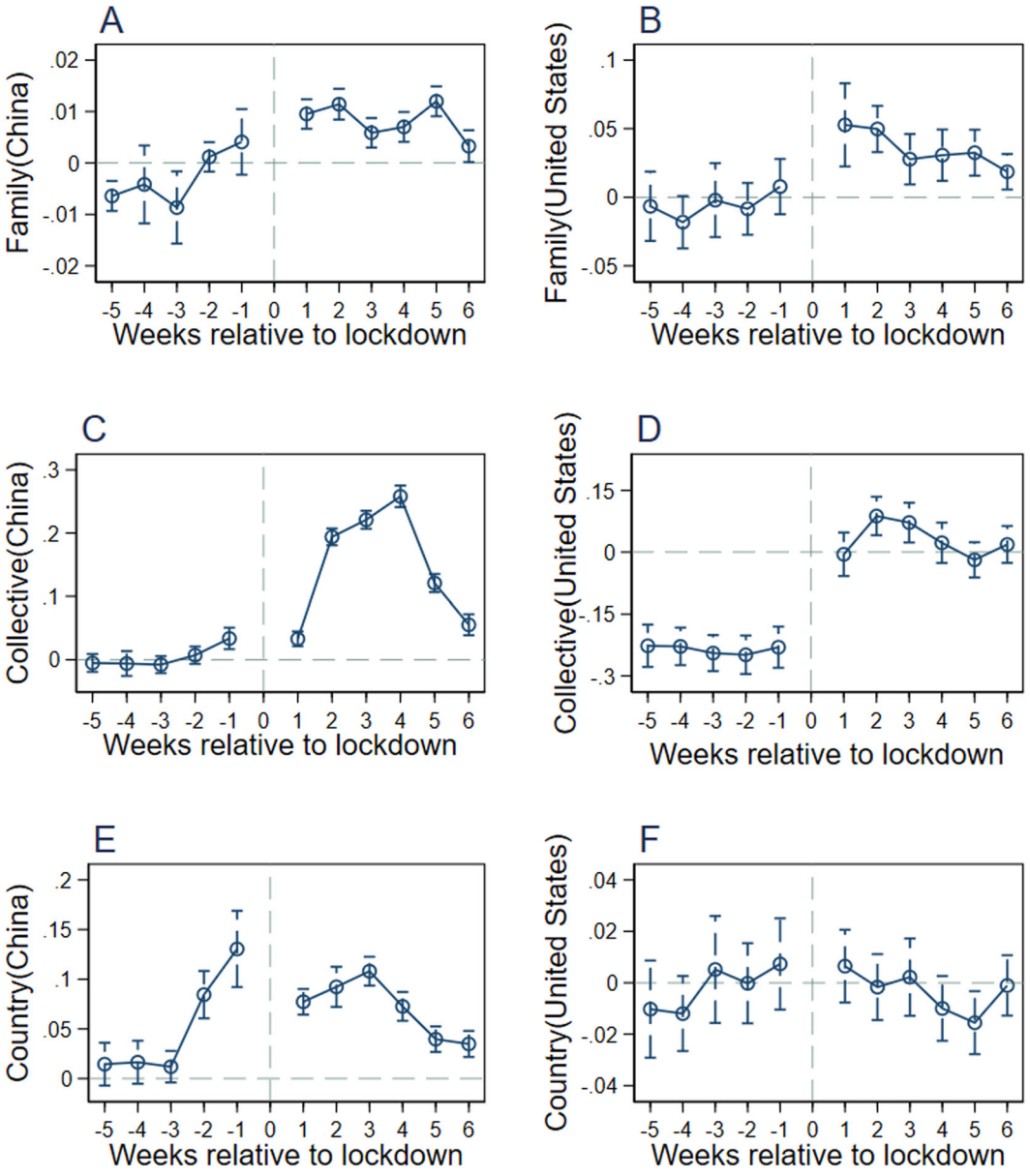

Fig. 7 The dynamic effects of lockdown policy on public social connection expressions. The figure illustrates the dynamic effects of policy changes on the natural logarithm of public social connection expression change rate over a 12-week time span, ranging from 5 weeks before the policy change to 6 weeks after the policy change. The dashed lines indicate 95% confidence intervals, accounting for relevant statistical adjustments. The subfigures labeled **A** (family), **C** (collective), and **E** (country) track the changes in China, and the subfigures labeled **B** (family), **D** (collective), and **F** (country) chart the corresponding changes in the United States.

"country" social connection ($b = -0.102$, $SE = 0.043$, $p < 0.05$) were inversely related to negative emotions, indicating statistical significance. In contrast, the "collective" social connection ($b = -0.012$, $SE = 0.015$, $p > 0.1$) did not show a statistically significant relationship with negative emotions. This suggests that the mentions of terms related to "family" or "country" were associated with a reduction in negative emotional expressions among the Chinese public. Regarding the impact on positive emotions, the "family" social connection ($b = -0.204$, $SE = 0.054$, $p < 0.01$) was found to be inversely related to positive emotions. Conversely, "collective" social connection ($b = 0.605$, $SE = 0.018$, $p < 0.01$) and "country" social connection ($b = 0.477$, $SE = 0.013$, $p < 0.01$) were positively related to positive emotions, indicating that mentions of "collective" or "country" were associated with an increase in positive emotional expressions among the Chinese public.

Panel B of Table 4 illustrates the analysis results of samples derived from American social media. The blue bar charts reveal that the "family" social connection ($b = 0.312$, $SE = 0.108$, $p < 0.01$), "collective" social connection ($b = 0.183$, $SE = 0.051$, $p < 0.01$), and "country" social connection ($b = 1.084$, $SE = 0.173$, $p < 0.01$) have a positive correlation with negative emotions, signifying that mentions of terms related to "family", "collective", or "country" are associated with an increase in negative emotional expressions among American users. Conversely, while the "family" social connection ($b = -0.246$, $SE = 0.157$, $p > 0.1$) did not show statistically significant relationship with positive emotions, "collective" social connection ($b = -0.679$, $SE = 0.073$, $p < 0.01$) and "country" social connection ($b = -0.562$, $SE = 0.258$, $p < 0.05$) were both found to be negatively correlated with positive emotions. This indicates that mentions of terms

Table 3 Comparative topic-focused analysis on social connections

Rank	United States		China	
	Topic Label	Percentage (%)	Topic Label	Percentage (%)
Panel A. Family				
1	Relationships	23.04	Public Health	18.11
2	Education	9.31	Pandemic	14.65
3	Healthcare	8.70	Relationships	8.69
4	Finance	7.10	Encouragement	7.88
5	Daily Activities	5.10	Local Affairs	4.41
Panel B. Collective				
1	Relationships	11.63	Encouragement	13.81
2	State Politics	10.55	Pandemic	9.31
3	Global Affairs	9.59	Public Health	7.36
4	Encouragement	6.36	Entertainment	4.66
5	Entertainment	5.86	Local Affairs	2.73
Panel C. Country				
1	State Politics	23.78	Encouragement	16.98
2	US Elections	19.2	Pandemic	13.34
3	Global Affairs	7.29	Global Affairs	10.81
4	Pandemic	5.93	Public Health	8.43
5	Finance	4.04	Charity	3.95

Table 4 The moderating role of social connections in the relationship between newcases and public emotional expression during the pandemic

	Neg.	Neg.	Neg.	Pos.	Pos.	Pos.
Panel A. China						
log(Newcases+1)	0.030 (0.022)	0.057*** (0.020)	0.046** (0.019)	0.058** (0.026)	0.065** (0.026)	0.049** (0.022)
Family	−0.146*** (0.045)			−0.204*** (0.054)		
Collective		−0.012 (0.015)			0.605*** (0.018)	
Country			−0.102** (0.043)			0.477*** (0.013)
log(Newcases+1)*Family	0.679 (0.416)			−0.708 (0.504)		
log(Newcases+1) *Collective		−0.145*** (0.047)			−0.319*** (0.056)	
log(Newcases+1) *Country			−0.135*** (0.045)			−0.053 (0.053)
Control Variables	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y	Y
Obs.	28421	28421	28421	28421	28421	28421
R-squal	23.52	23.51	23.51	39.98	42.36	42.92
Panel B. United States						
log(Newcases+1)	0.037*** (0.014)	0.018 (0.019)	0.007 (0.011)	−0.068*** (0.021)	−0.102** (0.050)	−0.053*** (0.016)
Family	0.312*** (0.108)			−0.246 (0.157)		
Collective		0.183*** (0.051)			−0.679*** (0.073)	
Country			1.084*** (0.173)			−0.562** (0.258)
log(Newcases+1)*Family	−0.139** (0.059)			0.129 (0.087)		
log(Newcases+1) *Collective		−0.025 (0.027)			0.130*** (0.038)	
log(Newcases+1) *Country			−0.007 (0.088)			0.029 (0.131)
Control Variables	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y	Y
Obs.	1620	1620	1620	1620	1620	1620
R-squal	6.0	14.1	5.65	11.1	8.7	15.5

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

related to "collective" or "country" by American users are associated with a decrease in expressions of positive emotions.

The results from the moderation effect analysis signify that the attributes of social connections, denoted by "country" and "collective" in China, and "family" and "collective" in the United States, play a pivotal role in moderating emotions during the pandemic. Figure 8 displays the results of the interaction effects, which include the Johnson-Neyman (J-N)

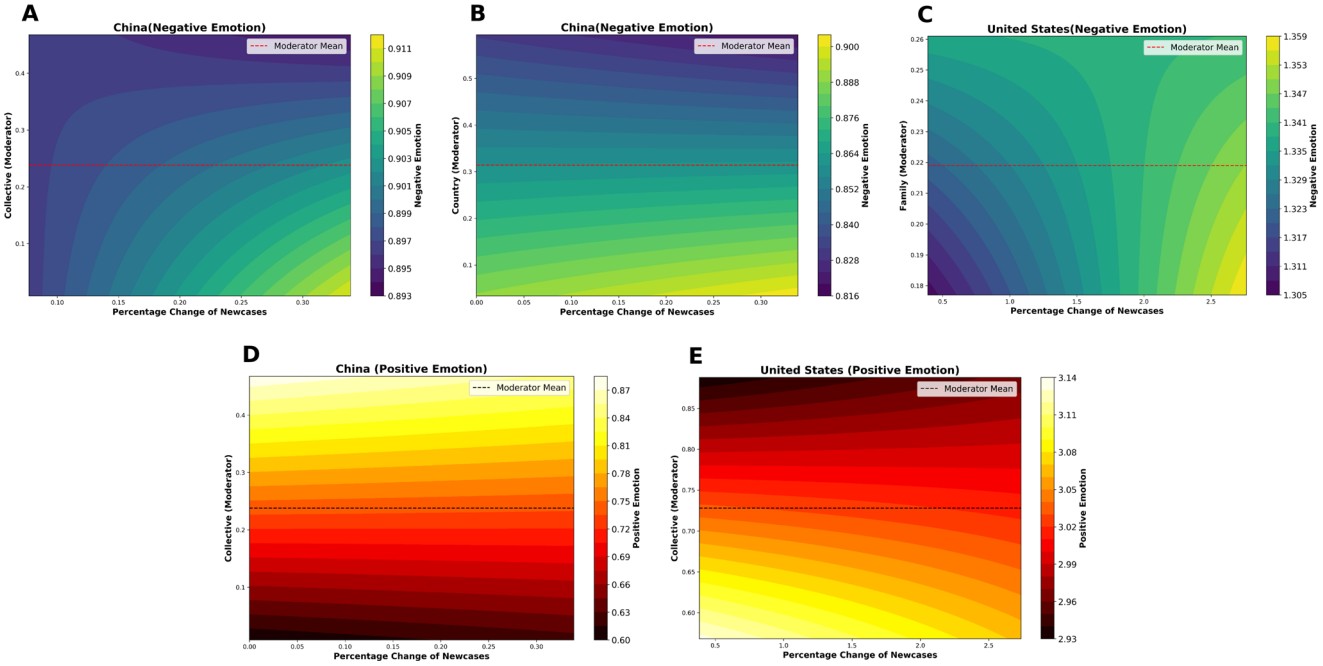

Fig. 8 Interactive effects of percentage change of new cases and social connections on public emotion. These Johnson–Neyman interaction plots illustrate the interactive effects of Percentage Change of New cases and Social connections (moderators) on Public Emotion in the contexts of China and the United States. Specifically, **A** China's "collective" effect on negative emotions, **B** China's "country" effect on negativeemotions, **C** US "family" effect on negative emotions, **D** China's "collective" effect on positive emotions, and **E** US "collective" effect on positive emotions. The dashed line represents the moderator's mean value.

test findings, elucidating the intricate ways through which these social connections attribute moderate emotions in different societal contexts.

Subfigure A depicts the moderation effect of "collective" social connections on negative emotions within the Chinese sample as the number of new COVID−19 cases changes. The contour plot deftly outlines the interaction between the "collective" social connections and the fluctuating new case rates, showcasing their joint impact on the public's emotional state. Although the "collective" variable alone does not show a significant main effect, the contour lines delineate the areas where "collective" social connections effectively mitigate the pandemic's negative emotional repercussions. The color gradient within the plot, ranging from deep blue to yellow, illustrates the variation in negative emotion levels: deep blue represents a lower level of negative emotions, suggesting a stronger moderation by "collective" connections, while yellow indicates a higher level of negative emotions, pointing to a weaker moderating effect.

Subfigure B depicts that as the social connection attributed to "country" strengthens in China, there is a corresponding decrease in negative emotions among the public, especially as the percentage change of new cases increases, showcasing its mitigating role on the adverse emotional impacts of COVID-19.

In Subfigure C, in the U.S context, when the social connection attributed to "family" intensifies while the percentage change of new cases is below 1.5, there is a corresponding increase in negative emotions. However, when the percentage change of new cases is above 2, a strengthening "family" connection correlates with a decrease in negative emotions, revealing its alleviating effect on negative emotions when the rise in cases is substantial.

Finally, Subfigures D and E illustrate the differential roles played by the social connection attribute "collective" in both China and the United States. In China (Subfigure D), a strengthening in "collective" connection correlates with increased positive emotions, particularly when the percentage change of new cases is smaller. However, in the United States (Subfigure E), an intensification of "collective" connection is associated with a reduction in positive emotions, with this diminishing effect becoming more pronounced as the percentage change of new cases decreases.

Robustness test. In terms of the sample, the US Reddit and X dataset encompasses 18 major cities, while the China Weibo data originate from 355 cities. To enhance the robustness and comparability of our conclusions, we selected the largest 19 cities from the 335 Chinese cities (i.e., 4 municipalities and 15 sub-provincial cities, as detailed in Appendix A4) for comparison with the 18 US cities. We also extracted all the users who mentioned COVID-19 in their posts in the Reddit and X dataset for analysis and comparison with the Weibo data in China. The analysis results were consistent with the above (see Appendix A5 for details).

Discussion

This study offers an in-depth examination of the disparities in public emotions and social connections between China and the United States during the COVID-19 pandemic. To elucidate the mechanisms underpinning these differences, we conducted a topic analysis of social media posts. Preliminary insights from this analysis subtly suggest that cultural divergences play a pivotal role in driving the observed disparities between the two nations.

Treading along the thread of cultural paradigms, it becomes apparent that the individualistic culture of the United States and the collectivist culture of China serve as robust frameworks that not only shape behaviors and perceptions but also carve emotional expressions and social connectivity during crisis scenarios, such as a pandemic. Within the American context, the individualistic culture, which puts a premium on personal freedom and expression (Schwartz, 1992), sharply contrasts with China's collectivist culture that prioritizes teamwork and social harmony

(Hwang, 2012). Notably, these cultural paradigms not only mold individual behaviors and cognitive processing but also sculpt perceptions and evaluations across varied situations (Markus & Kitayama, 1991). For instance, collectivist cultures tend to perceive crises as a collective responsibility, potentially suppressing individual anger but perhaps elevating anxiety within the group (Fischer and Poortinga, 2012). Collectivist norms may dictate the suppression of certain emotional expressions, such as anger or sadness, to preserve group harmony (Matsumoto et al., 2008) and often spotlight long-term group benefits over immediate individual gratification (Zimbardo and Boyd, 2014). This framework elucidates why China might experience elevated anxiety levels yet diminished sadness and anger during crises compared to the United States.

Concurrently, the dichotomy between collectivist and individualist cultures has also nuanced the differential focus on social connections between China and the United States. It propels Chinese users to forge deeper connections with the nation, while American users pivot towards familial connections. In discussions concerning "family", American users manifest a pronounced concern for "Employment" and "Education", potentially stemming from their individualistic culture and the pursuit of personal rights (Triandis, 1996). In stark contrast, Chinese users lean more towards "Pandemic" and "Health protection" topics, reflecting a collective cultural emphasis on crisis response and social welfare (Hofstede et al., 2010). Hence, during anxious times, Americans tend to prioritize discussions on politics and finance, perhaps aligning with a pursuit of individual rights and economic liberty, whereas Chinese counterparts, dictated perhaps by the cultural weightage towards harmony and collective well-being, steer their focus towards the pandemic and daily activities.

Unfurling the tapestry of these insights, a noteworthy finding emerges in the domain of positive emotional expressions amid the throes of the pandemic. With both nations under the rigors of lockdown protocols, Chinese social media witnessed an uplifting wave of positive emotional expressions, in stark contrast to a downswing noted in the United States.Thematic analysis discerns contrasting narratives in these expressions. In China, over 30% of content expressing positive emotions orbited around themes of "Searching for meaning" and "Cheer on the people of Wuhan", embodying the ingrained collectivist values of the society. Such communal identification and cooperation, inherent to collectivist cultures, foster a robust sense of collective responsibility and heightened positive emotions (Jetten et al., 2012; Chen and French, 2008). Conversely, in the U.S., positive emotion predominantly coalesced around "State Politics", indicating a societal emphasis on governance and policy directions, with the noticeable dip in positive emotion potentially reflecting the nation's individualistic tendencies and possibly divergent attitudes towards restrictive measures.

Navigating further into the intricacies of cultural variances, particularly in time orientations, an intriguing light is shed on the disparate emotional expressions between Chinese and American users as the pandemic unfolded. As delineated in Appendix A6, Chinese users exhibit a conspicuous orientation towards the future, symbolizing their anticipatory apprehensions during the pandemic and the pronounced anxiety often entwined with uncertainties about future eventualities. This forward-looking perspective appears diametrically opposed to American users who chiefly anchor their focus on the present, echoing immediate reactions to evolving scenarios. Emotions such as sadness and anger, experienced by American users, emanate from past experiences and current unmet expectations, demonstrating a prevalence of present-focused emotional expressions. In scrutinizing this temporal divergence, it becomes evident that the forward-looking orientation of Chinese users aligns coherently with their collective mindset, traditionally embracing a long-term view and placing substantial emphasis on future implications and collective wellbeing (Hofstede et al., 2010; Zimbardo and Boyd, 2014). This possibly facilitates a societal temperament that leans towards maintaining harmony and stability even amidst crises by cultivating a forward-thinking approach, which, in turn, modulates emotional expressions towards anticipatory anxiety rather than immediate frustration or sadness. Contrastingly, the predominantly present-focused orientation of American users aligns with the individualistic cultural paradigm that traditionally places a premium on immediate, personal experiences and outcomes (Schwartz, 1992). The emphasis on the present potentially translates into a direct, immediate emotional response to circumstances as they unfold, giving rise to emotions that reflect current predicaments, such as sadness or anger about ongoing events and challenges. Thus, time orientation, imbibed with cultural norms, emerges as a pivotal factor sculpting the emotional landscapes observed in Chinese and American users during the pandemic. It serves as a lens through which emotional responses to crises can be discerned and understood, indicating how embedded cultural frameworks not only shape perceptions of events but also guide emotional expressions and coping mechanisms amidst global crises.

In parallel, discerning the moderating effects of social connections within these cultural contexts brings forth fascinating discoveries. Specifically, the social connection with the "country" in China and "family" in the United States each served as a buffer, mitigating the proliferation of negative emotions during periods of surging case numbers. Moreover, in the context of slower case growth, "collective" social connections in both nations paradoxically intensified and dissipated positive emotional expressions, respectively. Examining these dynamics through the lens of cultural distinctions unveils the underpinnings of such variations. China, rooted in a collectivist culture, prioritizes the well-being and interests of the collective and the larger group, particularly in crisis contexts. The aphorism, "Sacrifice the interests of the individual family for the greater good of the community" (Zhang, 2020), encapsulates this ethos, suggesting that the Chinese public may value and depend more heavily upon "collective" and "country" social connections. Consequently, these connections serve a dual purpose: amplifying positive emotional expressions and assuaging negative ones during crises. Contrastingly, in the United States, where the cultural ethos leans towards individual rights and freedoms, 'family' social connections appear to assume a crucial role in attenuating negative emotions amid severe outbreaks. In this instance, "collective" social connections interestingly dissolve, rather than foster, positive emotions, reflecting perhaps an inherent skepticism or tension towards collective entities during times of crises, rooted in the nation's individualistic paradigm. These disparate sociocultural frameworks and their interactions with various types of social connections reveal a complex tapestry of emotional responses amidst a global crisis. By juxtaposing the influences of "family", "collective", and "country" connections in both China and the United States, the subtle and overt ways through which cultural norms navigate emotional landscapes during turbulent times are vividly illuminated.

However, as we synthesize these insights, it becomes imperative to highlight certain limitations and pave avenues for future research. The primary tether encircling our study emanates from the utilization of social media data, an approach that potentially introduces demographic biases and may not fully encapsulate the holistic emotional landscape of the wider populace. Accordingly, the integration of multiple data sources and harmonization of social media data with regional survey data in future research endeavors could cast a wider, more demographically representative net over the understanding of emotional expressions and

social interactions during crises. Furthermore, our examination of positive emotions is observed through a broader lens, potentially overlooking the fine-grained subtleties embedded in different shades and intensities of positive emotion. In the subsequent research, the granular nuances of positive emotion could be unravelled through the incorporation of machine learning and natural language processing, dissecting positive emotion into varied subcomponents such as joy, gratitude, and hope, thus offering a richer, nuanced depiction of emotional expressions amidst crises. While our methodology proficiently navigates through the labyrinth of emotional expressions, social connections, and crisis events, it does falter in assimilating potential confounding variables, such as information transparency and governmental trust (Lu et al., 2020), into the framework. This opens up expansive terrain for future researchers to weave into the analytical framework a myriad of macro and micro-level variables, perhaps employing multilevel modeling, to explore the simultaneous influences operating at individual and collective strata, thereby not only addressing the recognized limitations but also enriching the depth and breadth of exploration in the realms of emotional expressions and social connections amidst crises.

Data availability

The datasets and code generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Notes

1 Weibo's financial report for the first quarter of 2020. derive from https://finance.sina.com.cn/stock/usstock/c/2020-05-19/doc-iircuyvi3942770.shtml.

2 Baidu, often referred to as "China's Google", is a leading AI company with a robust internet foundation, boasting core search engine technologies. The Baidu Mobility Index, which is employed in our study, is computed based on Baidu Map's Open Platform geographical location services. The data source is the substantial location service data (Location-Based Services, LBS) from Baidu Map's Open Platform, derived from all software choosing to use Baidu's geographical location API services. Baidu's location services respond to over 120 billion global location service requests per day, providing a vast foundational dataset for mobility data.

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Author contributions

Conceptualization, LL, JX and JW; Data curation, LL, JX and JW; Formal analysis, LL, JX, JW and XLF; Writing - original draft, LL and JX; Writing - review & editing, LL, JX, JW, FLS and XLF. All authors commented on previous versions of the manuscript. LL and JX contributed equally to this work. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

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Additional information

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