



# Estimating geographic subjective well-being from Twitter: A comparison of dictionary and data-driven language methods

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Researchers and policy makers worldwide are interested in measuring the subjective well-being of populations. When users post on social media, they leave behind digital traces that reflect their thoughts and feelings. Aggregation of such digital traces may make it possible to monitor well-being at large scale. However, social media-based methods need to be robust to regional effects if they are to produce reliable estimates. Using a sample of 1.53 billion geotagged English tweets, we provide a systematic evaluation of word-level and data-driven methods for text analysis for generating well-being estimates for 1,208 US counties. We compared Twitter-based county-level estimates with well-being measurements provided by the Gallup-Sharecare Well-Being Index survey through 1.73 million phone surveys. We find that word-level methods (e.g., Linguistic Inquiry and Word Count [LIWC] 2015 and Language Assessment by Mechanical Turk [LabMT]) yielded inconsistent county-level well-being measurements due to regional, cultural, and socioeconomic differences in language use. However, removing as few as three of the most frequent words led to notable improvements in well-being prediction. Data-driven methods provided robust estimates, approximating the Gallup data at up to  $r = 0.64$ . We show that the findings generalized to county socioeconomic and health outcomes and were robust when poststratifying the samples to be more representative of the general US population. Regional well-being estimation from social media data seems to be robust when supervised data-driven methods are used.

Twitter | subjective well-being | language analysis | big data | machine learning

Many governments worldwide are incorporating subjective well-being measures as indicators of progress and success (1, 2) to complement traditional objective and economic metrics. Subjective well-being spans cognitive (i.e., life satisfaction), affective (positive and negative emotion), and eudaimonic dimensions (such as a sense of meaning and purpose) (3); most metrics are based on self-report surveys and interviews of individuals, which might be collected annually and aggregated to represent the well-being of regions or nations. Such metrics are time and resource intensive to gather, and there is a growing interest in identifying efficient methods to garner subjective well-being information (4).

Concurrently, social and information exchange has increasingly migrated to digital contexts, including social media platforms. Through language posted online, people leave behind psychological traces that can be mined to address real-world problems. The public nature of Twitter offers a way to augment the theory and practice of psychology and medicine with large-scale data collection. For example, researchers have used Twitter

to measure and understand mental illness (5), sleep disorders (6), physical health (7), and heart disease (8).

Studies over the past two decades have established links between autobiographical writing and the psychological well-being of individuals (ref. 9 has a recent review). Twitter-based studies (including those in refs. 10–12) have used different methods to extract overall scores of positive and negative emotion (also referred to as sentiment or valence) through either word-level or data-driven methods (Table 1). Word-level methods, such as the Linguistic Inquiry and Word Count (LIWC) dictionaries (13), involve the use of predetermined or annotated dictionaries (lists of words) that are expected to represent positive and negative emotion and count the relative frequency of words

## Significance

Spatial aggregation of Twitter language may make it possible to monitor the subjective well-being of populations on a large scale. Text analysis methods need to yield robust estimates to be dependable. On the one hand, we find that data-driven machine learning-based methods offer accurate and robust measurements of regional well-being across the United States when evaluated against gold-standard Gallup survey measures. On the other hand, we find that standard English word-level methods (such as Linguistic Inquiry and Word Count 2015's Positive emotion dictionary and Language Assessment by Mechanical Turk) can yield estimates of county well-being inversely correlated with survey estimates, due to regional cultural and socioeconomic differences in language use. Some of the most frequent misleading words can be removed to improve the accuracy of these word-level methods.

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Data deposition: The data and materials for this paper have been made publicly available via the Open Science Framework (OSF) and can be accessed at <https://osf.io/jqk6f>. County language estimates are available in the World Well-Being Project (WWBP) GitHub repository ([https://github.com/wwbp/county\\_tweet\\_lexical\\_bank](https://github.com/wwbp/county_tweet_lexical_bank)).

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**Table 1. The language-based emotion measures used in this study, which span four main methods: word-level methods and data-driven methods applied at the sentence, user, or county level**

| Type                             | Method (source)                       | No. of features | Categories                                                  |
|----------------------------------|---------------------------------------|-----------------|-------------------------------------------------------------|
| Word-level methods               |                                       |                 |                                                             |
|                                  | LIWC 2015 (13)                        | 1,364           | Positive emotion, negative emotion, anxiety, anger, sadness |
|                                  | PERMA dictionary (14, 15)             | 402             | Positive emotion, negative emotion                          |
| Word-level annotations           | ANEW (16)                             | 1,034           | Valence                                                     |
| Word-level annotations           | LabMT <sup>i</sup> (17)               | 10,218          | Valence                                                     |
| Data-driven methods              |                                       |                 |                                                             |
| Sentence-level annotations       | WWBP affect (18)                      | 7,265           | Affect                                                      |
| Sentence-level annotations       | Swiss Chocolate (19)                  | 7,168           | Positive, neutral and negative emotion                      |
| Person-level models              | WWBP life satisfaction (this study)   | 2,000           | Cantril Ladder score                                        |
| Direct prediction Cantril Ladder | County life satisfaction (this study) | 2,000           | Cantril Ladder score                                        |

appearing in the dictionary. For example, Golder and Macy (20) applied the LIWC (2007) dictionaries to Twitter posts to track longitudinal variation in affect. Other word-level methods, such as the Language Assessment by Mechanical Turk (LabMT) word list (21) and the Affective Norms of English Words (ANEW) (16), ask raters to annotate words for their valence. For example, LabMT provides the average rater-determined valence (between “sad” and “happy”) for the 10,000 most frequent words in the English language. These crowdsourced ratings have been applied to geotagged Twitter language to estimate the mood of US states and urban and metropolitan statistical areas (10).

Data-driven methods involve the use of machine learning to identify associations between the linguistic information contained in the text and its emotional content. The emotional content of sentences or documents (rather than words in isolation) is determined by annotation or based on a self-report survey. Natural language processing methods are used to extract language features, which are then used to predict emotional content using supervised machine learning.

How well do these different methods assess subjective well-being? Previous results with word-level methods are inconsistent (22, 23). At the regional level, LabMT’s state-level happiness estimates show inconsistent associations with life satisfaction reported by the Centers for Disease Control and Prevention (CDC) (10), and at the city level, LabMT’s estimates of happiness were negatively correlated with measures of physical health (24). The unexpected findings may arise from how people use language and differ in their use of social media; alternatively, they could be an artifact of the demographic and geographic effects of aggregating the language of individuals to represent geographies. On the other hand, data-driven methods, which train machine learning models on large corpora and then apply those models to other contexts, have been shown to offer performance improvements over word-based methods for predictive problems (25–27).

In the current study, we compare methods for regional estimates of subjective well-being from social media language against survey-based ground truth measures of county-level evaluative and hedonic well-being (excluding eudaimonic aspects). We use over a billion geolocated tweets from 2009 to 2015 (28), from which we extracted language features, normalized their frequency distributions, and aggregated them to yield county-level language estimates. From these, we extracted emotion/life satisfaction estimates (Table 1).

We aggregated 1.73 million responses to the Gallup-Sharecare Well-Being Index from 2009 to 2015 to obtain county-level measures of life satisfaction, happiness, worry, and sadness. In the primary analysis, we determined the convergent validity between the language-based methods and the Gallup county-level outcomes using an open-source Python codebase (29). We repli-

cated our analyses on county-level health and socioeconomic outcomes to show that the observed patterns generalize beyond self-reported well-being metrics. To account for sample differences, we replicated the primary analysis after poststratifying the Gallup and Twitter samples to match census demographics in age, gender, education, and income. Across a subset of 373 counties, we examined the stability of the findings across time. To investigate the impact of ecological aggregation, we ran parallel analyses across a sample of 2,321 Facebook users. In addition, we conducted a post hoc diagnosis to identify and suggest a solution for the main sources of error in word-level methods.

### Evaluation of Twitter-Based Estimates

Table 2 summarizes the convergent validity from the different methods against the Gallup county estimates. Unexpectedly, among the word-level methods, higher positive emotion/valence estimated from LIWC 2015, ANEW, and LabMT\* correlated with lower subjective well-being. For example, both LIWC’s positive emotion dictionary and LabMT correlated negatively ( $r = -0.21$  and  $r = -0.27$ ,  $P$  values  $< 0.001$ ) with life satisfaction—the most widely used measure of subjective well-being. Similarly, they correlated negatively with happiness and positively with sadness. The PERMA positive emotion dictionary (14, 15, 30) is limited to more unambiguous words and correlated with subjective well-being in the expected direction.† (PERMA is Seligman’s construct of well-being, an acronym for positive emotion, engagement, relationships, meaning, and accomplishment.)

The LIWC and PERMA negative emotion dictionaries showed the expected pattern of correlations. Throughout word-level and data-driven methods, negative emotion estimates showed larger and more consistent correlations than their positive counterparts, suggesting that they more consistently captured the absence of well-being on Twitter than its presence. None of the methods predicted worry well, which demonstrated weak correlations across all methods.

In contrast to the word-level methods, the data-driven methods consistently produced estimates that correlated with the Gallup measures in the expected directions, with positive language scores predicting higher life satisfaction and happiness and lower worry and sadness. Data-driven methods thus appear more robust than the word-level methods. Among the data-driven methods, the state-of-the-art sentiment model Swiss Chocolate (19) matched or outperformed the World Well-Being Project (WWBP) affect model (18) and the user-level life satisfaction

\*Following ref. 17, we removed “neutral” words with  $4 < \text{valence} < 6$ , leaving 3,731 words.

†SI Appendix, Table S16 has details on the approaches, and SI Appendix, Table S3 has extended results covering additional word- and sentence-level methods.

**Table 2. Pearson correlations ( $r$ ) between Twitter-based emotions and Gallup-Sharecare Well-Being Index estimates across 1,208 US counties**

| N = 1,208 U.S. counties | Word-level |                     |          |          |          |         |                    |         | Data-driven        |                |                 |          |                |                   |
|-------------------------|------------|---------------------|----------|----------|----------|---------|--------------------|---------|--------------------|----------------|-----------------|----------|----------------|-------------------|
|                         | LIWC 2015  |                     |          | PERMA    |          | ANEW    |                    | LabMT   |                    | Sentence-level |                 |          | Person-level   |                   |
|                         | Positive   | Positive (modified) | Negative | Positive | Negative | Valence | Valence (modified) | Valence | Valence (modified) | WWBP           | Swiss Chocolate |          | WWBP Life Sat. | Direct prediction |
|                         |            |                     |          |          |          |         |                    |         |                    | Affect         | Positive        | Negative |                |                   |
| Life Satisfaction       | -.21       | -.06                | -.32     | .22      | -.37     | -.03    | .15                | -.27    | .01                | .29            | .24             | -.29     | .39            | .62               |
| Happiness               | -.13       | .13                 | -.27     | .27      | -.17     | .04     | .18                | -.07    | .16                | .23            | .24             | -.30     | .23            | .51               |
| Worry                   | .11        | .01                 | .03      | -.01     | .02      | .03     | -.05               | .02     | -.04               | .00            | -.02            | .11      | -.03           | .52               |
| Sadness                 | .25        | -.01                | .22      | -.19     | .18      | .09     | -.10               | .19     | -.09               | -.18           | -.20            | .33      | -.23           | .64               |

The gray column headers identify the modified LIWC (removed 3 words), LabMT (removed 15 words), and ANEW (removed 2 words) dictionaries (in the text). The color indicates the direction and magnitude of correlation; white cells are nonsignificant, and all others are  $P < 0.05$  corrected for multiple comparisons.

model that we trained in this study. Direct prediction, also trained by this study, outperformed all other methods ( $r = 0.51$  to  $0.64$ ,  $P$  values  $< 0.001$ ). However, here the models benefited from being directly modeled on Twitter county data and the Gallup outcomes.

**Generalizability to Socioeconomic and Health Outcomes.** To go beyond self-reported measures, we replicated our analyses using county socioeconomic and health variables as dependent variables. We again found that data-driven methods were more robust, outperforming word-level methods.<sup>‡</sup> For the word-level methods, LIWC's positive emotion dictionary and LabMT were negatively correlated with an index of socioeconomic status (combining income and education; at  $r = -0.40$  and  $r = -0.43$ , respectively;  $P$  values  $< 0.001$ ) as well as positively correlated with CDC-provided measures of poor physical and mental health; therefore, the erroneous associations in Table 2 generalize beyond the well-being outcomes.

**Correcting for Sample Differences.** The population of users in the Gallup and Twitter datasets is notably different from one another and potentially not representative of the US population. Respondents in the Gallup sample were older and wealthier, while those in the Twitter sample were mostly from urban areas and estimated to be younger, with more Hispanics and African Americans than the average US population.<sup>§</sup> In a supplementary analysis, we poststratified both samples on age, gender, income, and education to render them representative of the county-level US population. For the Twitter sample, we used the language of users to estimate age, gender, income, and education following previously established demographic estimation and selection bias correction methods (31).<sup>¶</sup> We found that poststratification left the pattern of results largely unchanged; language associations with survey well-being were within  $r = 0.10$  of those reported based on the unstratified data.<sup>#</sup>

**Controlling for Demographic and Socioeconomic Confounds.** In order to control for endogenous differences, we added sociodemographic covariates for age, gender, and race when evaluating the language models (*SI Appendix, Table S10*). The resulting pattern of coefficients showed small differences in magnitude when compared with the main results in Table 2. As a stronger test, we entered dummy variables for US states and regions into the regression equations to adjust for unobserved endogenous variables at the state or regional level. Thereby, we only

compared counties with counties within the same states and regions. The pattern of correlations was unchanged. Up until this point, these findings suggested that the language-based well-being estimates are not merely attributable to demographic or state-by-state differences in unobserved variables. Finally, when we controlled for income and education, it largely reduced most language associations. This is likely because socioeconomic status was strongly associated with our dependent variable, subjective well-being (e.g., life satisfaction correlated  $r = 0.59$  with an income/education index).<sup>||</sup> We infer that the variance in the word-level methods overlaps with socioeconomic variance in language use. Some of the data-driven methods captured some variance in Gallup happiness over and above socioeconomic status.

**Stability of Results over Time.** We examined whether our findings were robust to the evolving use of Twitter and well-being trends over time. We repeated our analyses across two shorter windows of time (from 2012 to 2013 and from 2015 to 2016) across a smaller sample of 373 counties for which sufficient Gallup and Twitter data were available. The pattern of results was largely consistent with Table 2. We also evaluated how well models built on 2012 to 2013 Twitter language predicted 2015 to 2016 well-being, finding only a small reduction in performance.<sup>\*\*</sup>

**Comparison with Individual-Level Language Analyses.** To shed light on the ecological effects of community-level aggregation, we carried out an analogous comparison of language methods at the individual-level across a sample of 2,321 Facebook users who had answered the same survey questions as the Gallup sample. The associations of the LIWC 2015 positive emotion dictionary with well-being were weakly positive ( $r = 0.04$ ,  $P = 0.050$ ), which aligned with previous findings with LIWC 2007 (22). In general, all but LabMT showed weak associations in the expected direction at the individual level. The data-driven methods again produced the expected pattern of correlations, albeit with reduced magnitudes compared with the county level ( $r$  values  $< 0.25$ ).<sup>††</sup>

### Word-Level Error Analyses

LIWC's emotion dictionaries and LabMT are among the most popular tools for assessing emotion through language. To better understand their unexpected pattern of association with county-level well-being, socioeconomic and health variables, we conducted a set of post hoc diagnostic analyses, which suggested that the main sources of error in these word-level methods were

<sup>‡</sup>*SI Appendix, Table S5* has the detailed results.

<sup>§</sup>*SI Appendix, Table S6* has a general overview of the response biases.

<sup>¶</sup>Details on the model accuracies are in *SI Appendix, Table S7*.

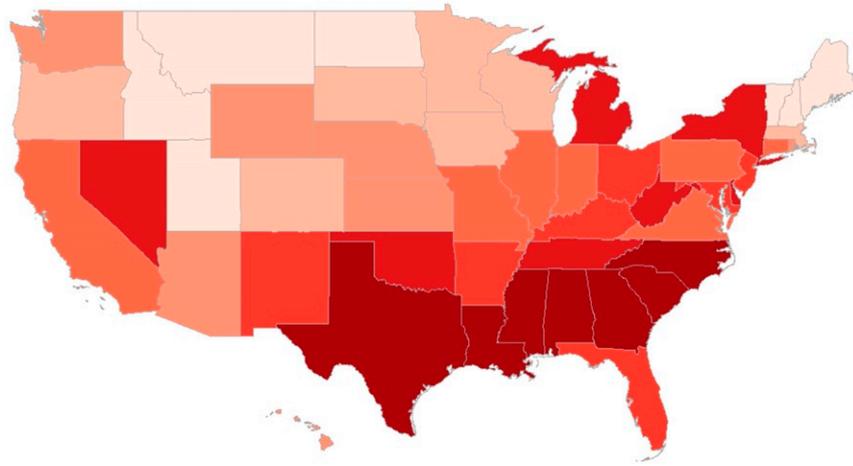
<sup>#</sup>The poststratification process is validated in *SI Appendix, Table S8*.

<sup>||</sup>*SI Appendix, Table S18* has details.

<sup>\*\*</sup>Additional information is in *SI Appendix, Table S11*.

<sup>††</sup>*SI Appendix, Table S13* has the full results.





**Fig. 2.** The relative frequency of false LIWC positive emotion words across the United States. States with a darker shade of red had relatively higher numbers of positive emotion words that correlated negatively with county Gallup happiness (Fig. 1, Upper Right) at  $P < 0.05$ , controlling for multiple comparisons.

that data-driven well-being estimates also predicted US county economic and health outcomes. They were largely unchanged when correcting for sample biases through poststratification, when including demographic covariates, or when comparing only counties to counties within states. We found that the pattern of correlations with county Gallup estimates was stable over time. Regarding the choice of language analysis method, our study had three main findings.

First, word-level methods for subjective well-being measurement should be used with caution. One of the primary difficulties in estimating psychological states for geographies using social media arises from applying methods designed to measure the emotion of sentences of individuals to the language of regional populations. The language of regions differs culturally, such as the South using more religious language. When these cultural differences interact with socioeconomic gradients, these differences may invert the expected relationship between word-level estimates and well-being and health outcomes.

Second, most of the discrepancies observed for word-level methods seem to be driven by the use of a few frequent words (such as lol, love, and good). Stylistic markers such as lol can be used to convey a variety of emotions (32); they may also symbolize meanings that are specific to cultures and communities. Removing these words from LIWC, ANEW, and LabMT dictionaries reduced the negative associations with Gallup happiness and thus, improved the convergence with survey-reported county-level well-being.

Third, data-driven language models using supervised machine learning based on the sentence-, person-, or county-level training data seem to generate valid geographical estimates of well-being. The same language models worked consistently across counties and individuals. Methods that directly predict county well-being from county language seemed able to capture counties' social and socioeconomic context and explain the regional variance in well-being over and above socioeconomic indicators.<sup>†††</sup> These models offer opportunities to augment other methods of spatial estimation by providing estimates with higher temporal resolution than annual surveys and by providing estimates for regions that are insufficiently covered by other sampling methods.

Our study also had three main findings about what explains the difference in performance between word-level and data-driven county-level well-being estimation. First, cultural norms may

shape the associations between world-level estimates, well-being, and health. To the extent that social media users underreport socially undesirable and overreport socially desirable emotions, methods that rely only on emotion language may misestimate well-being. These estimation errors may be critical to study subpopulations that share different cultural notions of ideal affect, such as Asian Americans' preference for low-arousal emotions (35)—as a result, emotion-focused language estimates may underestimate their well-being. In contrast, the use of the full vocabulary considers other kinds of signals, such as function words (e.g., “of,” “the,” “for”), which can also represent higher cognitive processing that covaries with subjective well-being (36). In support of this claim, employing 73 LIWC dictionaries as features in direct county-level prediction yielded a performance nearly at par with the data-driven Twitter language model.

Second, the data-driven methods do not inherit the annotator biases of word-level methods (as used by ANEW or LabMT), which may lead to words such as “conservative” and “exams” acquiring a negative valence and “baby” acquiring a positive one. Such annotations may reflect the view of the annotators of these words outside the broader cultural and socioeconomic context of these words and may differ by the cultural context of the annotators. Sentence- and person-level methods incorporate broader semantic contexts beyond single words.

Third, data-driven methods can capture the socioeconomic variance present in the samples on which they were trained. At times, these language associations deviate from the apparent valence of words outside their socioeconomic context. For example, individuals with higher socioeconomic status and well-being more frequently mention “taxes” and “penalty”—while negatively valenced for individuals, these are markers of relative prosperity at the county level. Similarly, “mortgages” are

**Table 3.** Pearson correlations ( $r$ ) between Facebook-based emotions and survey responses across 2,321 Facebook users

|                   | Word-level |                     |          |          |          |         |                    |         |                    |
|-------------------|------------|---------------------|----------|----------|----------|---------|--------------------|---------|--------------------|
|                   | LIWC 2015  |                     |          | PERMA    |          | ANEW    |                    | LabMT   |                    |
|                   | Positive   | Positive (modified) | Negative | Positive | Negative | Valence | Valence (modified) | Valence | Valence (modified) |
| Life Satisfaction | .04        | .07                 | -.26     | .14      | -.21     | .09     | .12                | -.02    | .00                |
| Happiness         | .04        | .06                 | -.21     | .11      | -.18     | .08     | .09                | .00     | .00                |
| Worry             | .07        | .05                 | .13      | .00      | .15      | .03     | .00                | .08     | .05                |
| Sadness           | .04        | .01                 | .15      | -.04     | .14      | .01     | -.02               | .07     | .03                |

The color indicates direction and magnitude of correlation; white cells are nonsignificant, and all others are  $P < 0.05$  corrected for multiple comparisons

<sup>†††</sup>Additional information is in *SI Appendix, Table S3C*.

**Table 4. Pearson correlations (*r*) between Gallup-Sharecare Well-Being Index-based estimates and Twitter use of subsets of LIWC positive emotion words that co-occur with other LIWC dictionaries across 1,208 US counties**

|                                      | Personal Concerns                            |                                   |                                             | Netspeak                      | Social                                 |
|--------------------------------------|----------------------------------------------|-----------------------------------|---------------------------------------------|-------------------------------|----------------------------------------|
|                                      | Religion                                     | Leisure                           | Work                                        |                               |                                        |
| Most frequent positive emotion words | bliss*, faith*, heaven*, worship*, paradise* | play, fun, party*, playing, joke* | champ*, award*, success, challeng*, credit* | lol, ;), haha*, lmao*, lmfao* | love, party*, welcom*, trust*, giving* |
| Life Satisfaction                    | -.11                                         | .15                               | .33                                         | -.13                          | -.32                                   |
| Happiness                            | -.12                                         | .15                               | .23                                         | -.25                          | -.17                                   |
| Worry                                | .08                                          | -.04                              | -.05                                        | .10                           | .12                                    |
| Sadness                              | .27                                          | -.21                              | -.30                                        | .23                           | .32                                    |
| Socioeconomic Index                  | -.33                                         | .26                               | .57                                         | -.33                          | -.50                                   |
| All Cause Mortality                  | .49                                          | -.22                              | -.48                                        | .30                           | .38                                    |
| Fair/Poor Health                     | .43                                          | -.25                              | -.44                                        | .42                           | .37                                    |
| Mentally Unhealthy Days              | .24                                          | -.13                              | -.23                                        | .15                           | .25                                    |

Color indicates direction and magnitude of correlation; white cells are nonsignificant, and all others are  $P < 0.05$  corrected for multiple comparisons

indicative of homeownership and socioeconomic status (37). Data-driven models capture these words as markers of higher well-being despite their apparent negative valence.

This study focused on language measures of valence and emotion as estimates of county well-being. Care is needed when pursuing the reverse analytic strategy and interpreting language correlations to characterize the well-being of individuals. For instance, many studies have shown that stronger religiosity (38, 39) and sociality (40, 41) benefit well-being. However, correlations with religious language or social words such as love may suggest the opposite at the population level unless socioeconomic contexts are properly considered.

**Limitations.** Limited by the availability of county-level Gallup data, we evaluated Twitter methods against county evaluative and affective dimensions of subjective well-being but did not include eudaimonic measures capturing meaning and purpose (42). Associations between eudaimonic measures and language-based estimates may differ.

While Twitter provides an unprecedented opportunity to observe the natural communications in communities, only a small fraction of Twitter posts has geolocation information (28). Still, the sample size of users who can be geolocated (5.73 million in this study) matches or exceeds the largest phone-based survey efforts. Our analysis was limited to English language posts on Twitter and thus, may have missed signals from other languages prominently used in the United States, such as Spanish and Chinese. Twitter's user base is not representative of the US population, and many people do not use Twitter—concerns that we addressed 1) through testing the Twitter language models against the Gallup samples using random dialing and 2) through replicating our analysis on samples that were poststratified toward age,

gender, income, and education distributions reported by official sources. It is not clear that regular social media users are substantially different from nonregular users; for example, recent work in a large cohort study of females aged 53 to 70 found a very similar profile of sociodemographic and psychosocial factors across both groups (43).

The findings reported in this paper are correlational and do not intend to make causal claims. They provide a snapshot of community health and well-being correlates, but as internet language evolves (32, 44, 45), the correlations between social media language features and well-being are likely to change over time. Although the data-driven methods in this paper, such as the WWBP affect model and the WWBP life satisfaction model, were trained on Facebook posts and then applied to Twitter, we do not expect this to have substantially affected their performance when applied to the county level (46, 47).<sup>† † †</sup>

## Materials and Methods

Full methods are in *SI Appendix*.

**County Twitter Data.** We used the County Tweet Lexical Bank from ref. 28, which comprises language estimates of US counties and corresponds in time to the Gallup well-being dataset.<sup>§ § §</sup>

**Gallup-Sharecare Well-Being Index.** We included 1,208 counties that had at least 300 Gallup respondents and sufficient Twitter language. To facilitate secondary poststratification analyses, we limited the sample to respondents for whom age, gender, income, and education were available before aggregating the well-being estimates to the county-level, which reduced the sample by 1.6%. In total, we aggregated 1,727,158 Gallup survey responses.<sup>¶ ¶ ¶</sup>

**Individual-Level Data.** We recruited adults in the United States via Qualtrics for a well-being survey, which included the same well-being items as used by Gallup; 2,321 individuals consented to share their Facebook data and had posted at least 100 posts on Facebook. Emotion measurements based on word-level and data-driven methods were obtained and compared against self-reported well-being. This study was approved by the Institutional Review Board at the University of Pennsylvania.<sup>###</sup>

## Data Availability

The Gallup-Sharecare Well-Being Index data are available by institutional subscription. County language estimates are available in the WWBP GitHub repository ([https://github.com/wwbp/county\\_tweet\\_lexical\\_bank](https://github.com/wwbp/county_tweet_lexical_bank)) (48). Replication code and the WWBP life satisfaction model are contained in the Open Science Framework archive (<https://osf.io/jqk6f/>) (49).

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<sup>† † †</sup> Additional information is in *SI Appendix, Supervised Person-Level Methods and Table S2*.

<sup>§ § §</sup> *SI Appendix* and ref. 28 have further details on the language data extraction process.

<sup>¶ ¶ ¶</sup> *SI Appendix, Fig. S1* shows the inclusion criteria.

<sup>###</sup> Dataset statistics are provided in *SI Appendix, Tables S1A and S12*.

- C. Exton, M. Shinwell, Policy use of well-being metrics. (2018). <https://www.oecd-ilibrary.org/content/paper/d98eb8ed-en>. Accessed 20 October 2019.
- M. Durand, *Countries' Experiences with Well-Being and Happiness Metrics* (Global Happiness, 2018).
- OECD, OECD Guidelines on Measuring Subjective Well-Being. (2013). <https://www.oecd-ilibrary.org/content/publication/9789264191655-en>. Accessed 20 October 2019.
- United Nations, About the Sustainable Development Goals. (2018). <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>. Accessed 20 October 2019.
- S. C. Guntuku, D. B. Yaden, M. L. Kern, L. H. Ungar, J. C. Eichstaedt, Detecting depression and mental illness on social media: An integrative review. *Curr. Opin. Behav. Sci.* **18**, 43–49 (2017).

- D. J. McIver *et al.*, Characterizing sleep issues using Twitter. *J. Med. Internet Res.* **17**, e140 (2015).
- R. M. Merchant *et al.*, Evaluating the predictability of medical conditions from social media posts. *PLoS One* **14**, e0215476 (2019).
- J. C. Eichstaedt *et al.*, Psychological language on Twitter predicts county-level heart disease mortality. *Psychol. Sci.* **26**, 159–169 (2015).
- M. Luhmann, Using big data to study subjective well-being. *Curr. Opin. Behav. Sci.* **18**, 28–33 (2017).
- L. Mitchell, M. R. Frank, K. D. Harris, P. S. Dodds, C. M. Danforth, The geography of happiness: Connecting Twitter sentiment and expression, demographics, and objective characteristics of place. *PLoS One* **8**, e64417 (2013).

11. H. Andrew Schwartz *et al.*, "Characterizing geographic variation in well-being using tweets" in *Seventh International AAAI Conference on Weblogs and Social Media*, E. Kiciman, N. B. Ellison, B. Hogan, P. Resnick, I. Soboroff, Eds. (Association for the Advancement of Artificial Intelligence, Cambridge, MA, 2013), pp. 583–591.
12. D. Quercia, D. O. Seaghdha, J. Crowcroft, "Talk of the city: Our tweets, our community happiness" in *Proceedings of the Sixth AAAI International Conference on Weblogs and Social Media*, J. Breslin, N. B. Ellison, J. G. Shanahan, Z. Tufekci, Eds. (Association for the Advancement of Artificial Intelligence, Dublin, Ireland, 2012), pp. 555–558.
13. J. W. Pennebaker, R. L. Boyd, K. Jordan, K. Blackburn, "The development and psychometric properties of LIWC2015" (University of Texas at Austin, Austin, TX, 2015).
14. M. E. Seligman, *Flourish: A Visionary New Understanding of Happiness and Well-Being* (Simon and Schuster, 2012).
15. H. Andrew Schwartz *et al.*, "Choosing the right words: Characterizing and reducing error of the word count approach" in *Second Joint Conference on Lexical and Computational Semantics (\*SEM), Volume 1: Proceedings of the Main Conference and the Shared Task: Semantic Textual Similarity*, M. Diab, T. Baldwin, M. Baroni, Eds. (Association of Computational Linguistics, Atlanta, GA, 2013), vol. 1, pp. 296–305.
16. M. M. Bradley, P. J. Lang, "Affective Norms for English Words (ANEW): Instruction manual and affective ratings" (Tech. Rep.C-1, The Center for Research in Psychophysiology, University of Florida, Gainesville, FL, 1999).
17. P. S. Dodds, K. D. Harris, I. M. Kloumann, C. A. Bliss, C. M. Danforth, Temporal patterns of happiness and information in a global social network: Hedonometrics and Twitter. *PLoS One* 6, e26752 (2011).
18. D. Preotiuc-Pietro *et al.*, "Modelling valence and arousal in Facebook posts" in *Proceedings of the 7th Workshop on Computational Approaches to Subjectivity, Sentiment and Social Media Analysis*, A. Balahur, E. van der Goot, P. Vossen, A. Montoyo, Eds. (Association for Computational Linguistics, San Diego, CA, 2016), pp. 9–15.
19. M. Jaggi, F. Uzdilli, M. Cieliebak, "Swiss-chocolate: Sentiment detection using sparse SVMs and part-of-speech n-grams" in *Proceedings of the 8th International Workshop on Semantic Evaluation SemEval 2014*, P. Nakov, T. Zesch, Eds. (Association for Computational Linguistics, Dublin, Ireland, 2014), pp. 601–604.
20. S. A. Golder, M. W. Macy, Diurnal and seasonal mood vary with work, sleep, and daylight across diverse cultures. *Science* 333, 1878–1881 (2011).
21. P. S. Dodds *et al.*, Human language reveals a universal positivity bias. *Proc. Natl. Acad. Sci. U.S.A.* 112, 2389–2394 (2015).
22. P. Liu, W. Tov, M. Kosinski, D. J. Stillwell, L. Qiu, Do Facebook status updates reflect subjective well-being? *Cyberpsychol. Behav. Soc. Netw.* 18, 373–379 (2015).
23. J. Sun, H. A. Schwartz, Y. Son, M. L. Kern, S. Vazire, The language of well-being: Tracking fluctuations in emotion experience through everyday speech. *J. Pers. Soc. Psychol.* 118, 364–387 (2019).
24. J. Gibbons *et al.*, Twitter-based measures of neighborhood sentiment as predictors of residential population health. *PLoS One* 14, e0219550 (2019).
25. H. A. Schwartz *et al.*, Personality, gender, and age in the language of social media: The open-vocabulary approach. *PLoS One* 8, e73791 (2013).
26. J. Devlin, M.-W. Chang, K. Lee, K. Toutanova, Bert: Pre-training of deep bidirectional transformers for language understanding. arXiv:1810.04805 (11 October 2018).
27. A. Radford, K. Narasimhan, T. Salimans, I. Sutskever, Improving language understanding by generative pre-training. (2018). [https://s3-us-west-2.amazonaws.com/openai-assets/research-covers/language-unsupervised/language\\_understanding\\_paper.pdf](https://s3-us-west-2.amazonaws.com/openai-assets/research-covers/language-unsupervised/language_understanding_paper.pdf). Accessed 14 April 2019.
28. S. Giorgi *et al.*, "The remarkable benefit of user-level aggregation for lexical-based population-level predictions" in *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, E. Riloff, D. Chiang, J. Hockenmaier, J. Tsujii, Eds. (Association for Computational Linguistics, Brussels, Belgium, 2018), pp. 1167–1172.
29. H. A. Schwartz *et al.*, "Dlatc: Differential language analysis toolkit" in *Proceedings of the 2017 Conference on Empirical Methods in Natural Language Processing: System Demonstrations*, L. Specia, M. Post, M. Paul, Eds. (Association for Computational Linguistics, Copenhagen, Denmark, 2017), pp. 55–60.
30. J. Butler, M. L. Kern. "The PERMA-Profilr: A brief multidimensional measure of flourishing." *Int. J. Wellbeing* 6, 1–48 (2016).
31. S. Giorgi, L. H. Ungar, H. A. Schwartz, Correcting sociodemographic selection biases for population prediction. arXiv:1911.03855 (10 November 2019).
32. G. McCulloch, *Because Internet: Understanding the New Rules of Language* (Riverhead Books, 2019).
33. J. W. Pennebaker, L. D. Stone, Words of wisdom: Language use over the life span. *J. Pers. Soc. Psychol.* 85, 291–301 (2003).
34. United States Census Bureau, Five-year trends available for median household income, poverty rates and computer and internet use. (2017). <https://bit.ly/2ClyrXJ>. Accessed 14 April 2019.
35. J. L. Tsai, B. Knutson, H. H. Fung, Cultural variation in affect valuation. *J. Pers. Soc. Psychol.* 90, 288–307 (2006).
36. J. W. Pennebaker, C. K. Chung, J. Frazee, G. M. Lavergne, D. I. Beaver, When small words foretell academic success: The case of college admissions essays. *PLoS One* 9, e115844 (2014).
37. W. M. Rohe, M. A. Stegman, The effects of homeownership: On the self-esteem, perceived control and life satisfaction of low-income people. *J. Am. Plann. Assoc.* 60, 173–184 (1994).
38. Ed Diener, M. E. P. Seligman, Beyond money: Toward an economy of well-being. *Psychol. Sci. Publ. Interest* 5, 1–31 (2004).
39. R. F. Baumeister, Religion and psychology: Special issue. *Psychol. Inq.* 13, 165–167 (2002).
40. J. F. Helliwell, R. D. Putnam, The social context of well-being. *Phil. Trans. Biol. Sci.* 359, 1435–1446 (2004).
41. S. Cohen, T. A. Wills, Stress, social support, and the buffering hypothesis. *Psychol. Bull.* 98, 310–357 (1985).
42. R. M. Ryan, E. L. Deci, On happiness and human potentials: A review of research on hedonic and eudaimonic well-being. *Annu. Rev. Psychol.* 52, 141–166 (2001).
43. E. S. Kim *et al.*, Social media as an emerging data resource for epidemiologic research: Characteristics of social media users and non-users in the Nurses' Health Study II. *Am. J. Epidemiol.*, 10.1093/aje/kwz224 (2019).
44. K. Jaidka, N. Chhaya, L. Ungar, "Diachronic degradation of language models: Insights from social media" in *Proceedings of the 56th Annual Meeting of the Association for Computational Linguistics*, I. Gurevych, Y. Miyao, Eds. (Association for Computational Linguistics, Melbourne, Victoria, Australia, 2018), vol. 2, pp. 195–200.
45. J. Eisenstein, B. O'Connor, N. A. Smith, E. P. King, Diffusion of lexical change in social media. *PLoS One* 9, e113114 (2014).
46. K. Jaidka, S. C. Guntuku, A. Buffone, H. A. Schwartz, L. Ungar, "Facebook vs. Twitter: Differences in self-disclosure and trait prediction" in *Proceedings of the International AAAI Conference on Web and Social Media*, J. Hancock, K. Starbird, I. Weber, Eds. (Association for the Advancement of Artificial Intelligence, Stanford, CA, 2018), pp. 141–150.
47. S. C. Guntuku, A. Buffone, K. Jaidka, J. C. Eichstaedt, L. H. Ungar, "Understanding and measuring psychological stress using social media" in *Proceedings of the International AAAI Conference on Web and Social Media*, J. Pfeffer, C. Budak, Y.-R. Lin, F. Morstatter, Eds. (Association for the Advancement of Artificial Intelligence, Munich, Germany, 2019), vol. 13, pp. 214–225.
48. World Well Being Project, U.S. County level word and topic loading derived from a 10% Twitter sample from 2009–2015. [https://github.com/wwbp/county\\_tweet\\_lexical\\_bank](https://github.com/wwbp/county_tweet_lexical_bank). Deposited 3 November 2018.
49. K. Jaidka, J. C. Eichstaedt, S. Giorgi, Data and resources for estimating geographic subjective well-being from Twitter: A comparison of dictionary and data-driven language methods. Open Science Framework. <https://osf.io/jqk6f/>. Deposited 7 April 2020.